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Low carbon transition in a distributed energy system regulated by localized energy markets

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ABSTRACT

Low carbon transition becomes an urgent need of modern societies for energy conservation and environmental protection. The purpose of this work is to evaluate the roles of market regulation, energy consumption and energy capacity in low carbon transition for distributed energy systems through an agent-based simulation. A set of agent behavioral rules for the competition of high carbon and low carbon energies mimics the local dynamics of the energy production of distributed energy systems and the energy consumption of industrial firms under the impact of energy market fluctuation. Simulation results show that under the condition of increased energy capacities with a positive feedback between supply and demand, low carbon transition can be facilitated by the combination of market adjustment favoring low carbon energies and the policy adjustment for low energy consumptions. By contrast, with low energy capacities and high energy consumptions, transitions from high-carbon economy to low-carbon economy inevitably render a catastrophic economic depression. Policy implications for different situations of countries are drawn regarding the regulation of localized energy markets for restricting the supply of high carbon energy while cultivating the demand for low carbon energy, and the improvement on energy saving, energy production efficiency, and storage capacity.

1. Introduction

In the 21st century, the usage of high carbon fossil fuels in industrial processes is the key driver of climate change (Edenhofer et al., 2014), and the industrialized urban areas have taken the major portions of energy consumption and carbon dioxide emissions especially in developing countries (Wang et al., 2016; Zhang and Lin, 2013). Accordingly, taking mitigation actions on an urban level is considered as more efficacious than on a national level (Rosenzweig et al., 2010). With the decrease in renewable energy cost and the increase in energy storage capacity brought by recent technological innovations (Nykvist and Nilsson, 2015; Kittner et al., 2017; Schmidt et al., 2017; Trancik, 2014), the building of distributed energy systems becomes a promising utilization that may significantly contribute to the reduction of greenhouse gas emissions, to the enhancement of energy efficiency and to the growing share of renewable energies (Howell et al., 2017; Facchini, 2017). As shown in Fig. 1, decentralized or controllably distributed multiple energy generation and storage of energies, such as electricity, thermal power and especially the low carbon energies, are locally provided to consumers in the distributed energy systems, while the introduction of carbon markets favors the development of low carbon energy and restricts the usage of high carbon energy. Additionally, on one hand, distributed energy systems can provide the regional economy with substantial benefits from the reduced social costs in terms of reduced fuel costs and health care costs, etc. (Paliwal et al., 2014; Allan et al., 2015). On the other hand, with the high penetration of low carbon energy in the distributed energy system, both the supply and the demand side of high carbon energy industries need to seriously consider the exhaustion of fossil fuels (Shafiee and Topal, 2009; Höök and Tang, 2013), as well as the extra cost for energy saving and environmental protection (Tang et al., 2015, 2017; Liu et al., 2015). The development of distributed energy systems entails the establishment of the localized energy markets for an easy regulation of the demand and supply of different types of energy, because the traditional one, namely the national energy market has difficulty to be integrated into the distributed energy systems (Ilic et al., 2012). Therefore, to facilities a smooth transition towards a low-carbon-dependent paradigm (hereafter shortened as “low carbon transition”), it is important to study the distributed energy systems with the consideration of localized energy industries and localized energy markets.

In recent years, extensive research on the low carbon transition has been done in aspects of social technical transition system, market

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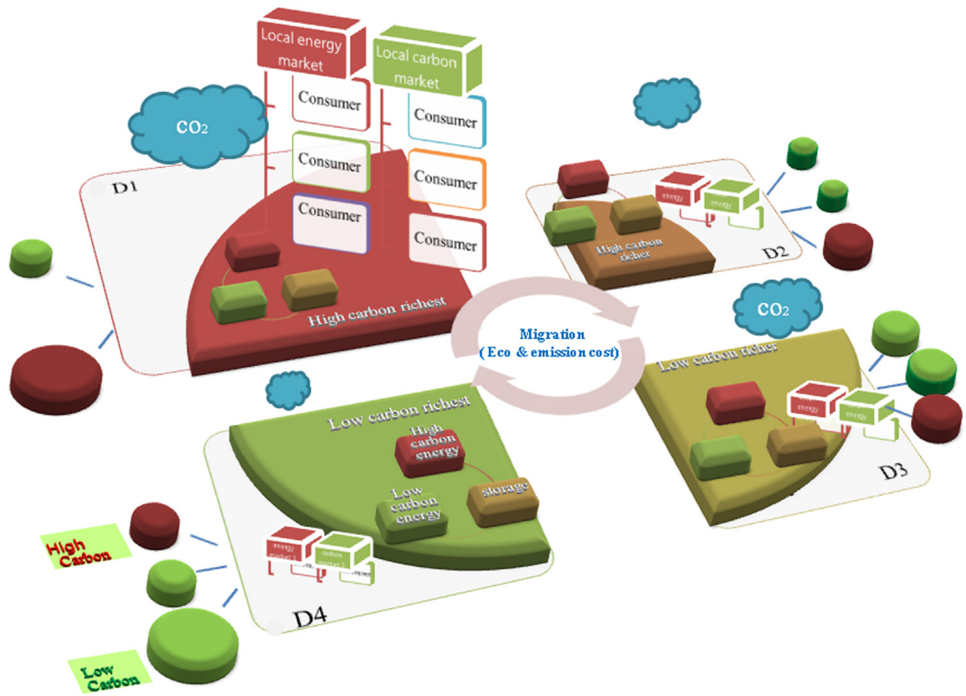

Fig. 1. A schematic map of distributed energy systems combined with localized energy markets.

regulation and technical innovation. Firstly, some of previous works have contributions from the socio-technical transitions theory to address low carbon transition (Rip and Kemp, 1998; Geels, 2004). These works conceptually described the importance of alignments between developments at multiple levels, characterized in the multi-level perspective (MLP) as niche-innovations, existing regimes and exogenous landscape. Geels and Schot (2007) subsequently constructed a typology based on combinations between two dimensions: the timing and nature of multi-level interactions to describe four different transition pathways resulted from different kinds of alignments: technological substitution, transformation, reconfiguration, and de-alignment and re-alignment. In addition, Schot et al. (2016) suggested that transitions shifting from one socio-technical regime and system to another, involving interactions between landscapes, regimes and niche dynamics can be conceptualized as a sequence of three phases: (1) Start-up (a window of opportunity for novelties emerge and mature in niches in which the internal problems of the regime are intensified by landscape pressure); (2) Acceleration (niches enter the mainstream market and start to compete with the incumbent regime);(3) Stabilization (the niche gradually establishes itself as a new regime).

Secondly, for the localization of energy markets in the distributed energy system, Ilic et al. (2012) concluded that if the trend of the distributed energy system continues, localized energy markets can be technically realized in future smart grid cities. Teotia and Bhakar (2016) envisaged the design and operation of a Local Energy Market (LEM), where it is pointed out that the traditional energy market is facing challenges in integrating the new sources of energy, infrastructure and the expanding demand emergent from the consumer-oriented market, and thence LEM can be a solution by which the distributed energy generation, the microgrid, and the smart grid could be organized within one energy market at the ends of distribution. In addition, carbon emission trading is considered as a powerful mechanism for regulating high and low carbon energy markets, in particular, Tang et al., (2015, 2017) and Liu et al. (2015) pointed out that China, as one of the largest carbon emitters, has promised to lower its carbon intensity by 40–45% of that in 2005 by 2020 by launching seven pilot carbon emission trading programs in 2011.

Thirdly, some researches paid more attention to the technical innovation of the energy generation and storage. Bajpai and Dash (2012) emphasized that developing new and renewable energies, and accelerating the modernization of energy industry systems should be the essential strategy for energy development under the low-carbon economy; Mahlia et al. (2014) reviewed various techniques of energy storage including compressed air energy storage (CAES), flywheel energy storage (FES), pumped hydro energy storage (PHES), battery energy storage (BES), flow battery energy storage (FBES), superconducting magnetic energy storage (SMES), super capacitor energy storage (SCES), hydrogen energy storage, synthetic fuels, and thermal energy storage (TES) with additional information about the recent update of the storage technology.

Moreover, many empirical studies have investigated the pragmatic issues involved in the low carbon transition. For instance, Goldthau (2017) stated that the world's energy system needs rebuilding by replacing fossil fuels with solar, wind, geothermal and biomass energy to meet the targets of the Paris Agreement (Rogelj et al., 2016; Hulme, 2016). Rutherford and Jaglin (2015) reviewed a special issue regarding the urban energy governance from the perspectives of local actions, capacities, and policies, from which they concluded that the distributed energy systems are crucial to the analysis of the degree, form, direction, and outcomes of low carbon transition processes. Finally, a comprehensive investigation of the relationship between energy supply/demand and the local carbon emissions in different local areas in China can be found in literatures (Zhang and Lin, 2013; Wang et al., 2016).

As shown in the literature review above, some studies considered the combination of distributed energy systems with localized energy markets merely on the conceptual level, while others mainly considered the low carbon energy penetration with the focus limited on the technical aspects. For a pragmatic application, however, further investigations are demanded on the coordination of the local economy and the distributed energy systems to attain constructive suggestions for the efficient realization of low carbon transition. Hence, our study adopts an agent-based model to simulate a distributed energy system coupled with localized energy markets for exploring the relationship among some key factors and their combined effect on the low carbon transition