

Death spiral, transmission charges, and prosumers in the electricity market

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ABSTRACT

The presence of prosumers with distributed renewable energy has been viewed as an effective way of enhancing the power sector's resilience. The current transmission charge is designed mainly to recover lumpy transmission investments and other routine costs. Thus, a decline in the reliance on the bulk power market owing to an increase in consumers becoming prosumers shifts transmission costs to traditional consumers, a situation known as a "death spiral". This study examines how the presence of prosumers affects the transmission charge and market outcomes by explicitly considering their optimization problem in the market. A prosumer is formulated either as a price-taker or as a strategic entity, and is assumed to make his/her own decision on the amounts of consumption, dispatchable energy to produce, and energy to sell into or buy from the bulk energy market, subject to non-dispatchable renewable output. We refute the common belief, demonstrating that the transmission charge does not necessarily increase with the proportion of prosumers in the market. The bulk power market could benefit from lower power prices owing to the prosumers' renewable production with low marginal costs. Strategic prosumers may cause the transmission charge to increase because they reduce their procurement from the bulk energy market. Therefore, our analysis contributes to the recent debate on transmission costs in the presence of prosumers.

1. Introduction

Electricity markets are undergoing a transformation. The increase of renewable production in an effort to mitigate climate change and pursue sustainability has led to significant changes and challenges in the design and operation of modern power markets. Smart meters and IT-related technologies, together with innovative business models, have led to a growing body of customers capable of producing renewable energy, including those behind meters. These customers have altered the conventional demand-side paradigm in energy production.

This major shift in the energy sector toward a more engaged and pliable demand-side involvement, although enhancing the sector's resilience, has direct effects on the behavior and participation of various agents in the sector. Prosumers are capable of generating and consuming power, in contrast to conventional consumers or suppliers who participate in only one side of the market. The presence of prosumers is expected to have significant implications for the design and operation of future competitive power markets [1]. This transformation is also facilitated by legislation. For example, in the U.S., the state of California mandated that all new residential construction must be zero net energy (ZNE) by 2020 [2]. More recently, the electricity community has

begun developing a platform that allows a distribution system operator to coordinate and align with prosumers, and an independent system operator at the transmission level to facilitate energy transactions.

The interactions between prosumers and the energy sector are enabled by the presence of aggregators. Aggregators collect and integrate the demand response and distributed energy resources at the distribution level, and then offer the aggregated energy bundle as a product to the wholesale market [3]. Examples include community choice aggregators, which are popular in California and other U.S. states. These aggregators operate renewable facilities over diverse households/facilities and geographical areas, thereby constituting a substantial distributed generation and energy management capability [4,5]. This allows prosumers to participate in a wholesale power market through an aggregator. However, they can also participate locally using peer-to-peer (P2P) transactions not available to ordinary customers, owing to their duality as a producer and a consumer [6,7].

An emerging issue that has received some attention is the fact that a decline in the reliance on the bulk power market by prosumers might shift transmission costs and other related costs to traditional consumers who rely on utilities procuring energy from the bulk energy market. In

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fact, Bushnell [8] argues that the increase in energy procurement costs (while the wholesale energy price has declined) by major utilities in California (e.g., Pacific Gas and Electric) is likely due to the recovery of fixed costs induced by the renewable capacity under the state's ambitious renewable portfolio standard (RPS). The aforementioned situation describes a “death spiral”, in which consumers might self-sort to become prosumers. In this case, consumers who are unable to become prosumers bear an increasing transmission charge. This has been the subject of recent debate, and is considered an unintended consequence [9,10]. This is corroborated by a 2018 survey of energy utility leaders indicating that more than 70% of respondents believed the death spiral to be a serious concern to the power industry in the U.S. [11].

This study examines the impact of prosumers' presence on transmission charges and market outcomes. We extend the model of Hobbs [12] by explicitly considering the transmission network and the prosumers' optimization problem in the market. For our analysis, we make the following assumptions: (i) While each prosumer might be relatively small in terms of size, with a limited ability to affect the bulk energy market, we assume that a large number of prosumers enter a contract with a single aggregator, who participates in the bulk energy market on their behalf. We therefore model the joint optimization of an aggregator and prosumers. In particular, the prosumers decide the amounts of consumption, dispatchable energy to produce, and energy to sell into or buy from the bulk energy market, subject to exogenous and non-dispatchable output from renewables. (ii) We vary the proportion of demand between prosumers and traditional consumers, while maintaining the same aggregated marginal benefit function to make the results comparable. In other words, if the prosumers were designated as conventional consumers, all the cases should lead to the same market outcomes. (iii) The transmission charge is endogenously determined in the model to cover the transmission owners' investment, routine operations & maintenance costs, and other administrative costs. The level of transmission charge is affected by the proportion of prosumers in the market. (iv) We assume four levels of exogenous renewable outputs (i.e., 500, 1000, 1500, and 2000 MW). These levels are chosen to illustrate possible cases of prosumers from short (i.e., buy power) to long (i.e., sell power) positions in equilibrium. (v) Because prosumers are relatively new to the market, they might be subject to relatively less oversight, partly as a result of an underdeveloped regulatory framework to address their behavior. Therefore, we assume a prosumer is either a price-taker or a strategic entity, subject to non-dispatchable renewables.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature and highlights our contribution. Section 3 formulates the simulation models. A numerical case study is presented in Section 4, while Section 5 discusses possible policy measures. Section 6 concludes the paper.

2. Existing literature

The effects of prosumers on the wholesale power market has received some attention in the literature. This is partly because prosumers are expected to play a crucial role in the future. Prosumers own distributed renewable energy resources, coupled with technologies that allow for P2P transactions or direct engagement in the bulk energy market through aggregators [13–15]. For example, Chen et al. [16] examine how a demand aggregator operating a conventional generator and a green energy management system affects the wholesale market by considering that the aggregator exercises a quantity-based strategy. Contreras-Ocaña et al. [17] explore the corporation between energy storage units and an aggregator using Nash bargaining theory. Ottesen et al. [18] consider a two-stage stochastic model in which a prosumer minimizes expected costs by deciding on his/her bidding (first stage), and then making scheduling decisions (second stage). A typical characteristic of existing works is to treat wholesale power prices as

given, and then to focus on finding optimal contracts with customers or schedules, while maximizing the expected payoff. However, such works do not allow us to examine the interplay between prosumers' decisions and price formation in the wholesale market. The number of prosumers is expected to grow significantly with the emerging decentralized market structure. Thus, further aggregation is likely to occur under the right business model to minimize transaction costs and maximize business opportunities, where prosumers' strategic actions could play an important role in the future.

Issues related to fixed cost recovery are always contentious and subject to policy debates. Prosumers may pay less than their fair share of the network and other costs (e.g., renewable procurement) because of their reliance on self-generation, thereby adversely affecting utilities' financial viability [8,19,20]. Utilities are forced to raise the grid tariff to compensate for the missing revenue, further exacerbating the situation and leading to a downward spiral [21–25]. Eid et al. [26] consider distributed generators that can offset their own power consumption with local generation under net metering. Using consumption and production data on low-voltage PV prosumers in Spain, they find that utilities reduced their income, which pushed up network tariffs for cost recovery. They also examine the effect of cross-subsidies from traditional consumers to prosumers. Evaluating the effect of various tariff designs, de Villena et al. [27] suggest that the net-metering system should be replaced by the net-purchasing system, in which different prices are set on the electricity imported from or exported to the grid. On the other hand, Soto et al. [28] propose P2P schemes as alternatives to net-metering programs. Using stylized theoretical models, Gautier et al. [29] show a decrease in the payment of prosumers, which is cross-subsidized by the higher bills of conventional consumers. With the exception of Gautier et al. [29], studies assume that excess power is either curtailed or sold at negotiated prices by utilities. Thus, the effect of low-cost renewable is not fully covered for. They also ignore the consideration of the transmission network, which is critical to understand the final outcomes in the power system.

Other studies focus on cost allocations for transmission expansion when the system is subject to non-dispatchable renewables. The models developed in these studies typically have multiple levels, because they are interested in the effects of transmission planning and cost allocation on capacity expansion and generation operations. For instance, Wang et al. [30] explore this issue using a tri-level model, where the first stage represents transmission planning, the second is renewable energy expansion, and the third is operations. Kristiansen et al. [31] apply a Shapley value approach to allocate the benefits and costs of international transmission investments, focusing on wind energy in the North Sea Offshore Grid. Other similar studies include those of Zhao et al. [32], Munoz-Delgado et al. [33] and Shen et al. [34].

This study differs significantly from previous works and contributes to the emerging issue of transmission cost allocations, given the presence of prosumers in the market. In summary, our work (1) explicitly considers the effect of a transmission network, and (2) treats locational power prices as endogenous, allowing the models to decide whether it is optimal for a prosumer to be a consumer or a producer. This allows prosumers to behave strategically. Finally, our analysis contributes to the current debate on the “death spiral” hypothesis and highlights the intrinsic relations between the amount of renewables, the proportion of prosumers, and the prosumers' strategy assumptions, as well as their joint effect on transmission charges. We demonstrate the circumstances at which the death spiral is not necessary a concern when bulk renewables flood to the market that lower the energy costs.

3. Simulation models

This section proceeds as follows. First, we introduce the optimization problem faced by each entity in the market, i.e., consumers, prosumers, producers, and the system operator. Second, we derive the Karush–Kuhn–Tucker (KKT) conditions associated with each variable

in the optimization problems. Third, the collection of KKT conditions together with the condition for revenue adequacy defines a market equilibrium problem, which can then be solved using complementarity solvers such as PATH [35].¹

Notation

(1) Indices and Sets	
$i \in \mathcal{I}$	Nodes.
$f \in \mathcal{F}$	Firms.
$h \in \mathcal{H}_{fi}$	Generating units at node i owed by firm f .
$k \in \mathcal{K}$	Transmission lines.
(2) Parameters	
P_i^0, Q_i^0	Vertical and horizontal intercepts of retail inverse demand function at node i (\$/MW, MW).
K_i	Renewable output of prosumers at node i (MW).
G_i	Production capacity of prosumers' dispatchable unit at node i (MW).
X_{fih}	Production capacity for generation unit h at node i owned by firm f (MW).
$PTDF_{ki}$	Power transfer distribution factor for a unit of power transferred from the hub to node i through line k (unitless).
T_k	Thermal limit for line k (MW).
T	Amortized fixed cost of transmission owners (\$).
(3) Primal variables	
d_i	Conventional consumer's demand at node i (MWh).
τ	Transmission charge (\$/MWh).
z_{fi}, b_{fi}	Prosumers' sales to and purchases from firm f at node i (MWh).
l_i	Prosumers' demand at node i (MWh).
g_i	Energy produced by prosumers' dispatchable unit at node i (MWh).
s_{fi}	Energy sales at node i by firm f (MWh).
x_{fih}	Energy produced by generation unit h at node i owned by firm f (MWh).
y_i	Energy injection/withdrawal at node i (MWh).
(4) Dual variables	
δ_i	Dual variable for prosumers' energy balance at node i (\$/MWh).
κ_i	Dual variable for prosumers' dispatchable generation capacity at node i (\$/MWh).
ρ_{fih}	Dual variable for capacity constraint of generation unit h at node i owned by firm f (\$/MWh).
θ_f	Dual variable for production and sales balance of firm f (\$/MWh).
λ_k^+, λ_k^-	Dual variables for limit of line k (\$/MWh).
ω_i	Dual variable for supply and demand balance at node i , which yields a congestion charge (\$/MWh).

Consumers. The preferences of conventional consumers at node i are represented through a linear inverse demand function as follows:

$$p_i^r = p_i + \tau = P_i^0 - (P_i^0/Q_i^0)d_i, \quad \forall i, \quad (1)$$

where P_i^0 and Q_i^0 represent the vertical and horizontal intercepts of the "retail" inverse demand function, respectively. The vertical intercept,

¹ The theoretical properties of the model, including the existence and uniqueness of the solutions, are documented in [36].

also referred to as choke price, indicates that consumption drops to zero when the price exceeds P_i^0 . The function takes positive values but is decreasing in consumption d_i ($= \sum_f s_{fi}$, or power sales, which are defined later). The term τ denotes the transmission charge based on the fixed network costs that need to be recovered on per MWh basis. Note that (i) the function represents only the marginal benefit associated with conventional consumers, which are separate from prosumers, and (ii) the retail price is p_i^r , while the bulk power price is p_i , exclusive of transmission charge τ .

Prosumers. The prosumer at node i is assumed to possess some renewables of output K_i with a negligible short-run marginal cost. Meanwhile, it also owns a dispatchable or backup resource to generate g_i with an increasing and convex cost $C_i^g(g_i)$ and a capacity of G_i .² The prosumer's aggregated benefit of consuming electricity is represented by $B_i(l_i)$, where l_i corresponds to the quantity consumed by the prosumer. The benefit function $B(l_i)$ is assumed to be increasing and concave, indicating that the prosumer's benefit increases in the level of consumption.³ Note that the marginal benefit $B'_i(l_i)$ of the prosumer is separate and different from the willingness-to-pay or the marginal benefit of conventional consumers. We posit that a prosumer maximizes its profit by deciding (i) the amount of power to buy from (b_{fi}) or sell to (z_{fi}) producer f in node i through bilateral contracts,⁴ (ii) the amount of consumption, l_i , given renewable K_i , and (iii) the 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. (Greek variables within the parenthesis to the right of an equation render the corresponding dual variables.)

$$\text{maximize}_{z_{fi}, b_{fi}, l_i, g_i} \sum_f (p_i z_{fi} - (p_i + \tau) b_{fi}) + \int_0^{l_i} B'_i(m_i) dm_i - C_i^g(g_i) \quad (2a)$$

subject to

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

$$g_i \leq G_i \quad (\kappa_i), \quad (2c)$$

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

The three terms in the objective function of (2), in order, correspond to revenue (+) or cost (-) from transactions with the producers, benefit of consuming energy, and costs incurred from backup generation, respectively. We assume that transmission charge τ , different from the congestion charge ω_i in the bulk market, is paid by the prosumers (and conventional consumers) as end users when acquiring power from the producers. Prosumers treat τ as given, while the model solves for τ endogenously for transmission cost recovery. On the other hand, when the prosumers sell power to the producers through bilateral transactions, it faces only the bulk energy market price p_i , i.e., the energy portion of the retail power prices. Two constraints are associated with the prosumers' problem: (2b) states that sale, purchase, and consumption of power should be balanced with the sum of renewable output and backup output; and (2c) limits the backup output g_i by its capacity G_i .

When a prosumer is modeled 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 "dwindling" some of its procurement of power, it could lower the bulk power price through (1), thereby exercising the buyer's market power. Conversely, it also notices that if it reduces power sales slightly,

² A dispatchable resource (e.g., diesel generator) can be owned and operated by an aggregator with whom prosumers enter a contract.

³ The basic model for the prosumer's demand can be also found in [37].

⁴ As the equivalence between a power market based on pool-type transactions and on bilateral contracts have been alluded to in [12], we believe that our assumption herein is reasonable and can be seen as an extension.

it might be able to push up power prices through (1), thereby exercising the 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.⁵

The KKT conditions associated with prosumers can then be displayed as follows:

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

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

$$0 \leq b_{fi} \perp -p_i - \tau + \delta_i \leq 0, \forall f, i \quad (3b)$$

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

$$0 \leq l_i \perp B'_i(l_i) - \delta_i \leq 0, \forall i \quad (3c)$$

$$0 \leq g_i \perp -C_i^{g'}(g_i) - \kappa_i + \delta_i \leq 0, \forall i \quad (3d)$$

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

$$0 \leq \kappa_i \perp g_i - G_i \leq 0, \forall i \quad (3f)$$

Note that (3a*) and (3b*) correspond to the conditions for the market power case.

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} . The set H_{fi} defines firm f 's generating units h located at node i . The optimization problem of firm f at node i is given as follows:

$$\begin{aligned} \text{maximize}_{s_{fi}, x_{fih}} \quad & \sum_i (p_i - \omega_i)(s_{fi} + b_{fi} - z_{fi}) \\ & - \sum_{i, h \in H_{fi}} (C_{fih}(x_{fih}) - \omega_i x_{fih}) \end{aligned} \quad (4a)$$

subject to

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

$$\sum_i (s_{fi} + b_{fi} - z_{fi}) - \sum_{i, h \in H_{fi}} x_{fih} = 0 \quad (\theta_f), \quad (4c)$$

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

The first term in the objective function of (4) is the revenue received from power sales $s_{fi} + b_{fi} - z_{fi}$ while paying for the congestion charge ω_i . The second term gives generation cost, minus congestion charge $-\omega_i$, 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 $C_{fih}(x_{fih})$ is assumed to be convex and increasing as in the literature (e.g., [39]). 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.⁶

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

$$0 \leq s_{fi} \perp p_i - \omega_i - \theta_f \leq 0, \forall f, i \quad (5a)$$

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

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

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

The Independent System Operator (ISO). Similar to Limpitoot et al. [40], the ISO decides on net injection or withdrawal, y_i , to maximize the wholesale market's social surplus subject to the transmission flows and nodal balance constraints. The net injection or withdrawal at node i , y_i , is determined by sales (s_{fi}), transactions between producers and prosumers (z_{fi} , b_{fi}) and local generation (x_{fih}), as expressed in (6d). The power flow in line k , $\sum_i PTDF_{ki} y_i$, is explicitly constrained by its thermal limit T_k in (6b) and (6c). In each node, the quantity demanded by consumers, d_i , is equal to power sales by producers, $\sum_f s_{fi}$, in equilibrium.

$$\text{maximize}_{y_i} \quad \sum_i \int_0^{d_i} (p_i^r(n_i) - \tau) dn_i - \sum_{f, i, h \in H_{fi}} C_{fih}(x_{fih}) \quad (6a)$$

subject to

$$\sum_i PTDF_{ki} y_i \leq T_k \quad (\lambda_k^+), \quad (6b)$$

$$-\sum_i PTDF_{ki} y_i \leq T_k \quad (\lambda_k^-), \quad (6c)$$

$$\sum_f (s_{fi} + b_{fi} - z_{fi}) - \sum_{f, h \in H_{fi}} x_{fih} = y_i \quad (\omega_i). \quad (6d)$$

The ISO's KKT conditions then are given as follows:

$$\omega_i + \sum_k PTDF_{ki} (\lambda_k^- - \lambda_k^+) = 0 \quad \forall i \quad (7a)$$

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

$$0 \leq \lambda_k^- \perp -\sum_i PTDF_{ki} y_i - T_k \leq 0 \quad \forall k \quad (7c)$$

$$\sum_f (s_{fi} + b_{fi} - z_{fi}) - \sum_{f, h \in H_{fi}} x_{fih} = y_i \quad \forall i \quad (7d)$$

Transmission Cost Recovery. While each participant's optimization problem represents its behavior in the power market, Eq. (8) helps determine the transmission charge τ collected from the prosumers and conventional consumers to reimburse the amortized fixed cost T of transmission owners.

$$\tau \left(\sum_i d_i + \sum_{f, i} b_{fi} \right) = T. \quad (8)$$

Market Equilibrium. The entire problem is then solved simultaneously by collecting the KKT conditions, one set from each entity, plus the condition for revenue adequacy. For the perfectly competitive case, they are (1), (3a), (3b), (3c)–(3f), (5a)–(5d), (7a)–(7d), and (8). In the market power case, they correspond to (1), (3a*), (3b*), (3c)–(3f), (5a)–(5d), (7a)–(7d), and (8). The resulting problem is known as a mixed

⁵ Raymar et al. [36] demonstrate that which of the two strategies should be implemented depends on the prosumers' net position, which is affected by renewable output K_r . One way of representing the prosumer's ability to manipulate the wholesale power market in the model is by treating its belief as a parameter based on a conjecture variation approach. One benefit of using this approach is that the parameter can be altered 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 un-observable. An example of this is the modeling market power of a tradable pollution permit market where the demand for tradable permits is actually implied from output decisions of generators in the power market [38].

⁶ 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 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 analogy is applied so the power prices are expected to lower in this case.

Table 1
Demand parameters.

Node	Vertical intercept [\$/MW]	Horizontal intercept [MW]
A	228.00	2160
B	169.79	1320
C	111.60	2292

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

complementarity problem (MCP), which can characterize a market equilibrium [41]. The problem naturally arises in a situation when the entities interact in a market by exchanging the information among them through the underlying market mechanism to reach an equilibrium [42]. In the current context, it refers to the quantities supplied and demanded by the entities in the wholesale electricity market, in which supply and demand are balanced in an auction mechanism.

4. Numerical case study

In this section, we discuss our results after describing the setup of the case study. In particular, Figs. 1–5 give the outcomes related to the perfect competition cases. Figs. 6–8 show the outcomes when prosumers are designated as strategic entities.

4.1. Setup

We use a representative three-node network with three firms, 10 generating units, and three transmission lines to illustrate the effects of a growing number of prosumers on the market outcomes. This setup is sufficiently generalized because it allows firms to own facilities and to compete across different locations. Information related to demand is provided in Table 1. Table 2 summarizes the characteristics of the 10 generating units, including their location, ownership, marginal cost, and generating capacity. The flows in the network are governed by Kirchhoff's laws and subject to the thermal limits as shown in Table 3.⁷

We vary the percentage of prosumers in node A from 0 to 100% with increments of 10%, whereas there are no prosumers in nodes B and C.

⁷ The data were previously used to examine carbon leakages under California climate change policy [43]. The three-node network is the simplest one that allows for looped flows, which is crucial in the electric power sector. Our intention is to refute the common belief, showing that the transmission charge does *not* necessarily increase with the number/proportion of prosumers in a market. Thus, we believe that using the data is reasonable.

Wholesale Generation

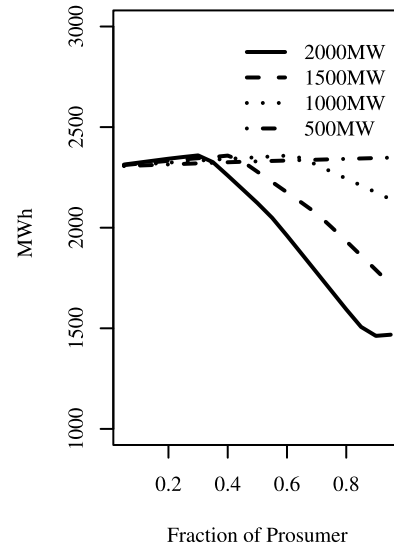


Fig. 1. Plots of wholesale generation against the proportion of prosumers in node A under perfect competition.

Specifically, we manipulate the proportion of 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 prosumers make up 20% of node A, the horizontal intercept in (1) that represents their maximum quantity demanded is $Q_A^0 \times 0.2$, while that of the corresponding conventional consumers is reduced to $Q_A^0(1 - 0.2)$. The analysis is subject to four levels of exogenous renewable outputs: 500 MW, 1000 MW, 1500 MW, and 2000 MW. These four levels are carefully selected to represent possible cases of prosumers from extremely short to extremely long positions in equilibrium.⁸ Finally, we consider prosumers as either price-takers or strategic entities who can exercise market power using a quantity-based strategy [36]. We report the results of the numerical case study in the next section.

4.2. Perfect competition

Fig. 1 plots total wholesale generation (y-axis) against the proportion of prosumers in node A (x-axis). Fig. 2 contains six plots directly related to prosumers. Fig. 1 shows that wholesale generation first increases with the proportion of prosumers, and then decreases, except the 500 MW case. The higher the renewable output K_i , the smaller the proportion of prosumers needed for this decrease to occur. This is a direct consequence of less power being purchased by prosumers from the grid, which effectively suppresses power generation (Fig. 2(b)).

A number of observations emerge from Fig. 2. First, the change in the transmission charge with respect to the proportion of prosumers moves in the opposite direction to the change in wholesale generation. The transmission charge could decrease with an increased proportion of prosumers in the market when they all act as consumers who procure energy from the bulk energy market (e.g., the 500 MW case), thereby rebutting the conventional wisdom. Prosumers with less renewable output tend to purchase a considerable amount of power, as shown in Fig. 2(b). This could more than offset the decrease in quantity

⁸ Recall that we are interested in market outcomes and the effects on transmission cost recovery, given the presence of prosumers in the market. The prosumers' net position cannot be determined a priori, but can be determined by the outcomes in a market equilibrium.

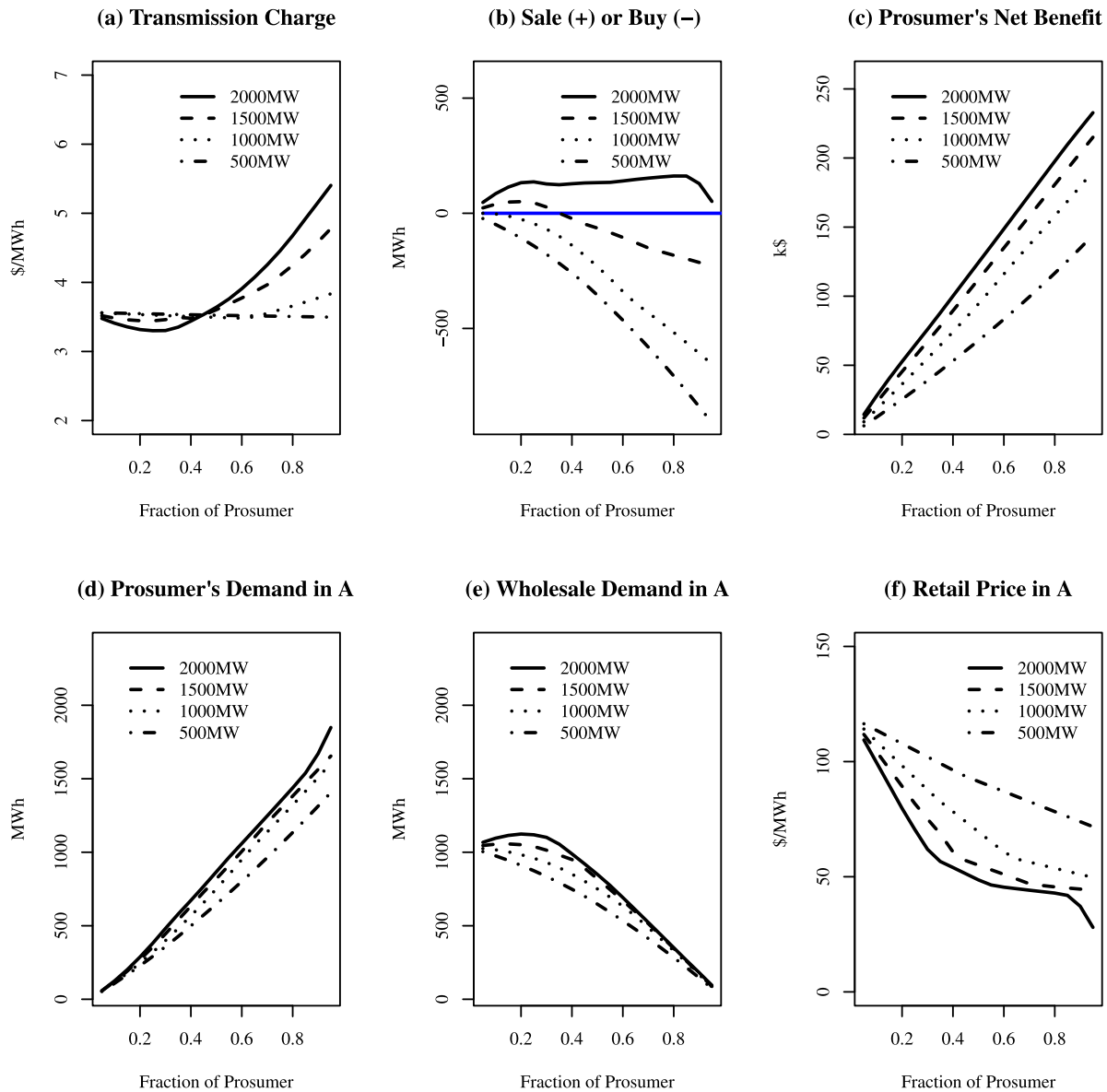


Fig. 2. Plots of (a) transmission charge, (b) prosumer's sales or purchases from main grid, (c) prosumer's net benefit, (d) prosumer's demand in node A, (e) bulk demand in node A, (f) retail price in node A against the proportion of prosumers in node A under perfect competition.

demanded by conventional consumers, thus increasing wholesale generation with the proportion of prosumers, as illustrated in Fig. 1. This, in turn, causes a decrease in the transmission charge. The transmission charge could first decrease, but then increase with the proportion of prosumers in the market (e.g., the 2000 MW case). This is mainly because prosumers, in a relative sense, have a considerable amount of renewables to offer in the market when their proportion is small. However, the “death spiral” effect then dominates the renewable effect, causing a decrease in the quantity demanded by the conventional consumers in node A.⁹ A similar observation emerges in the 1500 MW case for the transmission charge, except that the prosumers alter their position in the bulk energy market from being a net seller to being a net buyer. This is partly because of the diminished low marginal cost

effect of renewables when their renewable endowment is lower than that in the 2000 MW case.¹⁰

Second, consistent with how the scenarios were setup, the prosumers' demand increases as more consumers are designated as prosumers, who possess increasing amounts of renewable and dispatchable resources (Fig. 2(d)). For a given proportion of consumers designated as prosumers, the level of consumption is highest and lowest in the 2000 MW and 500 MW cases, respectively. Together with this outcome is the monotonic decline of consumption by traditional consumers in node A (Fig. 2(e)). For a relatively high level of renewable output (e.g., 2000 MW and 1500 MW), wholesale power sales in node A first increase until the prosumers' proportion is equal to 0.3, owing to the influx into the market of low cost renewables, and then decrease as the proportion of conventional consumers decreases.

⁹ See Fig. 2(e), where the prosumers' proportion is greater than 0.3.

¹⁰ The same is true for the 1000 MW case, albeit the curve in Fig. 2(b) is discernible from zero when the proportion of prosumers is less than 0.2.

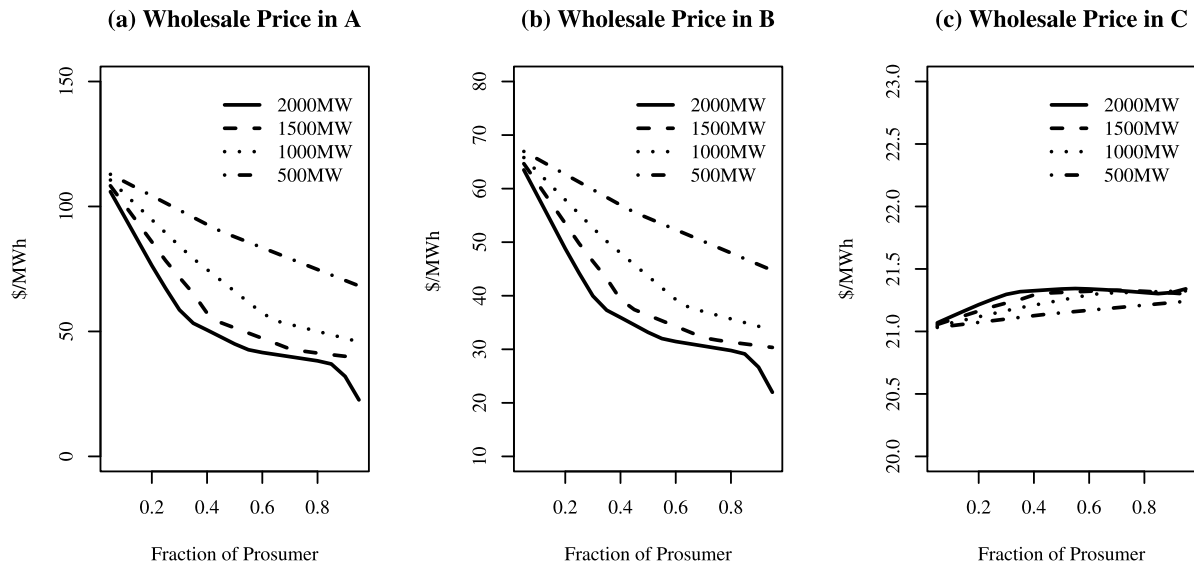


Fig. 3. Plots of (a) wholesale power price in node A, (b) wholesale power price in node B, and (c) wholesale power price in node C against the proportion of prosumers in node A under perfect competition.

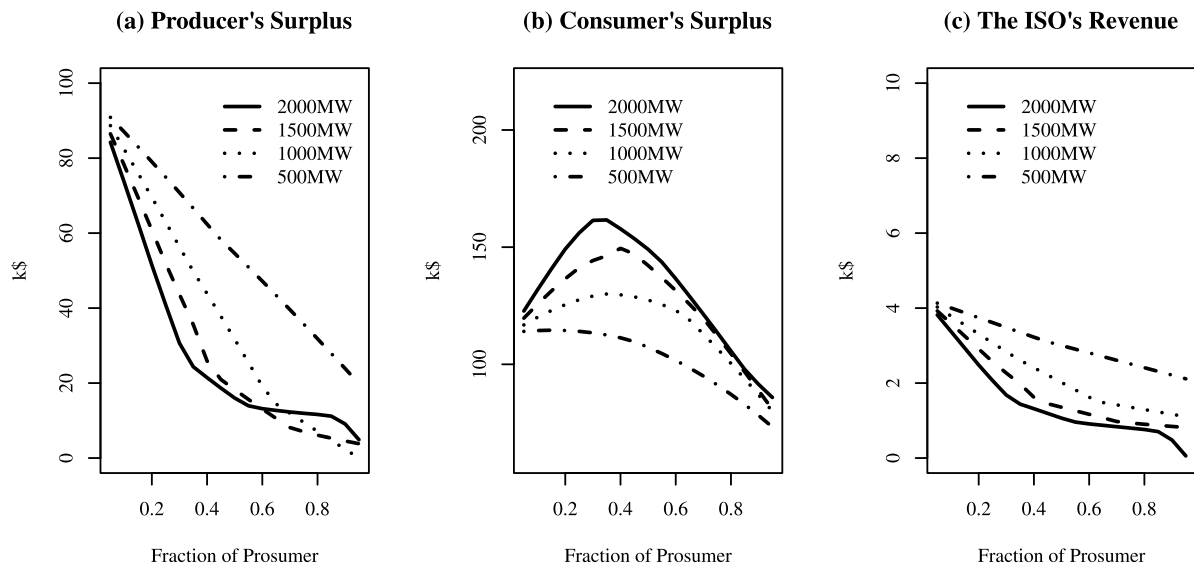


Fig. 4. Plots of (a) producer's surplus, (b) consumer's surplus, and (c) the ISO's revenue against the proportion of prosumers in node A under perfect competition.

Third, when prosumers own a relatively low amount of renewables (e.g., 500 MW and 1000 MW), they continue to act as buyers, purchasing energy from the main grid (Fig. 2(b)). This is because the amount of renewables under these two cases is not sufficient to sustain the net seller position. In contrast, a surplus of renewables in the 1500 MW case allows prosumers to act as sellers when their proportion is less than 0.4 in node A. For the 2000 MW case, prosumers serve as sellers throughout, with a drop in power sales when their proportion is greater than 0.8, owing to the weaker demand from conventional consumers. Fig. 2(c) also indicates that the prosumers' net benefit continues to grow in line with their proportion in node A. Furthermore, a higher net benefit is observed when they possess a larger amount of renewables.

We also plot the wholesale power prices in nodes A, B, and C against the proportion of prosumers in node A (x-axis) in Fig. 3. The

wholesale power price in node A continues to decrease as more renewables become available.¹¹ The market also benefits from an increased proportion of prosumers because more renewables become accessible to consumers in node A. In particular, the power price in node A, shown in Fig. 3(a), represents a declining trend against the proportion of prosumers. For nodes A and B, the higher the renewable endowment, the lower the power prices, where the case of 2000 MW renewables provides a lower envelope for the other cases. Interestingly, the effect of prosumers on the power prices in node C is not the same as those for nodes A and B. The case of 2000 MW in node C (Fig. 3(c)) forms an upper envelope for the other cases. A close examination of the flow

¹¹ In Fig. 3(a), the curves of cases with higher renewables lie below those with lower renewables.

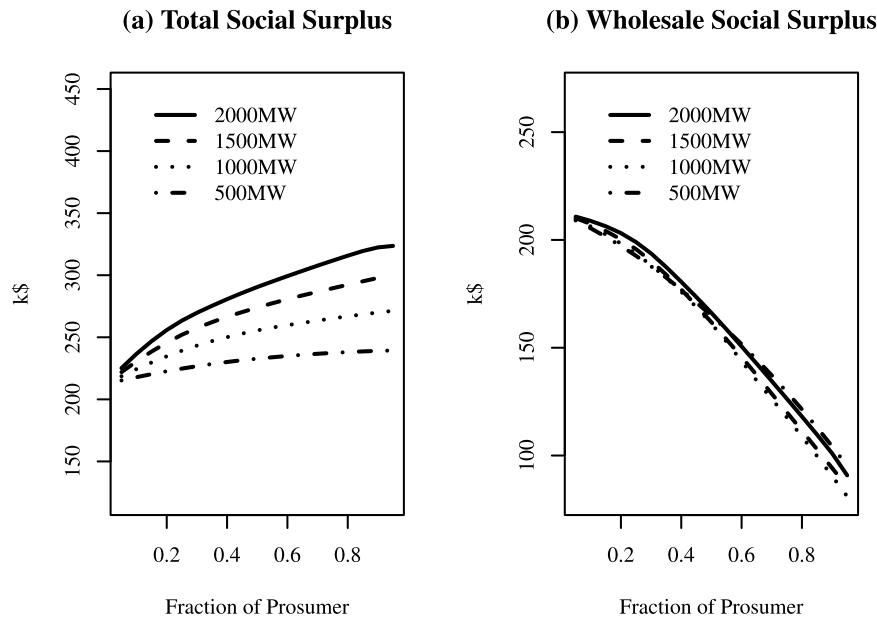


Fig. 5. Plots of (a) total social surplus and (b) wholesale social surplus against the proportion of prosumers in node A under perfect competition.

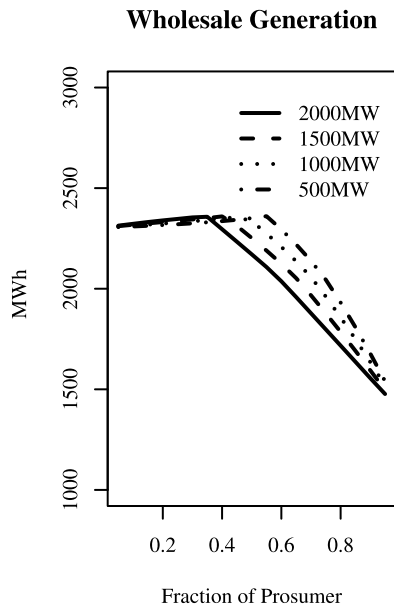


Fig. 6. Plots of wholesale generation against the proportion of prosumers in node A under imperfect competition.

patterns along the transmission lines and the net injection/withdrawal at nodes B and C indicates that while the power always flows from A to C at full capacity of 30 MW, the flow between B and C is case dependent. When the prosumers in node A are entitled to 2000 MW of renewables, the fact that this power price is the lowest (or demand is the highest) of the cases in this node (Fig. 3(a)) suggests that less power is available to export from node A to node B. This results in power flowing from C to B, leading to a higher price for the 2000 MW case in node C. The reverse is true for those cases in which the prosumers in node A own a lower amount of renewables (e.g., 500 MW). In this case, surplus energy from A can be supplied to C via the paths from A to B and B to C.

Fig. 4 plots the producer's surplus, consumer's surplus, and the ISO's revenue against the proportion of prosumers in node A. The producers in the wholesale market continue to be worse off when the proportion

of prosumers in node A increases, as shown in Fig. 4(a). The reason is that the energy demand at the wholesale level continues to decline as more consumers convert to prosumers. The cases associated with 1500 MW and 2000 MW renewable output are worse, because the power prices are lower when more renewable energy is available in the market. The crossing of the 1500 MW and 2000 MW curves toward the right of the x-axis can be partially explained by a relatively "moderate" decrease in energy demand in node A.¹² This also effectively flattens the power price at the retail level in node A in Fig. 2(f) for the 1500 MW case. Together, these cause the two curves to cross. The consumer's surplus in Fig. 4(b) shows that consumers with a lower proportion of prosumers benefit from renewables. Specifically, Fig. 2(b) shows that prosumers are more likely to sell power into the wholesale market or demand less power from the wholesale market when they are relatively small. Then, the surplus declines as prosumers either sell less or become a net buyer, competing with conventional consumers. Finally, the ISO's revenue, shown in Fig. 4(c), decreases with an increase in the proportion of prosumers in the market, and is worst in the 2000 MW case with the most renewables. This is mainly because when prosumers possess more renewables, this reduces their need to purchase from the main grid, decreasing the need to transfer power from/to other nodes, leading to a decline in the ISO's revenue.

Fig. 5 plots the total social surplus and the wholesale social surplus (producers, consumers, and grid operator) against the proportion of prosumers under perfect competition. Fig. 5(a) shows that the total social surplus, inclusive of the prosumers' benefit, continues to increase as prosumers introduce more renewable energy into the market as they grow in size. It almost reaches a plateau when the prosumers represent 80% of the load in node A. The total social surplus is highest in the 2000 MW case, and lowest in the 500 MW case, consistent with the fact that the market benefits from the zero marginal cost renewable offered by prosumers. Fig. 5(b) shows the wholesale social surplus, exclusive of the prosumers' benefit. In this case, the surplus continues to dwindle as more consumers become prosumers. Thus, the growth in prosumers' profits in Fig. 2(c) is at the expense of producers, consumers and the grid operator, as alluded to in Figs. 4(a)–(b), leading to the trend that we observed in Fig. 5(b).

¹² Fig. 2(e) shows that the two curves asymptotically overlap when the proportion of prosumers in node A increases beyond 0.4.

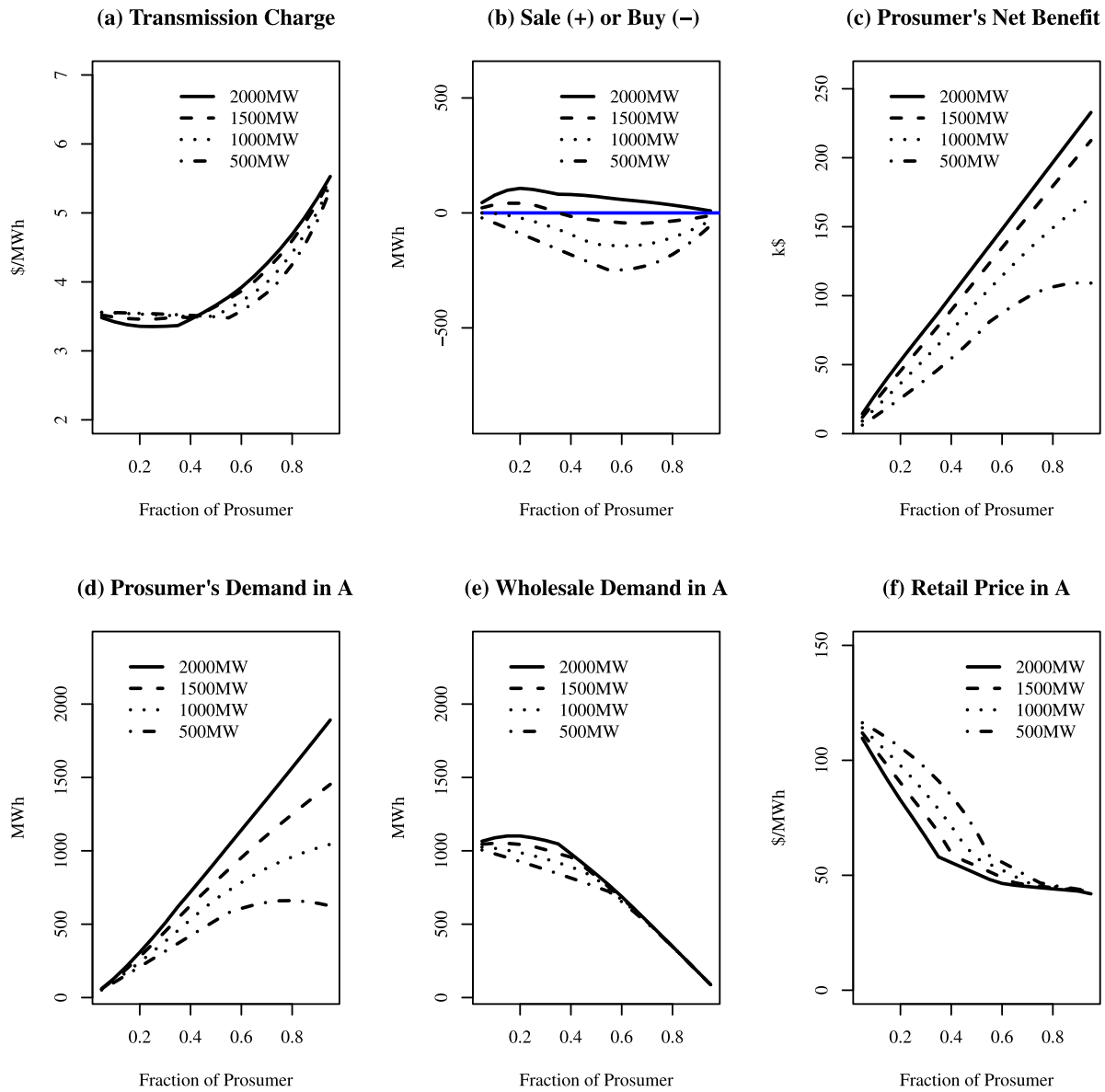


Fig. 7. Plots of (a) transmission charge, (b) prosumer's sales or purchases from main grid, (c) prosumer's net benefit, (d) prosumer's demand in node A, (e) bulk demand in node A, (f) retail price in node A against the proportion of prosumers in node A under imperfect competition.

4.3. Imperfect competition

This section reports the results for the case of imperfect competition. For completeness, we first include a plot of wholesale generation against the proportion of prosumers in Fig. 6. Overall, the figure demonstrates a similar pattern to that shown in Section 4.2.

Figs. 7–8 show the results for the cases in which the prosumers in node A are allowed to behave strategically. Specifically, prosumers can act as a monopoly (seller) or a monopsony (buyer), given the level renewable output they possess [36]. Overall, the results are broadly consistent with the findings in Section 4.2. We therefore focus our discussion on those cases that differ from the previous section.

Compared with Fig. 2(d), the curves depicting the quantity demanded by prosumers in Fig. 7(d) “bend” downward considerably, especially for the 500 MW and 1000 MW cases. This is mainly due to prosumers’ attempts to reduce their power procurement (monopsony power) when it is in a “short position”, as in Fig. 7(b), in order to reduce the power prices in node A. This is in contrast to Fig. 2(b), where the prosumers continue to satisfy their appetite for energy by increasing their procurement from the bulk market with their increased

presence in the market. Reducing energy procurement in the 500 MW case (Fig. 7(b)) also suppresses the power prices in node A, thereby increasing the demand of traditional consumers in node A (Fig. 7(e)) beyond that shown in Fig. 2(e), especially for the 500 MW case. A similar observation emerges for the 1000 MW case.

The results of the transmission charge reflect the joint effects of imperfect competition on the (i) conventional consumers’ consumption in the market and (ii) prosumers’ purchases from the wholesale market. When purchasing from the wholesale energy market, prosumers also need to pay their share of the transmission cost. The consumption by conventional consumers, shown in Fig. 7(e), and the sales/procurement by prosumers, shown in Fig. 7(b), result in the pattern of transmission charges in Fig. 7(a), which is broadly consistent with that of Section 4.2 for the 2000 MW and 1500 MW cases. However, for the 1000 MW and 500 MW cases, prosumers’ deliberate and strategic reductions in procurement, illustrated in Fig. 7(b), increase the transmission charge significantly in Fig. 7(a) compared with that in Fig. 2(a).

We also plot the power prices in Fig. 8 against the proportion of prosumers under imperfect competition. Overall, the bulk power prices in Fig. 8 show a similar trend to those in Fig. 3. However, the drop in

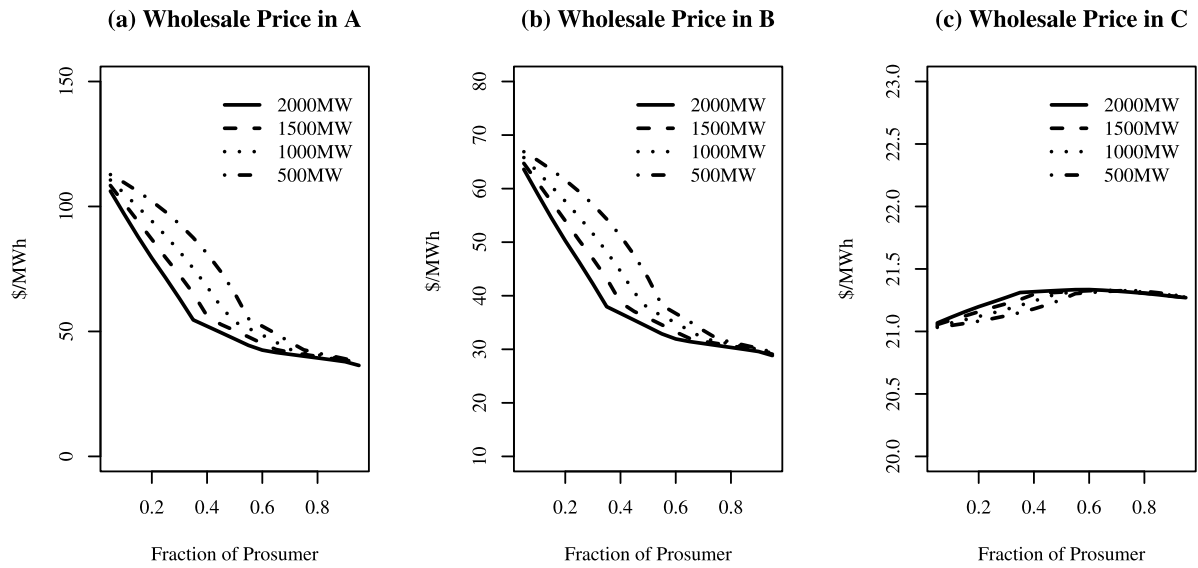


Fig. 8. Plots of (a) wholesale power price in node A, (b) wholesale power price in node B, and (c) wholesale power price in node C against the proportion of prosumers in node A under imperfect competition.

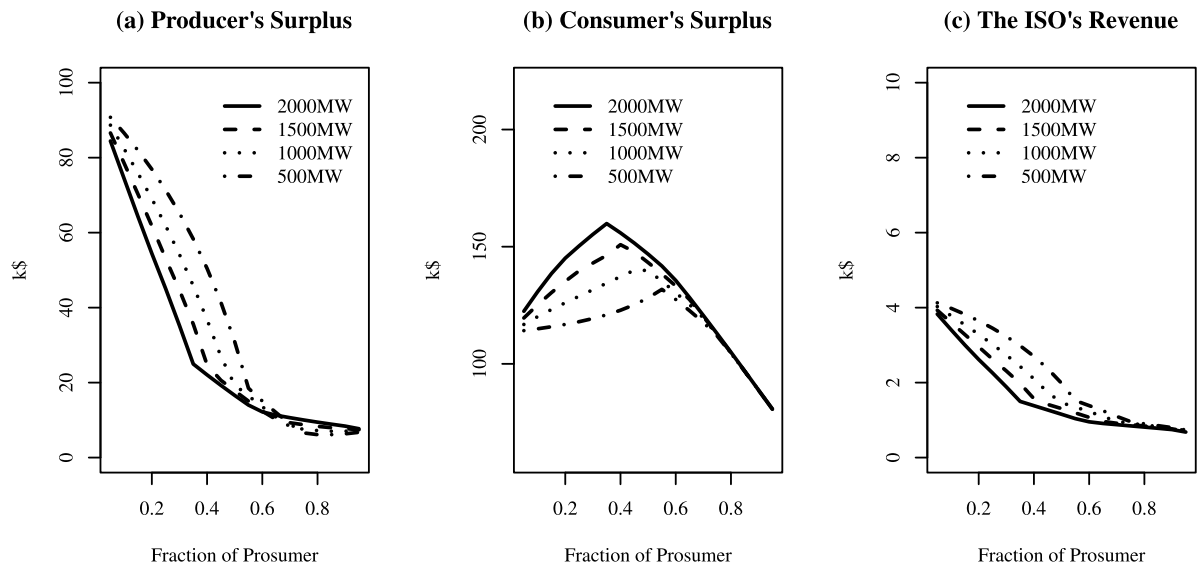


Fig. 9. Plots of (a) producer's surplus, (b) consumer's surplus, and (c) the ISO's revenue against the proportion of prosumers in node A under imperfect competition.

the power price along the x -axis is more significant for the 500 MW and 1000 MW cases. This is a direct result of the prosumers' strategy of reducing their power procurement from the wholesale market when they experience a short position in equilibrium in order to lower power prices.

The patterns displayed in Figs. 9 and 10 are comparable to those in Figs. 4 and 5, respectively. One noticeable difference is that the producer's surplus in Fig. 9 for the 500 MW and 1000 MW cases drops at a faster rate than that in Fig. 4 when moving to the right on the x -axis. This is because prosumers reducing their power procurement effectively lowers power prices. Thus, producers earn less profit, especially when prosumers represent a greater proportion of the load in node A.

With regard to social surplus, the curves in Fig. 10 mostly follow the same trends as those in Fig. 5, except for the 500 MW and 1000 MW cases. Under perfect competition in Fig. 5(a), the total social surplus, inclusive of prosumers' profits, continues to grow with the proportion of prosumers in the market. Nevertheless, the total social surplus in Fig. 10(a) for these two cases starts to decrease when the

proportion of prosumers increases beyond 0.6. This illustrates the ability of prosumers to exercise market power when their presence in the market becomes significant. Moreover, while the consumer's surplus in Fig. 9(b) represents a concave shape in the prosumers' proportion, akin to Fig. 5(b), the social surplus (exclusive of prosumers' profits) in Fig. 10(b) also decreases with the increasing presence of prosumers, because the profits earned by both the producers and the ISO are decreasing along the x -axis.

5. Policies to mitigate the death spiral

All policies aimed at mitigating the death spiral problem entail some form of wealth transfer. We consider a fiscal policy that charges a volumetric tax on consumers who, in a sense, "unsubscribe" from the main grid to become prosumers.¹³ This tax is applied to prosumers'

¹³ This "unsubscribe fee" is similar to the "back-up fee" in Spain, used by the utilities to recover fixed costs in distribution systems under a net-metering framework [26].

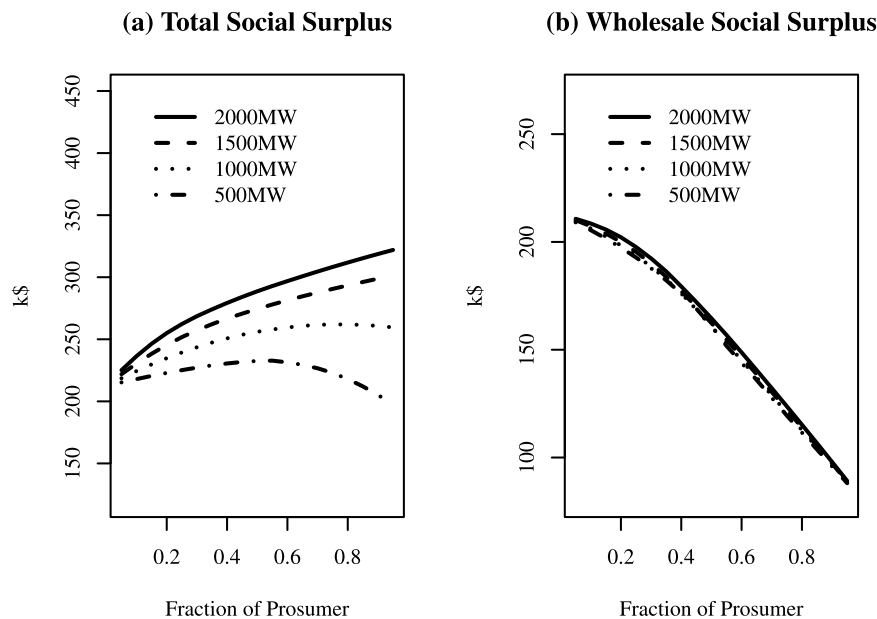


Fig. 10. Plots of (a) total social surplus and (b) wholesale social surplus against the proportion of prosumers in node A under imperfect competition.

procurement from the wholesale market. The collected tax then offsets the transmission cost (i.e., T) that needs to be reimbursed to the grid investors. We experiment with two levels of tax, \$5 and \$10/MWh, focusing on the 1000 MW perfectly competitive case, because this experiences an increased transmission charge when the proportion of prosumers is greater than 0.6. Fig. 11 plots (a) the transmission charge and (b) the percentage of the transmission cost paid by the prosumers for tax levels equal to \$0, \$5, and \$10/MWh, with the proportion of prosumers on the x -axis. Overall, a fixed tax effectively mitigates the death spiral, evidenced in Fig. 11(a) by a continuous decline of transmission charges when more consumers self-sort to prosumers, and is more profound in those cases with a higher tax. Fig. 11(b) also suggests that prosumers are subject to an increasing proportion of the transmission cost burden under a higher tax, or when their presence increases in the market. For instance, when 80% of the consumers are prosumers, the transmission cost burden increases from 20% to 40% to 70% when the tax is equal to \$5 and \$10/MWh, respectively. Consequently, because prosumers bear a disproportionate amount of the transmission cost under the tax policies, consumers' incentives to become prosumers might diminish accordingly [29].

6. Conclusion

The lumpiness of an investment, which incurs a type of nonconvex cost, has historically presented a great regulatory challenge for utilities in the power sector trying to recover their costs. The postage stamp approach, based on the share of demand or peak load, is commonly used by regional grid operators or ISOs to allocate transmission costs. An emerging entity, a prosumer who owns a set of renewable units, is likely to complicate this transmission cost allocation. While their presence strengthens the grid's resilience by shifting energy supply to local energy sources, thereby bypassing energy transmission in the bulk market, it also creates financial burden for those consumers who rely on their utility's procurement of energy from the bulk market. In a "death spiral", increases in the power price (due to an elevated transmission charge) are borne by the remaining traditional consumers, causing some of them to "exit" the grid themselves through self-generation. This is a direct consequence of the cross-subsidy from conventional consumers to prosumers.

This study explicitly considers the prosumers' problem in the market in order to analyze the impact of their presence on transmission charges

and other market outcomes when they are price takers or strategic entities. Our results show that, contrary to conventional beliefs, the effects of prosumers on the transmission charge are ambiguous. On the one hand, the transmission charge could decrease with an increased proportion of prosumers in the market when the prosumers act only as consumers who procure energy from the bulk energy market (e.g., the 500 MW case). On the other hand, with a significant amount of renewables (e.g., 2000 MW), the transmission charge could first decrease (owing to inflated demand) and then rise with an increase in the proportion of prosumers in the market.

Of course, whether a death spiral occurs is an empirical question. The fact that four European countries (France, Germany, the Netherlands, and the U.K.) currently have a favorable framework for collective prosumers suggests they may be more concerned about the death spiral than other countries. Similarly, about half of all the U.S. residential PV systems are in California, suggesting that it could be subject to the death spiral. However, even if an increase in distributed renewables halts the death spiral, other costs might still apply, such as those incurred from increasing the ramping capability to mitigate the uncertainty of renewables. Moreover, prosumers' strategic behavior could make the allocation of transmission costs more regressive because they contract their procurement from the bulk energy market in order to reduce their energy prices. This leads to a decrease in bulk energy demand, and an increase in transmission charges.

Our analysis contributes to the current debate on the "death spiral" hypothesis, and highlights the intrinsic relations between the amount of renewables, number of prosumers, and prosumers' strategy assumption, as well as their joint effect on the transmission charge. We also demonstrate that incentives for consumers to self-sort to prosumers could be eclipsed when a per-MWh-based tax policy is implemented to mitigate concerns related to the death spiral. Our study thus echoes other studies in calling for the ISO to craft better cost allocation agreements, given the growing presence of prosumers.

Our analysis is subject to a number of limitations. We limit our study to the situation where a lump sum of transmission costs needs to be allocated to consumers in proportion to their energy demand. In reality, the provision to allocate transmission costs could be more complicated than our assumption. Additionally, our analysis does not consider the possibility that prosumers operate equipment that can store energy. In the current marketplace, some prosumers are able to operate energy storage (e.g., electrical vehicles), which provide services

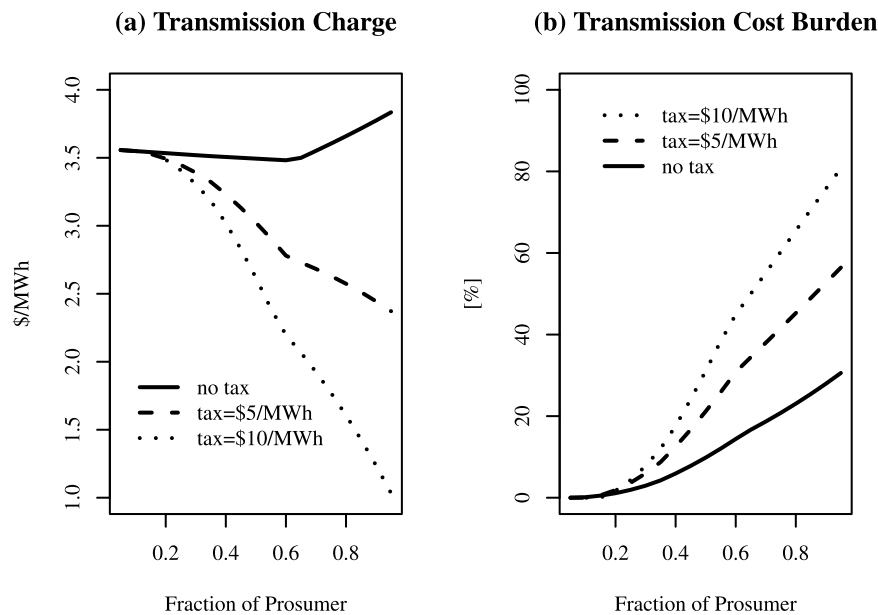


Fig. 11. Plots of (a) transmission charge and transmission cost burden against proportion of prosumers under 1000 MW perfect competition and unsubscribing taxes.

to both energy and ancillary service markets. In this case, a multiple-period model is needed, which considers the cross-elasticities of energy demand between periods in order to examine the effect of the power price in one period on demand in other periods. We also posit that market participants other than prosumers are price takers. Even though our model can be readily modified to account for the strategic behavior of conventional producers, we believe that allowing other producers to behave strategically might complicate the analysis. This will make inferences more difficult because isolating the effect induced by the prosumers becomes less straightforward. Finally, 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 provide a more realistic representation of the reality faced by the power market. However, this may make our findings more difficult to interpret. We leave the aforementioned considerations to future work.

CRedit authorship contribution statement

Yihsu Chen: Conception and design of study, Material preparation, Data collection, Analysis, Writing – original draft. **Makoto Tanaka:** Conception and design of study, Material preparation, Data collection, Analysis, Writing – original draft. **Ryuta Takashima:** Conception and design of study, Material preparation, Data collection, Analysis, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yihsu Chen reports financial support was provided by National Science Foundation.

Data availability

Data will be made available on request.

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All authors approved the version of the manuscript to be published.

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