Death Spiral, Transmission Costs, and Prosumers in the Power Market

Yihsu Chen
Associate Professor of Technology Management in Sustainability, Baskin School of Engineering, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, United States. (831) 502-7184
Email: yihsuchen@ucsc.edu.

Ryuta Takashima
Associate Professor, Tokyo University of Science, Kagurazaka, 1 Chome-3, Shinjuku 162-0825, Tokyo, Japan.
Email: takashima@rs.tus.ac.jp.

Death Spiral, Transmission Costs, and Prosumers in the Power Market

Yihsu Chen[*] Ryuta Takashima[†]

Abstract

Presence of prosumers who own distributed renewables coupled with backup options, such as fossil-fueled units and storage, has been viewed as an effective option to enhance the power system's resilience. The current rate design is that the transmission surcharge mainly is for recovering costs associated with lumpy transmission investment, variable cost related to routine maintenance, and expected revenue to cover other costs of transmission system. Thus, a decline in reliance of bulk power market owing to an increase of consumers converting to prosumers will therefore shift transmission costs to other traditional consumers. Death spiral, which describes a situation by which consumers might self-sort to become a prosumer, thereby leaving consumers who are financially unable to convert to prosumers, bear an increasing transmission surcharge, is recently subject to debates and considered as an unintended consequence.

This paper studies the impacts of transmission surcharge in presence of prosumers by explicitly considering their optimization problem in the market. The prosumers are formulated either as a price-taker or a strategic entity and are assumed to decide amount of renewable to forgo, amount of dispatchable energy to produce, and amount of energy to sell into or buy from the bulk energy market while subjecting to uncertain output from renewables. We find that transmission cost does not necessarily increase with proportion of prosumers in the market. The bulk power market could benefit from lower power prices due to zero marginal cost renewables introduced by prosumers. Transmission surcharge could be worsened by strategic prosumers as they

---

[*] Corresponding author. Associate Professor of Technology Management in Sustainability, Electronic and Computer Engineering, Baskin School of Engineering, University of California Santa Cruz, Santa Cruz, CA, United States. Email: `yihsuchen@ucsc.edu`.

[†] Associate Professor, Tokyo University of Science, Chiba, Japan. Email: `takashima@rs.tus.ac.jp`.

reduce their procurement from the bulk energy market. Our analysis, therefore, contributes to the recent debates to the transmission costs in presence of prosumers.

1 Introduction

The electricity markets are undergoing transformation. An increase in renewable's presence as an effort of mitigating climate change and pursuing sustainability has led to significant changes and challenges in the design and operation of modern power markets. With the availability of smart meters and IT-related technologies together with innovative business models, a growing body of customers with renewable power generation capabilities, including those behind the meter, combined with emerging distributed technologies has altered the conventional demand-side paradigm in electricity markets.

This major shift in power markets towards a more engaged and flexible demand-side involvement, although enhancing the sector's resilience, has direct impacts on the behavior and participation of various agents in the market. In particular, the presence of prosumers, who are capable of concurrent generation and consumption of power as opposed to the conventional consumers or suppliers who only participate in one side of the market, are expected to have significant implications on the design and operation of the future competitive power market (Parag and Sovacool, 2016). For example, recent focus of the power community has been on developing a platform that allows a distribution system operator to coordinate and to align with prosumers and an independent system operator at the transmission level to facilitate energy transactions.[1]

The interactions between prosumers and the wholesale power market are also facilitated by the presence of aggregators who collect and integrate demand response and distributed energy resources at the distribution level and offer the aggregated energy bundle as a product to the wholesale market (Rahimi and Ipakchi, 2010). Examples include community choice aggregators, which are popular in California and other states. These aggregators operate renewable facilities over diverse households/facilities and geographical

---

[1] In particular, the final rule of the FERC Order 745 stipulates that demand response resources participating in an organized wholesale energy market must be compensated for the service they provide to the energy market at the market price for energy, namely the locational marginal price (LMP). Moreover, issues related to the distributed energy resources aggregation reforms have been discussed by the FERC.

areas, thereby constituting a substantial distributed generation and energy management capability (Papavasiliou and Oren, 2014; Gkatzikis et al., 2013). This allows prosumers participate in the wholesale power markets through an aggregator or locally by peer-to-peer transactions beyond ordinary customers due to their duality as a producer and a consumer (Baroche et al., 2019; Eisen, 2018)

One emerging issue that has received some attention is the fact that a decline in reliance of bulk power market by prosumers might shift transmission costs to other traditional consumers who rely on utilities to procure energy from the bulk energy market as transmission cost is known to be lumpy. In fact, Bushnell (2018) argues that increasing energy procurement cost (while the wholesale energy price actually declines) by major utilities in California, such as Pacific Gas and Electric, is likely due to the recovery of fixed cost from renewable capacity induced by ambitious Renewable Portfolio Standard in California.[2,3] It is also worsened by the current rate design that the transmission surcharge mainly is for recovering costs associated with lumpy transmission investment, variable cost related to routine maintenance, and expected revenue to cover other costs of transmission system based on proportion of load share or peak energy demand, also known as postage stamp approach.[4] The situation is given the term "death spiral," which describes a situation at which consumers might self-sort to become a prosumer, thereby leaving consumers who are financially unable to convert to prosumers, bear an increasing transmission surcharge, and is recently subject to debates and considered as an unintended consequence (Graffy and Kihm, 2014; Jacobs,

---

[2] Other examples include i) "uplift cost" provision commonly used in the U.S. regional organized markets to recover lumpy capacity cost, startup, and other none-convex costs-FERC (2018) and ii) provision of the Power Charge Indifference Adjustment or PCIA under the Community Choice Aggregation program to recover the asset's stranded costs (California Public Utilities Commission, 2019).

[3] Of course, the recent announcement of PG&E's intention to file Chapter 11 bankruptcy protection due to expected liability from wildfire might reverse the trend (University of California Energy Institute, 2019).

[4] For instance, in Pennsylvania-New Jersey-Maryland (PJM) regional market, Network Integration Transmission Service is the main mechanism by which the transmission owners recover their annual transmission cost and revenue requirement from customers Constellation (2018). A second mechanism related to transmission cost in PJM is the Transmission Enhancement Charge. Those are costs associated with projects related to transmission system upgrades and enhancements in order to provide for the operational, economic, and reliability requirements of PJM customers. The costs in this case are allocated across the zones based on a resulting net benefit from those projects Constellation (2018). Rates are only set for one year and are updated in either January or June. For more information on the transmission cost allocation, see, for example, reports by (Fink et al., 2011; California ISO, 2019).

2017).

This paper studies the impacts of transmission costs and market outcomes in presence of prosumers. We extend the model by Hobbs (2001) with an explicit consideration of prosumers' optimization problem in the market. For our analysis, we make the following assumptions. i) While each prosumer might be relatively small it his/her size with a limited ability to impact the bulk energy market, we assume that a large number of prosumers enter a contract with single aggregator, who participates in the bulk energy market on their behalf. We therefore model the joint optimization of a aggregator and prosumers together. In particular, the prosumers decide amount of renewable to forgo, amount of dispatchable energy to produce, and amount of energy to sell into or buy from the bulk energy market while subjecting to exogenous and uncertain output from renewables. ii) Amount of renewable and dispatchable capacity owned by prosumers changes in commensurate with the proportion of the prosumers in the market. For example, when the percentage of the prosumers is double, the renewable output and dispatchable capacity will be double as well. In particular, we assume four levels of renewables 500, 1,000, 1,500, and 2,000 MW. iii) A fixed amount of transmission cost needs to be collected in order to recover transmission owners' investment, routine operations & maintenance cost, and other administrative costs. As prosumers are relatively new to the market, they might be subject to relatively lesser oversight, partly as a result of underdeveloped regulatory framework to address their behavior. We therefore assume them to be either a price-taker or a strategic entity while subjecting to uncertain renewables. The analysis then alters proportion of demand associated with prosumers and with traditional consumers while maintaining aggregated marginal benefit function. In order words, had the prosumers been designated as conventional consumers, all the scenarios should lead to the same market outcomes.

Our analysis has the following central findings. First, for a relatively high level of renewable output (e.g., 2,000MW case), the wholesale power sales increase first due to influx of zero-cost renewables entering the market that effectively lowers the power prices, and then decline, in part because of "death spiral" effect as prosumers rely on local energy sources rather than on procurements from the bulk energy market. Second, contrary to conventional wisdom, the impact on the transmission cost is ambiguous. On the one hand, the transmission cost could decline with an increased fraction of prosumers in the market when the prosumers only act as consumers who procure energy from the bulk energy market, e.g., 500MW case. On the other hand, with significant amount of renewable (e.g., 2,000 MW), the transmission cost could decline first (due to inflated demand) and then increase with an increased fraction of prosumers in the market. Third, the notable difference between perfect and imperfect competition lies in 500MW case. In particular, while the sales in the bulk energy market continue to rose when more consumers become prosumers under perfect competition, the fact that strategic prosumers contract their procurement from the bulk energy in order to lower the energy prices leads to a decline of the bulk energy demand as well as an elevation of the transmission costs. Our analysis, therefore, contributes to the current debates on the "death spiral" hypothesis and highlights the intrinsic relations among amount of renewables, size of prosumers, and their strategy assumption as well as their joint effect on the transmission costs.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 gives the model formulation. A numerical case study is presented in Section 4 with its results are discussed in Section 5. We then conclude our analysis in Section 6.

2 Existing Literature

Research concerning the impacts of prosumers in the power sector has received an increasing attention partly because prosumers who own distributed renewable energy resources coupled with technologies, which allow for peer-to-peer tractions or directly engage in the bulk energy market through aggregators are expected to play a crucial role in the future. For example, Chen et al. (2012) examine how a demand aggregator, operating a conventional generator and a green energy management system, affects the wholesale market by considering the aggregator exercise a quantity-based strategy. A more recent paper (Ruhi et al., 2017) studies a situation at which a load aggregator, formulated as a leader, operates renewables, a wind source for example, and contemplates to "spillover" and "curtail" its wind power to reduce energy offering into the wholesale market in order to push up the wholesale power prices. A number of other papers also contributed to understanding behavior of aggregators or prosumers. Contreras-Ocãna et al. (2019) explore the corporation between energy storage units and an aggregator using Nash Bargaining theory. The paper concludes that i) a profit-seeking energy storage aggregator is always beneficial to the system when compared to a system without storage, and ii) there could be welfare loss when an aggregator behave as a monopoly. Tveita et al. (2018) compare two cooperative game theory based approaches –nucleolus and the Shapley value– for cost allocation among prosumers (owning distributed generators and storage) and consumers. The study concludes that two approaches produce compatible outcomes. A common trait of those works, similar to reference Chen et al. (2012), is that the main focus is on generation side, where the buyer's market power is not considered in the analysis.

Another thread of research studies how might prosumers or aggregators participate in the bulk energy market. Parvania et al. (2013) investigate DR's (demand response) participation in the wholesale power market in which a DR aggregator maximizes expected payoff by offering contracts to customers based on physical constraints and capabilities, including storage, on-site generation, load shifting, and load shedding. Authors in Ottesen et al. (2016) consider a two-stage stochastic model where a prosumer's bidding (first stage) and scheduling decisions (second stage) with the objective of minimizing the prosumer's expected cost. Another study by Gabriel et al. (2006) examines optimal contract design between a retailer and an end-user when facing uncertain power prices. (To some extent, a power retailer is similar to a prosumer as it is capable of both purchasing and selling electricity except that they do not own physical assets.) The paper also treats the power prices exogenously and decides the contract price. While power price paths are simulated based on time series and artificial neural network techniques in Parvania et al. (2013), it is subject to the same limitation. Therefore, a common characteristics of the existing papers is to treat the wholesale power prices as given, and focus their attention on finding optimal contracts with customers or schedules while maximizing expected payoff. These papers fall short of allowing for examining the interplay between prosumer's decisions and price formation at the wholesale market. The fact that number of prosumers is expected to grow significantly with emerging decentralized market structure, more "layers", e.g., DSO or Distributional System Operator, to govern and facilitate energy transactions, while more aggregation is likely to occur under the right business model to minimize transaction cost and maximize business opportunity, prosumers' strategic actions could play an important role in the future.

While issues related to the transmission cost allocation are always contentious and subject to policy debates, to our best knowledge, considering the effect prosumers' participation on the transmission cost, i.e., death spiral, is not yet received any attention. Most existing studies focus on cost allocation with consideration of transmission expansion, including its effect on operation and uncertain renewables. Models developed in these studies are typically multiple-level, since they are interested in the impacts of transmission planning and cost allocation on capacity expansion and generation operation. For instance, Wang et al. (2018) explore this issue with a tri-level model, where first stage represents transmission planning, and second stage is renewable energy expansion, followed by operation in the last stage. Kristiansen et al. (2018) apply a Sharply value approach to allocate the benefit and cost of international transmission investments with a focus on wind energy in the North Sea Offshore Grid. Other studies along this line of inquiry include Zhao et al. (2011); Munoz-Delgado et al. (2015); Shen et al. (2017). Therefore, our work differs from aforementioned work but contributes to the existing work and to emerging issues related transmission cost allocation in presence of prosumers in the market.

3 Models

This section proceeds as follows. First, we introduce the optimization problem faced by each entity in the market, including prosumers, producers, the grid operator, and an arbitrageur. Second, we derive the Karush-Kuhn-Tucker (KKT) conditions associated with each variable in the optimization problem. Third, the collection of KKT conditions together together with market clearing conditions will define a market equilibrium problem in form of a linear complementarity problem, which can then be solved using complementarity solvers, e.g., PATH (Dirkse and Ferris, 1995). The theoretical properties of the model, including existence and uniqueness of the solutions, are documented in Raymar et al. (2018).

3.1 Consumers

Consumers are assumed to be price-taking agents, and their willingness-to-pay for power is represented by the inverse function:

$$p_i = P_i^0 - (P_i^0/Q_i^0)d_i, \qquad \forall i \tag{1}$$

where P_i^0 and Q_i^0 represent the vertical and horizontal intercepts of the inverse demand function, respectively. The vertical intercept, also referred to as choke price, indicates that consumption drops to zero when price exceeds P_i^0. The function is positive but decreasing in d_i $(= \sum_f s_{fi} + a_i)$. Note that this function represents only the marginal benefit associated with bulk consumers, which are separate from prosumers.

3.2 Prosumers

The prosumer (or an aggregator) at node i is assumed to possess some renewables with i) a negligible short-run marginal cost and ii) uncertain output K_i. Meanwhile, it also owns a dispatchable or backup resource with a capacity of G_i in order to hedge against uncertain output K_i. The prosumers' aggregated benefit of consuming electricity around level K_i is represented by $B_i(l_i)$, where l_i corresponds to the quantity consumed by prosumer when renewable

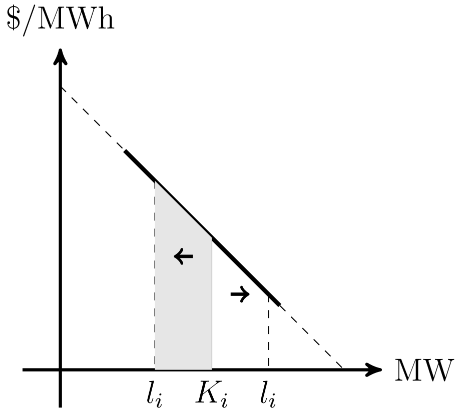

Figure 1: An illustration of prosumer's marginal benefit function

output equals K_i (Fig.1). B_i is entirely separate and different from $p_i(d_i)$, which represents willingness-to-pay or benefit of consumers in the wholesale market.[5] The benefit function $B(\cdot)$ is assumed to be increasing and strictly concave, indicating that the prosumer's objective function is increasing in the level of consumption. We posit that a prosumer maximizes its profit by deciding i) amount of power to buy from (b_{fi}) or sell to (z_{fi}) firm f in node i through bilateral contracts[6], ii) amount of forgone consumption, $K_i - l_i$, and iii) amount of power to be generated from the backup dispatchable technology, g_i. The optimization problem faced by the prosumer at node i is displayed as follows. (The greek variables within the parenthesis to the right of an equation render the corresponding dual variable.)

---

[5] A couple of notes about function B_i are worth-mentioning. It represents a local benefit function centered around consumption level at K_i. As a prosumer engages in the market, directly through bilateral trading with firms, there is limited opportunity for the market to solicit prosumers' preferences through market settlements, i.e., a preference revelation process. One indirect note on this is the well known "endowment bias", identified in Kahneman et al. (1991), which points out that consumers tend to place irrationally higher value on their possessions or something they own, i.e., zero marginal cost renewables in this case. This implies that this forgone benefit is expected to be higher than value derived from traditional demand function.

[6] Because the equivalence between a power market based on pool-type transactions and on bi-lateral contracts have been alluded to in Hobbs (2001), we believe that our assumption herein is reasonable and can be seen as an extension.

$$\underset{z_{fi}, b_{fi}, l_i, g_i}{\text{maximize}} \quad \left(\sum_f (p_i z_{fi} - (p_i + \tau) b_{fi})\right) - \int_{l_i}^{K_i} B_i'(x)dx - C_i^g(g_i) \tag{2a}$$

subject to

$$\sum_f (z_{fi} - b_{fi}) + l_i - K_i - g_i \leq 0 \qquad (\delta_i), \tag{2b}$$

$$g_i \leq G_i \qquad (\kappa_i), \tag{2c}$$

$$z_{fi}, b_{fi}, l_i, g_i \geq 0.$$

The three terms in the objective function of (2), in order, correspond to revenue (+) or cost (-) from transactions with the bulk energy market, foregone benefit (if $K_i > l_i$) or incremental benefit (if $l_i > K_i$) of consuming energy, and generation costs incurred from backup generation, respectively. We assume that transmission cost τ, different from the congestion charge ω_i in the bulk market, is paid by the prosumers (and conventional consumers) when acquiring power from the wholesale market. Prosumers treat τ exogenously as given when the model solves for τ endogenously. However, when the prosumers sell power into the grid, it receives only the bulk energy market price p_i, i.e., energy portion of the retail power prices. Formulating this way helps us capture the benefit when prosumers decides to rely on local sources to satisfy their demand. Two constraints are associated with the prosumers' problem. (2b) states that the sum of renewable output K_i. (2c) limits the output g_i by its capacity G_i.

When a prosumer is modeled in our analysis as a price-taker, it takes the price p_i as given and decides on $(z_{fi}, b_{fi}, l_i, g_i)$ accordingly. However, when a prosumer in our model is designated as a strategic entity, it realizes that by "contracting" some of its procurement of power, it could lower the bulk power price, thereby exercising buyer's market power. On the contrary, it is also aware that if it reduces power sales slightly, it might be able to push up power prices, thereby exercising seller's market power. While a prosumer only participates in the wholesale market indirectly through bilateral contracts rather than, say directly submitting bids into the market, one can assume that it acquires "strategic" knowledge through its repeated observations of power price clearance processes of the bulk energy market.[7]

---

[7] Raymar et al. (2018) demonstrates that which of the two strategies should be implemented depends on the prosumers' net position, which is affected by renewable output K_i. One way of representing prosumer's ability to manipulate the wholesale power market

Therefore, the first-order conditions associated with prosumers then can then be displayed as follows.

$$0 \leq z_{fi} \perp p_i - \delta_i \leq 0, \forall f, i \tag{3a}$$

$$0 \leq z_{fi} \perp p_i - (P_i^0/Q_i^0)\sum_f (z_{fi} - b_{fi}) - \delta_i \leq 0, \forall f, i \tag{3a*}$$

$$0 \leq b_i \perp -p_i - \tau + \delta_i \leq 0, \forall f, i \tag{3b}$$

$$0 \leq b_{fi} \perp -p_i - \tau + (P_i^0/Q_i^0)\sum_f (z_{fi} - b_{fi}) + \delta_i \leq 0, \forall f, i \tag{3b*}$$

$$0 \leq l_i \perp A_i^0 - B_i^0 l_i - \delta_i \leq 0, \forall i \tag{3c}$$

$$0 \leq g_i \perp -C_i^{g\prime} - \kappa_i + \delta_i \leq 0, \forall i \tag{3d}$$

$$0 \leq \delta_i \perp l_i - K_i - g_i + \sum_f (z_{fi} - b_{fi}) \leq 0, \forall i \tag{3e}$$

$$0 \leq \kappa_i \perp g_i - G_i \leq 0, \forall i \tag{3f}$$

3.3 Producers

Our analysis assumes that suppliers or firms are price-takers in the wholesale power market as they are constantly subject to rigorous regulatory oversight. We assume that firm f maximizes its profit by deciding the output x_{fih} and sales s_{fi}. A supplier f's problem is given as follows:

$$\begin{aligned} \underset{s_{fi}, x_{fih}}{\text{maximize}} \quad & \sum_{i,f} (p_i - \omega_i)(s_{fi} + b_{fi} - z_{fi}) \\ & - \sum_{fih} \left(C_{fih}(x_{fih}) - \omega_i x_{fih}\right) \end{aligned} \tag{4a}$$

subject to

$$x_{fih} \leq X_{fih} \qquad (\rho_{fih}), \tag{4b}$$

$$\sum_i s_{fi} - z_{fi} + b_{fi} - \sum_{ih} x_{fih} = 0 \qquad (\theta_f), \tag{4c}$$

$$s_{fi}, x_{fih} \geq 0.$$

---

in the model is by treating its belief as a parameter based on conjecture variation approach. One benefit of using this approach is that the parameter can be altered in order to explore the impact of a prosumer's belief of its "manipulating" strength on market outcomes. However, the approach is mainly useful in a situation when the demand function of underlying commodity is unobservable. An example of this is modeling market power of tradable pollution permit market where the demand for tradable permits is actually implied from output decisions of generators in the power market (Chen and Hobbs, 2005).

The first term in the objective function (4) is the revenue received from power sales $s_{fi} + b_{fi} - z_{fi}$ while paying for the wheeling/transmission charge ω_i. The second term gives generation cost, minus transmission charge $-w_i$, effectively representing a payment received by the generator from the grid operator for its service of providing counterflows to de-congest the line from i to hub. The cost function C_{fih} is convex and marginally increasing as in the literature Hobbs and Pang (2004).

Turning to the constraints, (4b) limits the output x_{fih} to be less than its capacity X_{fih}. (4c) assures that total power sales equal its supply while accounting for its bilateral transactions with the prosumers.[8]

The KKT conditions of the producer f in the wholesale market are summarized as follows:

$$0 \leq s_{fi} \perp p_i - \omega_i - \theta_f \leq 0, \forall i \tag{5a}$$

$$0 \leq x_{fih} \perp -C'(x_{fih}) + \omega_i - \rho_{fih} + \theta_f \leq 0, \forall i, h \in H_{fi} \tag{5b}$$

$$\sum_i (s_{fi} + b_{fi} - z_{fi}) - \sum_{i,h} x_{fih} = 0 \tag{5c}$$

$$0 \leq \rho_{fih} \perp x_{fih} - X_{fih} \leq 0, \forall h \in i, H_{fi} \tag{5d}$$

3.4 Grid Operator

The grid owner operates the power network and decides how to allocate transmission resources while charging producers w_i to move power from hub to node i . The optimization problem faced by the grid operator is given in (6).

$$\underset{y_i}{\text{maximize}} \quad \sum_i \omega_i y_i \tag{6a}$$

$$\text{subject to}$$

$$-T_k \leq \sum_i PTDF_{ki} y_i \leq T_k \qquad (\lambda_k). \tag{6b}$$

The grid operator is a price-taker with respect to ω_i and aims to maximize its revenue by deciding y_i given the power flow in each line k is within its thermal limit T_k. Similar to Hobbs and Pang (2004), power flows in the

---

[8] More specifically, when b_{fi} is positive, (4c) suggests that additional x_{fih} needs to be produced by the generator to satisfy demand other than s_{fi} . This effectively reduces the amount of power available to the power pool, thereby, expectedly, driving up the bulk energy prices. Similarly, when z_{fi} is positive, output from firm f is reduced as a portion of the wholesale demand is met by the prosumers. The reverse analogue is applied so the power prices are expected to lower in this case.

network are governed by the power distribution transfer factor (PTDF) based on linearized Directed-Current principle (Schweppe et al., 1998). In this context, the grid operator maximizes the value obtained from the sales of nodal transmission rights based on the topology of the network Daxhelet and Smeers (2001). The grid operator represents the behavior of the transmission operator or owner that seeks to maximize the value of its network given the set of prices w_i (Oren, 1998). The grid operator's KKT conditions then are given as follows:

$$\omega_i - \sum_K PTDF_{ki}\lambda_k = 0 \qquad \forall i \tag{7a}$$

$$0 \leq \lambda_k^+ \perp \sum_i PTDF_{ki} y_i - T_k \leq 0 \qquad \forall k \tag{7b}$$

$$0 \leq \lambda_k^- \perp -\sum_i PTDF_{ki} y_i - T_k \leq 0 \qquad \forall k \tag{7c}$$

3.5 Market Clearing Conditions

While each market participant's optimization problem represents its behavior in the wholesale market, the market clearing conditions tie them all together and ensure the demand and supply balance. This is shown in (8) for mass-balance in each node. Equation (9) helps determine the transmission cost, τ, to reimburse to the transmission owners for their revenue adequacy T.

$$\sum_f s_{fi} - \sum_{f,h \in H_{fi}} x_{fih} - \sum_f (z_{fi} - b_{fi}) = y_i, (\omega_i), \forall i \tag{8}$$

$$\left(\sum_i \left(\sum_f s_{fi} \right) + \sum_{i,f} b_{fi} \right) \tau = \mathrm{T}. \tag{9}$$

4 Numerical Case Study

A representative three-node network with three firms, ten generating units, and three transmission lines is used to illustrate of the impacts of growing size of prosumers on the market outcomes. This setup is sufficiently generalized as it allows firms to own facilities and to compete across different locations. The information concerning demand is in Table 1. The data were previously used to examine carbon leakage under California climate change policy (Chen et al., 2011). Table 2 summarizes the characteristics of those ten generating units, including their location, ownership, marginal cost, emission rate, and generating capacity. These parameters are obtained by solving a cost-minimization problem while subjecting each location to a fixed demand. The flows in the network are governed by Kirchhoffs laws with the information on thermal limits given in Table 3.

Table 1: Demand parameters

Node	Vertical intercept [$/MW]	Horizontal intercept [MW]
A	228.00	1080
B	169.79	660
C	111.60	1146

Table 2: Characteristics of generating units

Unit	Firm	Node	Marginal cost [$/MW]	Capacity [MW]
1	3	A	38.00	250
2	1	A	35.72	200
3	2	A	36.80	450
4	1	B	15.52	150
5	2	B	16.20	200
6	3	B	0.00	200
7	1	C	17.60	400
8	1	C	16.64	400
9	1	C	19.40	450
10	3	C	18.60	200

Table 3: Transmission data

Line	Thermal limit [MW]
AB	255
BC	120
AC	30

Our analysis considers a number of scenarios by varying the percentage of the prosumers' fraction in node A from 0 to 100% (10% increment), where there is no prosumer located to nodes B and C. We then manipulate the proportion of the prosumers in node A by changing the horizontal intercept of the inverse demand function in (1) while maintaining the same vertical intercept. For instance, when there is a 20% of prosumers in node A, the horizontal intercept in (1) that represents prosumers' max quantity demanded is reduced to $Q_A^0 \times 0.2$ while that of the corresponding conventional consumers is $Q_A^0(1-0.2)$. The analysis is subject to four levels of exogenous renewable outputs pro-rated by the size of the prosumers: 500, 1,000, 1,500, and 2,000 MW. These four levels of renewable output are carefully selected to represent possible cases of prosumers from extremely short to extremely long position in equilibrium.[9] Finally, we also consider the prosumers as either a price-taker or a strategic entity who could exercise market power using quantity-based strategy (Raymar et al., 2018). In particular, under market power cases, p_A in (2a) is then replaced by (1) when deriving the prosumers' first-order conditions. We report results of the numerical case study in next section.

5 Results

5.1 Perfect Competition

A number of observations emerge from Figures 2–3. Consistent with how the scenarios were setup, the quantity demanded by prosumers continues to increase when more consumers are designated as prosumers who possess their renewable and dispatchable units at distribution level, see Figure 2(a). When prosumers are endowed with more renewables with a zero marginal cost , their consumption also increases. For a given fraction of consumers that are designated as prosumers, the level of consumption is highest in 2,000MW case, followed in an order by 1500, 1000, and 500 MW cases. Accompanied with is the monotonic decline of consumption by traditional consumers in node A, see Figure 2(b). The pattern of the total wholesale in Figure 2(c) reflects the combined effect of Figure 2(a)–(b).For a relatively high level of renewable output, e.g., 2,000 and 1,500MW, the wholesale power sales increase first until the prosumers' fraction equal to 0.3, due to influx of low cost renewables flooding the market that effectively lowers the power prices,

---

[9] We are interested in market outcomes and the impacts on transmission costs in the presence of prosumers in the market. The net position of the prosumers cannot be determined a priori, but the outcomes from market equilibrium.

and then decline, in part because of "death spiral" effect. For 500MW case, the wholesale power sales increase monotonically, reflecting that increase in zero-cost renewable lowers the power prices and augments the demand while prosumers act as "consumers."

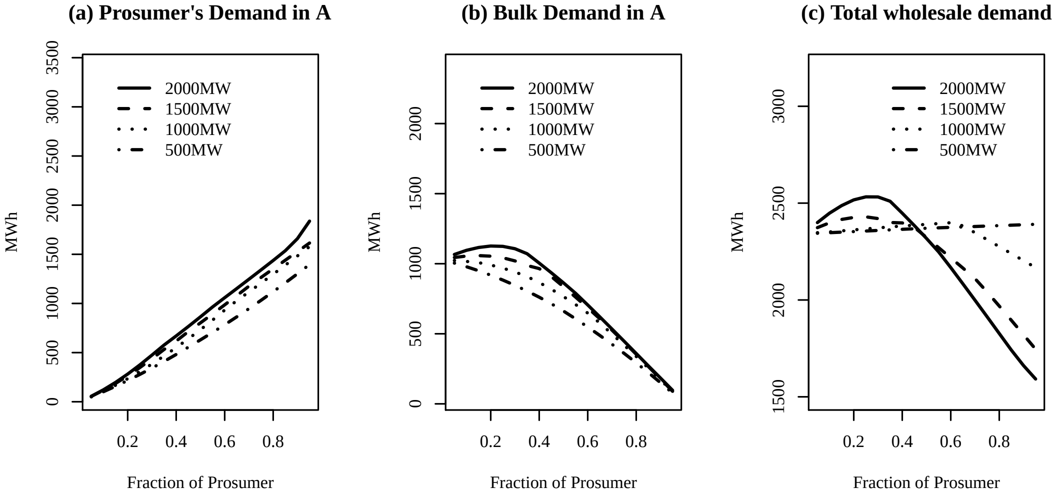

Figure 2: Plots of transmission costs, wholesale demand, and prosumers' demand against the fraction of prosumers in node A under perfect competition

Contrary to conventional wisdom, the impact on the transmission cost or surcharge is ambiguous. More specifically, the transmission cost could decline with an increased fraction of prosumers in the market when the prosumers, throughout, act as consumers who procure energy from the bulk energy market, e.g., 500MW case in Figure 3(a). The decline is because of the increase of zero-marginal cost renewable that enters the market, thereby lowering the power prices, inflating bulk energy sales, and causing a decline in transmission cost. Transmission cost could also decline first, then increase with the fraction of the prosumers in the market, e.g., 2,000MW case. This is mainly due to the fact that the prosumers, in relative sense, have a considerable amount of renewables to offer into the market when their fraction is small, but then the "death-spiral" effect dominates the renewable effect, leading to a decline of quantity demanded by conventional consumers in node A, see Figure 2(b), when the prosumers' fraction is greater than 0.2. A similar observation is also emerged in 1,000 and 1,500MW cases for the transmission cost, except that the prosumers alter their position from a net seller to a net buyer of the bulk energy market, see Figure 3(b), partly due to diminished zero-marginal-cost renewable effect as its renewable endowment is lower compared to 2,000MW case.

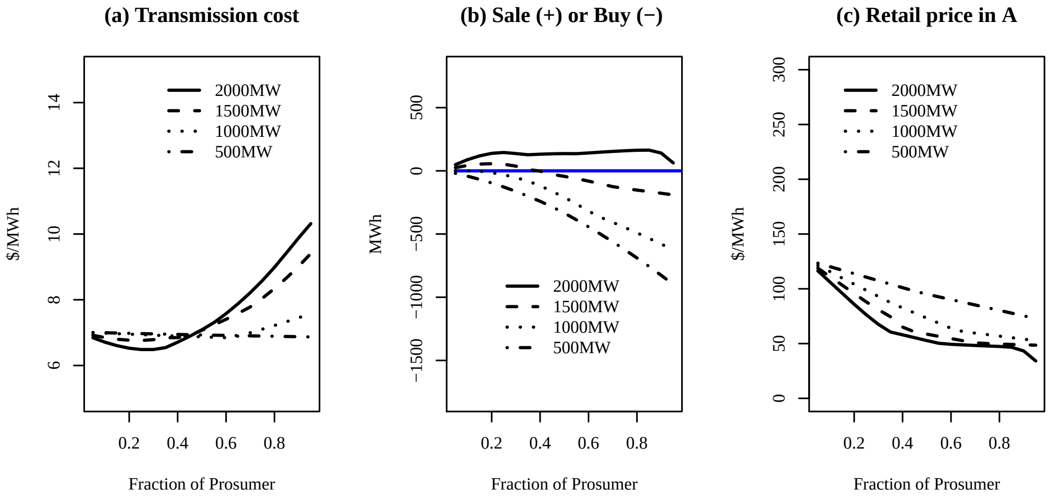

Figure 3: Plots of conventional consumers' demand, prosumers' sales (+) or purchase (-) power, and node A's retail power prices against the fraction of prosumers in node A under perfect competition

We also plot the power prices in nodes B, C, and the sale-weighted power price in the bulk market against the fraction of the prosumers in node A in x-axis in Figure 4. Overall, an increased fraction of prosumers in node A effectively introduces zero marginal-cost renewables into the wholesale market, which effectively suppresses the bulk sale-weighted energy price in Figure 4(c). The more renewable endowment, the lower the power prices are, as the case with 2,000 MW renewables provides a lower bond, a lower envelop, of other cases. Interestingly, the impact of the prosumers on the power prices in nodes B and C is not uniform as the case of 2,000MW renewable respectively provides a lower and an upper bond of other cases in nodes B and C in Figure 4(a) and 4(b). A close examination at the flow patterns along transmission lines and net injection/withdraw at nodes B and C indicates that while the power flow is always in the direction from A to C at full capacity of 30 MW, the flow between B and C depends on cases. When the prosumers in node A entitled 2,000 MW of renewables, the fact that the power price in node A is lower (or demand is higher) among all the cases, see Figure 2(c), suggests that less power is available to export to node B. This results in power to flow from C to B, leading to a higher price in node C. The reverse is valid for the cases when less renewable is possessed by the prosumers, e.g., 500 MW, so that surplus energy from A can then be supplied to C through path along A-B and B-C lines.

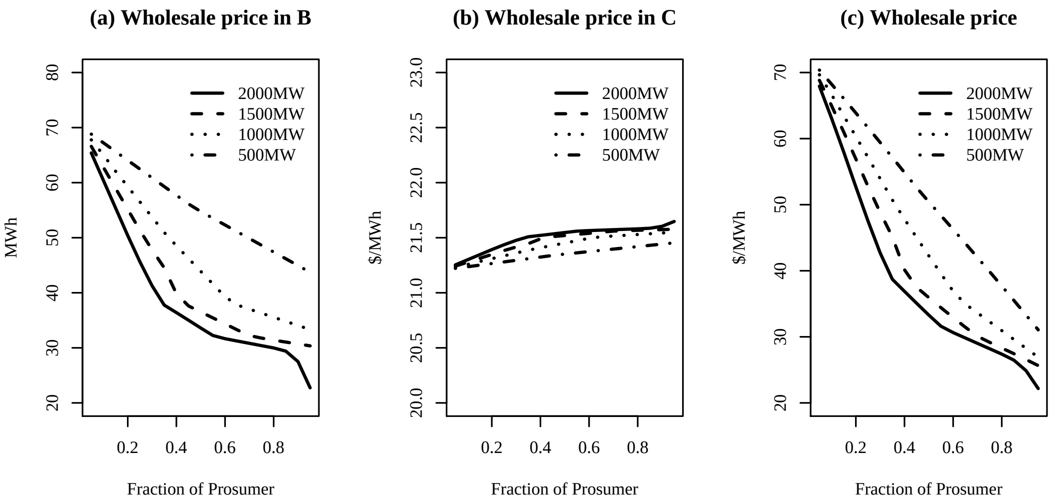

Figure 4: Plots of power prices in nodes B, C, and sale-weighted power prices in the bulk market under perfect competition

5.2 Imperfect Competition

Figures 5–7 display the results from allowing the prosumers in node A to behave strategically. More specifically, the prosumers could either act as a monopoly (seller) or a monoposony (buyer) given the level of possessed renewable output (Raymar et al., 2018) Overall, the results are broadly consistent with the findings in Section 5.1. We therefore focus our discussions on those that are different from the previous section.

Compared to Figure 2(a), the curves depicting quantity demanded by the prosumers Figure 5(a) “bend” down considerably, especially for 500MW and 1,000 MW cases. This is mainly because the prosumers intend to reduce power procurement (monoposony power) when in a “short position,” see Figure 6(b), in order to lower power prices in node A. This is contrast to Figure 3(b), where the prosumers continue to satisfy their appetite of energy by increasing procurement from the bulk market with their increased presence in the market. Contrary to Figure 2(c), at which the total wholesale demand continues to raise for 500MW case, Figure 5(c) shows that the total wholesale demand persistently declines when facing prosumers ≥ 0.6. This is also related to the discussion earlier concerning Figure 5(a) where lowering energy procurement in 500 MW suppresses the power prices, elevating the demand by the traditional consumers in node A in Figure 5(b) compared to Figure 2(b).

Impacts on the transmission cost reflect the effects of imperfect competition on the total wholesale in Figure 5(c) and the prosumers’ purchase from

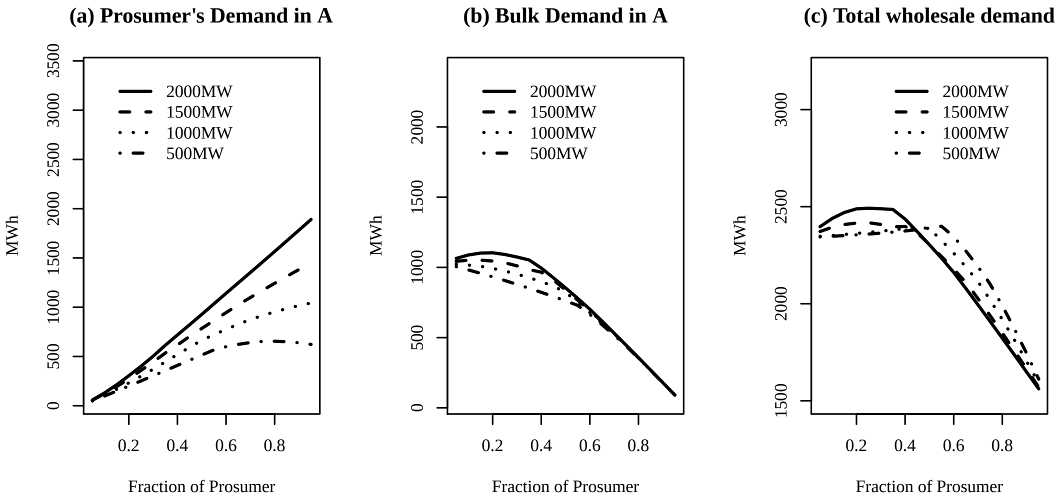

Figure 5: Plots of transmission costs, wholesale demand, and prosumers' demand against the fraction of prosumers in node node A under imperfect competition

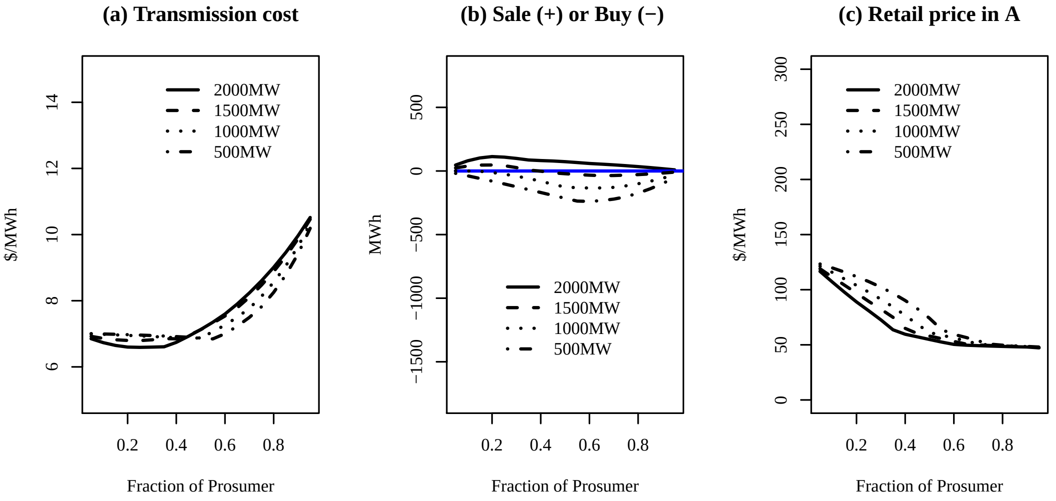

Figure 6: Plots of conventional consumers' demand, prosumers' sales (+) or purchase (-) power, and node A's retail power prices against the fraction of prosumers in node A under imperfect competition

the wholesale market.[10] The decline of consumption by conventional consumers and increase in procurement by the prosumers result in the pattern of transmission cost to be broadly consistent with that of Section 5.1, especially exemplified by 500MW case. Finally, the pattern displayed in Figures 7(a)–7(c) is consistent with those in Figures 4(a)–4(c).

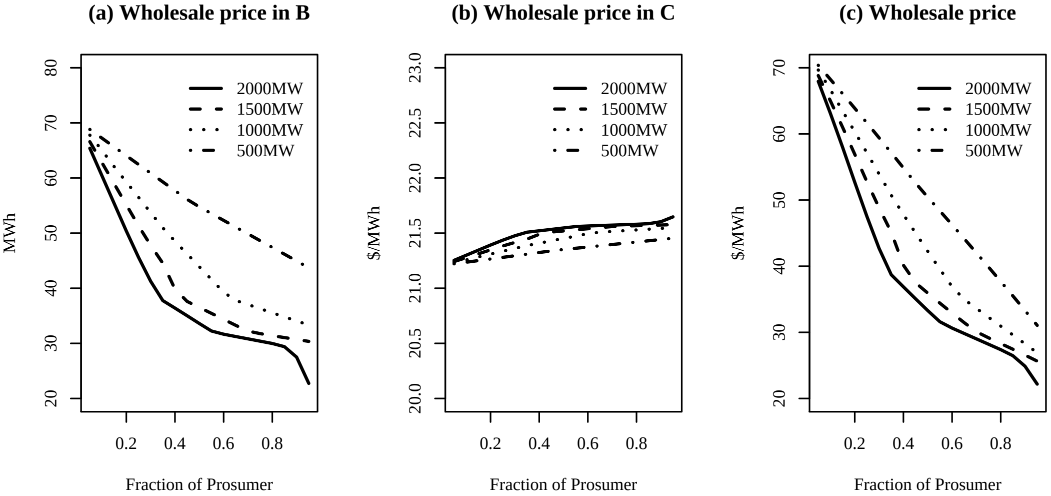

Figure 7: Plots of power prices in nodes B, C, and sale-weighted power prices in the bulk market under imperfect competition

We also plot the node A's power price in Figure 8 against the fraction of the prosumers in node A under perfect and imperfect competition. The attention is limited to the cases of 500MW, 1,000MW, and 2,000MW as the case of 1,500MW lies between that of 2,000MW and 1,000MW. When going from (a) to (c) in Figure 8, the prosumers' net position in equilibrium moves from as a net seller to a net buyer from the bulk energy market. Thus, the prosumers possess an incentive to exercise seller's market power by reducing their sales into the bulk energy market to elevate the power prices in A. This is demonstrated in Figure 8(a), where the dash line representing the outcomes of imperfect competition lies above the solid line. The opposite is the case for Figures 8(b) and 8(c) when the prosumers purchase energy from the bulk market to meet their demand, i.e., exercising buyer's market power. When the fraction of the prosumers is small (toward the left of the x-axis), the ability to influence the bulk market is limited, gauged by the price gap between the dash and sold lines. Interestingly, the difference remains small in Figure 8(a) throughout even if the size of the prosumers grows

---

[10] Recall when purchasing from the wholesale bulk energy market, prosumers also need to pay their share of the transmission costs together with the conventional consumers.

larger toward to the right of the x-axis. This is mainly because that other producers in the market are designated as price-taker, the effect of exercising sellers' market power by the prosumers is attenuated by increases in output by other producers, even from other nodes. The same analogy cannot be applied to the effects on Figures 8(b) and 8(c) since the effect of exercising buyer's market power is likely to be local, constrained by consumers' location, thereby leading to an increasing large price gap toward the right of the x-axis.

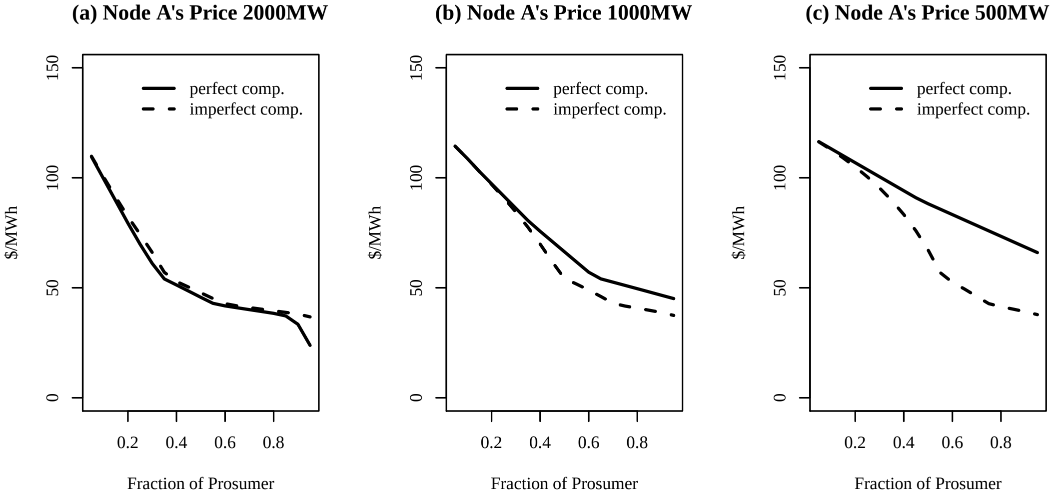

Figure 8: Plots of the node A's power prices under perfect and imperfect competition against the fraction of the prosumers in node A

6 Conclusion

Lumpiness of investment and other none-convex cost has historically presented a great regulatory challenge for utilities in the power sector to recover their costs (Grigoryeva et al., 2018). A postage stamp approach, based on the share of demand or peak load, is commonly used by regional grid operators or the independent system operators to allocate transmission costs. An emerging entity, prosumers, is likely to complicate the transmission cost allocation. A prosumer who owns a set of renewable units coupled with backup options, such as fossil-fueled units and storage, in order to maintain a stable energy supply, has been viewed as an effective distributed energy source to enhance the power system resilience. While their presence strengthens the grid resilience by shifting energy supply to local energy sources, thereby bypassing energy transmission in bulk market, it also creates financial burden to those consumers who rely on their utility's procurement of energy from the bulk market. "Death spiral", which describes a situation at which as power price increases (due to elevated transmission cost) transferred to remaining traditional consumers cause some of those customers to exit the grid themselves through self-generation, is a direct consequence from cross-subsidy from conventional consumers to prosumers (Jacobs, 2017).

The paper, built upon the model by Hobbs (2001) with an explicit consideration of prosumers' problem in the market in order to analyze their impacts on transmission cost and other market outcomes when they are either a price taker and a strategic entity. Instead of modeling optimized decision by consumers of self-sorting into prosumers, we assume exogenously the percentage of consumers are prosumers. Our analysis finds that, in contrary to conventional belief, the impact on the transmission cost is ambiguous. On the one hand, the transmission cost could decline with an increased fraction of prosumers in the market when the prosumers only act as consumers who procure energy from the bulk energy market, e.g., 500MW case. On the other hand, with significant amount of renewable (e.g., 2,000 MW), the transmission cost could decline first (due to inflated demand) and then increase with an increased fraction of prosumers in the market. Moreover, strategic behavior by the prosumers could exacerbate transmission cost allocation as they contract their procurement from the bulk energy in order to lower the energy prices, thereby leading to a decline of the bulk energy demand as well as an elevation of the transmission costs. Our analysis, therefore, contributes to the current debates on the "death spiral" hypothesis and highlights the intrinsic relations among amount of renewables, size of prosumers, and their strategy assumption as well as their joint effect on the transmission costs. Our results also call for more careful attention to be paid by the ISO to craft cost allocation agreements in face of a growing presence of prosumers in the future (Olmos et al., 2018).

Our analysis is subject to a number of limitations. We limit to the situation where a lump sum of transmission cost needs to be allocated to consumers in proportion to their energy demand. In reality, provision to allocate transmission cost could be more complicate than our assumption. Additionally, our analysis does not consider the possibility that the prosumers operate equipment with capability of storing energy. In current marketplace, some prosumers are able of operating energy storages, e.g., electrical vehicles, that provide services to both energy and ancillary service markets. A multiple-period model considering cross elasticities of energy demand among time periods in order to examine the effect of power price in one time period on the demand other time periods would be needed in this case. We also posit that market participants, other than the prosumers, are price takers. We believe that even though our model is readily modified to account for strategic behavior of conventional producers, allowing other producers behave strategically might complicate the analysis, making it difficult to isolate the impact induced by the prosumers. Third, while we simulate different levels of renewable outputs, our analysis is essentially deterministic. Implementing a stochastic modeling framework using scenario paths of renewable outputs and correlated demand, for example, will undoubtedly be more realistically to represent the reality faced by the power market, but might again make detanglling our findings more difficult. We leave the aforementioned considerations to our future work.

Acknowledgement

References

T. Baroche, P. Pinson, R. Le Goff Latimier, and H. Ben Ahmed. Exogenous Approach to Grid Cost Allocation in Peer-to-Peer Electricity Markets, 2019. URL `http://pierrepinson.com/docs/Barocheetal2018.pdf`.

J. Bushnell. 100% What?: Energy Institution Blog, University of California at Berkeley, 2018. URL `https://energyathaas.wordpress.com/2018/10/08/100-of-what/`.

California ISO. How Transmission Cost Recovery Through the Transmission Access Charge Works Today, January 2019. URL `www.caiso.com/Documents/BackgroundWhitePaperReviewTransmissionAccess-ChargeStructure.pdf`.

California Public Utilities Commission. California Public Utilities Commission: FACT SHEET–Power Charge Indifference Adjustment, January 2019. URL `http://www.cpuc.ca.gov/uploadedfiles/cpuc_public_website/content/news_room/fact_sheets/english/pciafactsheet010917.pdf`.

C. Chen, S. Kishore, Z. Wang, M. Alizadeh, and A. Scaglione. How Will Demand Response Aggregators Affect Electricity Markets? A Cournot Game Analysis. In *2012 5th International Symposium on Communications, Control and Signal Processing*, pages 1–6, May 2012. doi: 10.1109/ISCCSP.2012.6217839.

Y. Chen and B. F. Hobbs. An Oligopolistic Power Market Model with Tradable NOx Permits. *IEEE Transactions on Power Systems*, 20(1):119–129, February 2005. ISSN 0885-8950. doi: 10.1109/TPWRS.2004.840440.

Y. Chen, A. L. Liu, and B. F. Hobbs. Economic and Emissions Implications of Load-based, Source-based and First-seller Emissions Trading Programs under California AB32. *Operations research*, 59(3):696–712, 2011.

Constellation. Understanding Transmission Costs in Your Power Bill, December 2018. URL `https://blogs.constellation.com/energy-management/understanding-transmission-costs-in-your-power-bill-2/`.

J. E. Contreras-Ocãna, Miguel A. Ortega-Vazquez, and Baosen Zhang. Participation of an Energy Storage Aggregator in Electricity Markets. *IEEE Transactions on Smart Grid*, Accetped, 2019.

O. Daxhelet and Y. Smeers. Variational Inequality Models of Restructured Electricity Systems. In *Complementarity: Applications, Algorithms and Extensions*, Applied Optimization, pages 85–120. Springer, Boston, MA, 2001. doi: 10.1007/978-1-4757-3279-5_5.

S. P Dirkse and M. C. Ferris. The PATH Solver: A Nommonotone Stabilization Scheme for Mixed Complementarity Problems. *Optimization Methods and Software*, 5(2):123–156, 1995.

J. B. Eisen. Free Trade in Electric Power. *Utah Law Review*, 49:49–117, 2018.

FERC. Staff Analyiss on Uplift and ISO Markets, December 2018. URL `https://www.ferc.gov/legal/staff-reports/2014/08-13-14-uplift.pdf`.

S. Fink, K. Porter, C. Mudd, and J. Rogers. A Survey of Transmission Cost Allocation Methodologies for Regional Transmission Organizations. Technical Report NREL/SR-5500-49880, National Renewable Eneryg Laboratory, 2011.

S. A. Gabriel, A. J. Conejo, M. A. Plazas, and S. Balakrishnan. Optimal Price and Quantity Determination for Retail Electric Power Contracts. *IEEE Transactions on Power Systems*, 21(1):180–187, February 2006. ISSN 0885-8950. doi: 10.1109/TPWRS.2005.860920.

L. Gkatzikis, I. Koutsopoulos, and T. Salonidis. The Role of Aggregators in Smart Grid Demand Response Markets. *IEEE Journal on Selected Areas in Communications*, 31(7):1247–1257, 2013.

E. Graffy and S. Kihm. Does Disruptive Competition Mean a Death Spiral for Electric Utilities? *Energy Law Journal*, 35(1):1–30, 2014.

A. Grigoryeva, M. R. Hesamzadeh, and T. Tangerås. Energy System Transition in the Nordic Market: Challenges for Transmission Regulation and Governance. *Economics of Energy & Environmental Policy*, 7(1):127–146, 2018.

B. E. Hobbs. Linear Complementarity Models of Nash-Cournot Competition in Bilateral and POOLCO Power Markets. *IEEE Transactions on Power Systems*, 16(2):194–202, May 2001. doi: 10.1109/59.918286.

B. F. Hobbs and J.-S. Pang. Spatial Oligopolistic Equilibria with Arbitrage, Shared Resources, and Price Function Conjectures. *Mathematical Programming*, 101(1):57–94, August 2004. doi: 10.1007/s10107-004-0537-4.

S. B. Jacobs. The Energy Prosumer. *Ecology Law Quarterly*, 43(3):519–579, 2017.

D. Kahneman, J. L. Knetsch, and R. H. Thaler. Anomalies: The Endowment Effect, Loss Aversion, and Status Quo Bias. *Journal of Economic Perspectives*, 5(1):193–206, 1991.

M. Kristiansen, F. D. Muñoz, S.S. Oren, and M. Korpås. A Mechanism for Allocating Benefits and Costs from Transmission Interconnections under Cooperation: A Case Study of the North Sea Offshore Grid. *The Energy Journal*, 39(6):209–234, 2018.

G. Munoz-Delgado, J. Contreras, and J. M. Arroyo. Joint Expansion Planning of Distributed Generation and Distribution Networks. *IEEE Transactions on Power Systems*, 30(5):2579–2590, 2015.

L. Olmos, M. Rivier, and I. Pérez-Arriaga. Transmission Expansion Benefits: The Key to Redesigning the Regulation of Electricity Transmission in a Regional Context. *Economics of Energy & Environmental Policy*, 7(1): 47–62, 2018.

S. S. Oren. Authority and Responsibility of the ISO: Objectives, Options and Tradeoffs. In *Designing Competitive Electricity Markets*, International Series in Operations Research & Management Science, pages 79–95. Springer, Boston, MA, 1998. doi: 10.1007/978-1-4615-5547-6_5.

S. Ø. Ottesen, A. Tomasgard, and S.-E. Fleten. Prosumer Bidding and Scheduling in Electricity Markets. *Energy*, 94:828–843, January 2016. doi: 10.1016/j.energy.2015.11.047.

A. Papavasiliou and S. S. Oren. Large-scale Integration of Deferrable Demand and Renewable Energy Sources. *IEEE Transactions on Power Systems*, 29 (1):489–499, 2014.

Y. Parag and B. K. Sovacool. Electricity Market Design for the Prosumer Era. *Nature Energy*, 1(4):16032, April 2016. ISSN 2058-7546. doi: 10.1038/nenergy.2016.32.

M. Parvania, M. Fotuhi-Firuzabad, and M. Shahidehpour. Optimal Demand Response Aggregation in Wholesale Electricity Markets. *IEEE Transactions on Smart Grid*, 4(4):1957–1965, December 2013. doi: 10.1109/TSG.2013.2257894.

F. Rahimi and A. Ipakchi. Demand Response as A Market Resource under the Smart Grid Paradigm. *IEEE Transactions on Smart Grid*, 1(1):82–88, 2010.

S. Raymar, A. L. Liu, and Y. Chen. A Power Market Model in Presence of Strategic Prosumers. Technical report, University of California Santa Cruz, 2018.

N. Azizan Ruhi, K. Dvijotham, N. Chen, and A. Wierman. Opportunities for Price Manipulation by Aggregators in Electricity Markets. *IEEE Transactions on Smart Grid*, pages 1–1, 2017. doi: 10.1109/TSG.2017.2694043.

F. C. Schweppe, M. C. Caramani, R.D. Tabors, and R. E. Bohn. *Spot Pricing of Electricity*. Kluwer Academic Publishers, 1998.

X. Shen, M. Shahidehpour, Y.Han, S. Zhu, and J. Zheng. Expansion Planning of Active Distribution Networks with Centralized and Distributed Energy Storage Systems. *IEEE Transactions on Power Systems*, 8(1): 126–134, 2017.

E. Tveita, M. Löschenbrand, S. Bjarghov, and H. Farahmand. Comparison of Cost Allocation Strategies among Prosumers and Consumers in a Cooperative Game. In *2018 International Conference on Smart Energy Systems and Technologies*, 2018.

University of California Energy Institute. Stabilizing Utilities in an Unstable Climate, January 2019. URL `https://energyathaas.wordpress.com/2019/01/22/stabilizing-utilities-in-an-unstable-climate/`.

J. Wang, H. Zhong, W. Tang, R. Rajagopal, Q. Xia, and C. Kang. Tri-Level Expansion Planning for Transmission Networks and Distributed Energy Resources Considering Transmission Cost Allocation. *IEEE Transactions on Power Systems*, 9(4):1844–1866, 2018.

J. Zhao, J. Foster, Z. Y. Dong, and K. P.Wong. Flexible Transmission Network Planning Considering Distributed Generation Impacts. *IEEE Transactions on Power Systems*, 26(3):1434–1443, 2011.