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Optimal management of energy hubs and smart energy hubs – A review

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ABSTRACT

The increase of environmental concerns, scarcity of fossil fuel resources, uncontrolled growth of demand, along with the development of efficient multi-generation systems have made the restructuring of current energy systems inevitable. Future energy systems will be in the form of sustainable multi-energy systems. The optimal operation of such systems requires an integrated energy management system for optimal planning, control and management. Energy hub is a new and promising concept for optimal management of systems with multiple energy carriers. Energy hub has a large potential for realization of energy system models and moving towards sustainable multi-energy systems. This paper provides a comprehensive overview of the concepts and different applications of energy hubs in various energy consumption sectors including residential, commercial, industrial, agricultural, and the integration of these systems. The potential role of energy hub as an integrated energy management system to solve the main challenges in these consumption sectors is evaluated. This study focuses on the benefits earned by integration of the options such as demand side management, distributed energy resources, renewable energy resources, multi-generation systems, storage systems as well as using the smart technologies by introducing the concept of smart energy hubs.

1. Introduction

Energy has always been one of the basic human needs and now with the advent of various energy consumer technologies and increasing the dependence of human life style on energy, this need becomes more apparent. Therefore, supplying a sustainable, clean, secure and affordable energy is one of the main challenges of the present century [1]. In the past century, fossil fuels were the main source of energy in different parts of the world. The dominant form of this energy supply was in the form of electricity production through centralized power plants. However, the scarcity and environmental effects of fossil fuel resources are among the challenges leads to thinking about the alternative solutions and more efficient energy resources [2].

The traditional power systems have a hierarchical structure and the energy generated in central power plants is transported long distances to the place of consumption. However, the low efficiency of primary energy consumption, huge investment costs, high losses, control and protection problems, have led to serious problems in the performance of such systems. In these systems, intelligent equipment can only be used locally by protection, control and data collection systems. But now, power systems are getting smarter and automated which called smart grid [3]. Smart grid in addition to traditional network's tasks such as generation, transmission, and distribution of power has the ability to store, interact and make decisions. Smart grids try to use advanced applications and the use of communications, information management and automated monitoring technologies to develop, optimize and improve the performance of the electricity network infrastructures. Smart grid leads to increase efficiency in demand supply and optimal using of existing infrastructure that minimizes the need to system development. On the other hand, smart grid facilitates the integration of renewable energy sources (RES) especially in the form of distributed generation (DG) on the demand side [4].

The development of distributed energy resources (DER), in particular, RES and multi-generation systems, are promising options that can change the energy production concept from large centralized power plants to the local and distributed generation in the future. In the past five years, new renewable energy investments in each year have been at least $ 200 billion and this amount was $ 265 billion in 2016. In this context, the share of renewable energy from total global energy consumption was 19.3% in 2015 and 24.5% of the global electricity was

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supplied from RES in 2016. Different scenarios have predicted the share of RES in global energy consumption up to 82% in 2050 [5].

The development of more efficient prime movers and improvement of market conditions for efficient technologies such as micro-turbines and internal combustion engines have provided the possibility to integrate the advantages of DER, in the form of cogeneration systems such as combined heat and power (CHP) systems. Trigeneration systems can be created by adding equipment such as chiller to these systems for production of cooling. Adding renewable technologies such as fuel cells leads to the integrated production of electricity, heating, cooling, hydrogen, water, chemicals and so on. This combination results in poly-generation systems and increases the hope to create clean multi-energy systems (MES) with higher efficiency. The optimal management of such systems can bring many technical, economic and environmental advantages [6].

The existence of DER in demand side, in addition to the supplying of the local consumers' demand, can lead to active participation of consumers in demand-side management (DSM) programs and network management. DSM is a broad concept which includes features such as load growth, energy conservation, energy efficiency, and demand response (DR) programs. DER, especially local RES and energy storage systems (ESS), can provide consumer's demand in hours of high energy prices that reduce the dependence of consumers on the main grid. The shifting of the consumers' demand from high energy price periods to lower energy price periods reduces consumers' energy costs and reduce the amount of peak demand on the network. In a different manner, reducing unnecessary loads at the certain periods (peak demand periods or at the request of the system operator) will lead to further savings in energy consumption and cost reduction. Therefore, the implementation of DSM programs in addition to the many advantages for consumers can lead to improved stability and reliability of the main grid [7].

However, utilizing the benefits of the concepts outlined above, such as DER, smart grid, MES, and DSM programs requires an integrated modeling and management framework. Energy hub is an efficient and promising concept which has been introduced in recent years for the MES management [8]. Energy hub is defined as a framework where production, conversion, storage and consumption of different energy carriers is done [9]. Energy hub has a high potential in the modeling and management of the systems with multiple energy carriers or the interconnected energy systems. A Huge number of researches have been done on energy hub concept and prove that considering the different energy carriers in the energy hub framework can lead to better performance than systems which are independently planned and controlled. Energy hubs do not have any size limitation and can include many cases such as a single home, large residential complexes, commercial buildings, shopping malls, hospitals, industrial units, greenhouses, rural energy systems and even an entire city energy system. However, the main questions are: What is the potential of the energy hub concept in each consumption sectors? What is the application of the energy hub model in a residential home or commercial buildings or industrial sector or agriculture? What are the major energy issues in these sectors? And what is the potential role of the energy hub in these sectors and aggregation of these sectors?

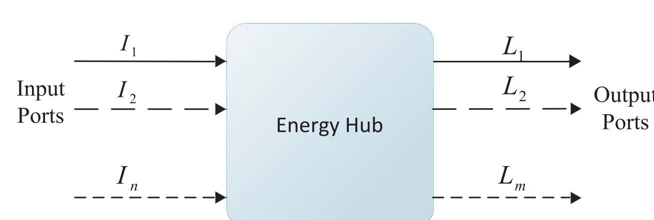
This paper presents a holistic review of the concepts and applications of the energy hub to answer the above questions. In the current study, based on consumption sector, the energy hubs are divided into the four main sectors: residential, commercial, industrial and agricultural micro energy hubs. Energy systems in each sector are assessed individually to determine the main challenges in each sector. The potential role of energy hub concept for solving the challenges of each consumption sector is discussed. This paper also discusses the benefits and challenges related to the integration of the energy sectors and creation of a network of interconnected energy hubs. The main objective of this review is to present a comprehensive overview of the concepts and applications of energy hub, focusing on the concepts such as DSM, multi-generation systems, DER especially RES, and ESS.

In this regard, the analysis framework of this manuscript is organized as follows. Section 2 provides an introduction to the concepts and definition of the energy hub and discuss why using this concept is useful to analysis energy systems and new energy technologies to achieve a realistic model of sustainable energy systems. The energy hubs based on the consumption sector are divided into four main micro energy hubs. Section 3 discusses the features and challenges of energy systems in residential, commercial, industrial, and agricultural sectors and evaluates the potential role of energy hub as an integrated energy management system in solving these challenges in each of these micro energy hubs. The integration of micro energy hubs creates a concept called macro energy hub, in which a set of the energy hubs can be controlled and programmed coordinately. Section 4 discusses the benefits and challenges related to the integration of the micro energy hubs and creation of a network of interconnected energy hubs. However, due to a large number of energy carrier and technologies in micro energy hubs and also many connections in a macro energy hub and the need to exchange and process large volumes of data, the use of smart grid technologies can improve the performance of energy hubs. The Smart energy system is the advanced form of smart grid concept that is able to optimally manage different energy carriers and systems. Section 5 discusses the use of intelligent technologies to exploit the advantages of smart energy systems in the form of smart energy hubs. Section 6 contains the concluding remarks.

2. Energy hub concept

The energy hub concept was presented in the context of a project called A Vision of Future Energy Networks (VOFEN) [10]. The aim of this project was to create a picture of the future energy systems in long-term (20–30 years). The concept of energy hub for the first time was defined as the interfaces between consumers, producers, storage devices and transmission devices in different ways: directly or via conversion equipment, handling one or several carriers [10]. Fig. 1 shows the matrix model of the energy hub concept which correlates various energy carriers at the input and output via the coupling matrix. Each of the matrix element represents the energy hub interior features, including the connection and transform coefficients and the efficiency of the converter and internal components of the energy hub.

The definition of an energy hub was presented later in [9] as a unit where multiple energy carriers can be converted, conditioned, and stored. A more precise definition of the energy hub can be found in [12] as a unit that provides the features of input, output, conversion, and storage of multiple energy carriers. Sometimes the hybrid energy phrase is used for the energy hub where the hybrid word refers to the interaction of different energy carriers in the energy hub [13]. Therefore, the energy hub or hybrid energy hub can be defined as the place where production, conversion, storage, and consumption of different



$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{m1} & C_{m2} & \cdots & C_{mn} \end{bmatrix} = \begin{bmatrix} L_1 \\ L_2 \\ \vdots \\ L_m \end{bmatrix}$$

Fig. 1. The matrix model of the energy hub concept [11].