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Market designs for a 100% renewable energy system: Case isolated power system of Israel

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ABSTRACT

This paper examines market design options for a 100% renewable energy system taking a behavioral simulation approach. Various market models are tested to understand whether the current energy only market design is suitable to provide investment incentives and operate the 100% RES reliably and economically, or whether an additional capacity remunerative mechanism might be needed. Markets are analyzed with respect to the short-term operation of the technologies and the long-term development of the generation mixes in the 100% RES, and compared in terms of reliability and costs for the consumers. The results indicate that with the energy only market design, it is possible to solve the cost recovery and investment incentive problem in the 100% RES if market prices take account of the opportunity costs of flexible resources. A capacity mechanism may be needed to reduce the risk of underinvestment in flexible resources. The 100% RES system will require markets to accommodate the operational specifics of renewable energy generation. Therefore, the feasibility of radical market designs should be considered when analyzing the market design options for 100% RES systems.

1. Introduction

Mitigation of climate change is increasingly pushing energy systems towards decarbonization. Often, this is achieved by increasing the proportion of renewable energy production (wind, photovoltaics, biomass, and biogas) in the system. Transformation into a 100% renewable electricity system (RES) will require markets to accommodate the operational specifics of renewable energy generation. Numerous studies have shown the potential and technical feasibility of 100% RES in different regions. These studies apply an optimization model and provide a vision of a cost-minimum 100% RES, yet do not specify a transition path to it. Models on country-specific renewable systems of various degrees have been made for Australia [1], Denmark [2], Finland [3,4], Germany [5], Ireland [6], Portugal [7], and even on a global scale [8]. However, as long as most of the electricity markets are deregulated, the question remains: what kind of a market design is feasible in the fully renewable system?

The existing deregulated electricity markets can mainly be classified as energy only markets or energy plus capacity markets. Energy only markets trade electricity (€/MWh) and, without market imperfections, are believed to provide adequate cost recovery [9]. However, there are many discussions on whether the short-term operation in energy only markets could provide sufficient incentives for long-term investments [10–12]. Binding price caps and other regulatory failures may create a risk of “missing money” in energy only markets leading to a shortfall in revenues to provide adequate investment incentives. Recently, the “missing money” problem has been aggravated by the growing proportion of variable renewable generation. Renewable production technologies have typically a low marginal cost and a high volatility, which reduces the price level and raises concern over capacity adequacy. A high proportion of variable renewable energy production needs complementary flexible capacity in order to maintain power balance. In addition to dispatchable generation such as biomass plants, demand-side management [13], energy storages [14,15], and enhanced use of transmission connections [16] are often assumed to be the main sources of flexibility. If energy only markets fail to attract sufficient capacity to meet certain reliability standards, regulatory mechanisms for ensuring the security of supply such as capacity mechanisms could be introduced. The purpose of capacity mechanisms is to ensure the profitability of the existing power plants and to guarantee or at least support investments [17]. There are different forms of capacity remunerative mechanisms ranging

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from capacity auctions and capacity payments to strategic reserves (SR) [18]. To the authors' knowledge, the literature fails to acknowledge simulations on fully renewable markets to understand if the current energy only market or the energy plus capacity markets are suitable to provide investment incentives and operate 100% RES reliably and economically. Some studies focus on analyzing the possible effect of renewables on the wholesale prices [19–21], yet do not contribute to the question of the preferred market design. In Ref. [22], potential electricity market designs for neo-carbon society scenarios are investigated by taking an approach that relies on theoretical and social studies; nevertheless, a quantitative analysis of the viability of the market designs in 100% RES receives only limited attention in the paper [23]. provides qualitative analysis of market design options for the 100% RES and concludes that the current energy only model may be suitable for a fully renewable system by adopting certain market rules. The study also discusses more radical market design options such as compensating generators by the average production or long-term marginal costs while maintaining the marginal-cost-based dispatch or introducing long-term feed-in tariffs or technology-specific auctions with an obligation to supply power. However, with the long asset lives of the electricity industry, the viability of different market options has to be carefully evaluated quantitatively. This paper fills the research gap and tackles the question about the market designs that provide cost recovery and continuous investments in the 100% RES. The European policy discussions seem to focus on developing energy only markets instead of the more radical design options [24,25]; therefore, we rather focus on testing the feasibility of existing market design models in the 100% RES. By applying the methodology of soft-linking of optimization and simulation models, numerous existing market designs are tested numerically and analyzed with respect to the short-term operation of the technologies and the long-term development of the generation mixes in the 100% RES, and compared in terms of reliability and costs for the consumers. The paper is structured as follows. Section 2 details the modeling approach we have used to test the market design options numerically. Section 3 presents the input data. The results are given in Section 4, while Section 5 provides a conclusion and policy implications.

2. Methodology

Electricity market models can be divided into optimization, equilibrium, and simulation models [26]. Optimization models maximize or minimize a specific objective function, that is, the profit function of a single firm. Equilibrium models are able to address several market participants' profit maximization simultaneously. A comprehensive review on the optimization and equilibrium modeling tools used for energy system analysis is presented in Ref. [27]. Among these tools, there are models with more than 1000 users, such as RETScreen, HOMER, LEAP, BCHP Screening Tool, and energyPro, while Homer and EnergyPlan optimization tools are used to model the 100% RES for different regions ([2] [3] [6]). Yet, optimization and equilibrium approaches are largely static and present limitations to assess transitional stages or systems away from equilibrium. Considering simulation models, an example could be agent-based models, which usually take a behavioral simulation approach, and the final structure of the system depends on the market rules applied to the agents and their corresponding behavior [28]. Opposite of equilibrium and optimization models, simulation models allow observation of the dynamic evolution of the system under different policies and scenarios, and are able to integrate such aspects of electricity markets as imperfect competition, asymmetric information, players' individual behavior, and strategic interactions in a more realistic way. Thus, simulation models reflect realistic market conditions and close to real-world short-term operating and long-term investment decision-making processes, which is highly important due to challenges arising in the integration of variable renewable generation into electricity markets [29]. Extensive discussion on the application of agent-based simulation models in electricity markets can be found for instance in literature review studies in Refs. [30–32]. A detailed overview of the existing multi-agent energy system simulation tools is provided in Ref. [33]. These tools include EMCAS (The Electricity Market Complex Adaptive System), AMES (Agent-based Modeling of Electricity Systems), MASCEM (Multi-agent Simulator for Competitive Electricity Markets), MAN-REM (Multi-Agent Negotiation and Risk Management in Electricity Markets), and many others. The simulation models have been applied to address various electricity market research questions, for instance the impact of energy and environmental policies and market designs on the long-term evolution of power systems [30,34,35].

The following sections present the description of the model applied in this paper to numerically test the market design options in the 100% RES. At this stage, we are not proposing radical changes in the market design as described in Ref. [23]. We rather focus on testing the feasibility of the present market design models in the 100% RES. Table 1 provides an overview of the market design options considered in the paper.

2.1. Model description

To analyze the impact of market design rules and policies on the short-term operation and long-term development of the 100% RES, we apply the methodology of soft-linking of two separate models: optimization and simulation. Firstly, we use a static optimization approach to obtain an initial cost-minimum 100% RES for the reference year 2030. The initial system is a result of an energy system optimization model with an objective of minimizing the total costs of a renewable energy system from the perspective of a central planner or regulator. For more details of the model, see Ref. [36]. We do not specify how the 100% RES would be achieved by 2030; it is outside the scope of the paper to model a roadmap and market policies for the purpose. Rather, we are interested in analyzing which market designs will advance this scenario, that is, provide incentives for further investments and enable reliable operation of the 100% RES at the lowest possible costs for consumers. In other words, we want to simulate the possible market dynamics of the 100% RES showing possible and realistic short-term and long-term behavior of market players, market prices, and evolution of generation mixes over years depending on the market rules applied. For this purpose, we apply a simulation

Table 1
Market design options.

	Market design	Electricity market	Capacity mechanisms
EO	“Energy only” market	Pool with marginal pricing	No
EO-CA	“Energy-plus-capacity” market	Pool with marginal pricing	Pay-as-bid capacity auction
EO-SR	“Energy-plus-strategic reserve” market	Pool with marginal pricing	Strategic reserve