Locational Market Power in Network Constrained Markets

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Abstract

This paper studies the issue of locational market power of suppliers in a market that is situated on a network. Locational market power arises when locational advantage allows suppliers to act non-competitively and raise prices above competitive levels. We propose a quantifiable definition of locational market power and analyze its properties over a general network. We also conduct a detailed analysis of the topological cause of the market power for a real electrical network using network analysis tools. We show that strategic alliances among small generators with geographical advantage can lead to significant amounts of market power. In the case of inelastic demand, the collusive behavior among suppliers leads to higher incidence of locational market power. The market power is curtailed as demand becomes more responsive to price, supporting the view that efficient markets require active participation from the consumers. We also observe that if the supply is more elastic than demand then supply can override some of the effects of elastic demand.

1 Introduction

Market power is the ability of a firm to raise the price of a product above its fair and competitive level. Locational market power is a special kind of market power that arises when locational advantage allows suppliers to act non-competitively. For example, in case of the electricity market, binding transmission constraints can prevent adequate competition. Transmission constraints can create isolated geographic markets where generators can have local monopoly. Such constraints may occur naturally or by manipulation of transmission facilities or generator dispatch patterns [8, 16]. Generators can exert monopoly power over the local load if network topology allows no other suppliers to serve the load. Also, strategically placed generators or phase shifters can be operated to deliberately congest lines that are needed by the competitors [1, 3].

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In this paper, we focus on the issue of locational market power arising out of the locational and network constraints in the electricity market. The topic of market power is of particular interest to policy makers and regulators as they consider restructuring the electricity market. Exercise of market power by the suppliers can wipe out any potential gains to the consumers that would be expected to result from a deregulated and restructured electricity market. Research by [4] finds that the welfare loss due to finite transmission capacity in California between 1998 and 2000 accounted for 29-38% of the total welfare loss. Many other researchers in the past have addressed the concerns related to market power, for instance, [1–3, 6–9, 12, 14, 15, 17]. However, most of the previous studies have analyzed this issue from the generation capacity perspective because high concentrations of ownership of generation usually allows the exercise of market power. Studies on the transmission aspects have mainly examined the issue of open transmission access and its impact on market power. Our contribution lies in understanding the transmission level market power which can be measured by the generators' control on the network flow given an indiscriminate access to the transmission network. The network flow is determined by many factors including transmission constraints, network topology and geographic location of the generators and consumers. These factors determine the extent of control each supplier can exert at the distribution level regardless of its production capacity. The network used in this study is a real network of the city of Portland, Oregon, with over 600 nodes and over 700 transmission lines.

We propose a quantifiable definition of locational market power and conduct a detailed analysis of the topological cause of the market power. This study addresses questions of the following kind: (i) Does larger generation capacity always imply higher market power? (ii) How critical is the location of the generator and the topology of the network? (iii) Can strategic collusive behavior by the generators result in higher market power? (iv) Does average market power of the generators increase with the increase in coalition size? (v) How do the results differ for elastic demand and supply versus inelastic demand and supply functions? (vi) What can the policy maker do to limit the market power of the suppliers?

2 Definitions

We first propose a new quantitative definition of market power. In Section 2.1, we establish a model for markets with network constraints and describe how the market power definition applies to such markets. Then we show that it is a general model; a normal market that has no network constraint can be fitted into this model as a special case.

Definition (*Market Power*) Let S be the set of suppliers and T be the set of buyers in a market. For a subset of suppliers S' and a subset of buyers T', let E(S', T') be the amount of realizable exchange in the market if only S' and T' participate. For any supplier s, her market power, denoted by $P(s)$, is defined as the decrease in realizable exchange if s does not participate in the market, i.e., $P(s) = E(S,T) - E(S - s, T)$. If a subset A of suppliers, called a coalition, opts out of the market, their collective market power is defined as $P(A) = E(S,T) - E(S - A, T)$.

In other words, a supplier s has $P(s)$ units of market power if the total amount of the demand that can be fulfilled decreases by $P(s)$ in the absence of supplier s. The market power of a single supplier s_i is of particular interest. It describes how much supplier s_i is guaranteed to provide, which in turn will affect her selling price. The quantity $P(A)$ when $|A| > 1$ is important as well because it signifies how much market power the suppliers in A have if they were to merge into a single entity.

Example 2.1. Consider a market with one buyer b who has a demand of 10 units of a good, and three suppliers, s_1, s_2, and s_3 who can produce 9, 5, and 3 units, respectively.

In Example 2.1, the three suppliers can satisfy all 10 units of demand of the buyer. Supplier 1 has 2 units of market power, because without her in the market, only 8 units of demand would be sold. Neither supplier 2 nor 3 has market power because the entire demand can be fulfilled if either one was absent. Market power is defined for any subset of suppliers too. For example, if suppliers 2 and 3 were to merge into one entity, they would have 1 unit of market power because without them, supplier 1 could only supply 9 units of demand. The emergence of market power through mergers is one of the central topics of this paper.

2.1 Market Power in a Network Constrained Market

We establish a model for studying markets over a network before applying the previous definition to such a setting. Let $G = (V, E)$ be a directed graph with edge capacities $C : E \rightarrow \mathbb{R}^+$. There is a set of suppliers $S \subset V$ and buyers $T \subset V$. Each supplier has a production capacity, and each buyer has a demand. These are given by the functions $M : S \rightarrow \mathbb{R}^+$ and $d : T \rightarrow \mathbb{R}^+$, respectively. Let $D = \sum_{t \in T} d(t)$ be the total demand. The goods sold to the buyers over a network must be delivered as a feasible network flow, which is a non-negative function $f : E \rightarrow \mathbb{R}$ such that (i) at each node $v \notin S \cup T$, the flow is conserved, i.e., $\sum_{w:e=(v,w) \in E} f(e) = \sum_{u:e'=(u,v) \in E} f(e')$, and (ii) the flow satisfies the edge capacity constraints, i.e., for each $e \in E$, $f(e) \leq C(e)$. In the context of this paper all of our graphs are undirected, which means that each undirected edge $\{u, v\}$ of capacity $C(\{u, v\})$ is simply two directed edges (u, v) and (v, u) each with the same capacity. Henceforth, unless explicitly stated, all edges are assumed to be undirected, otherwise the notation becomes quite cumbersome.

In a market subject to network constraints, the realizable exchange $E(S, T)$ is the maximum flow from S to T subject to not only the production capacity constraints, but also the network capacity constraints. It can be computed as a maximum flow in the *market graph* $G(S)$, which is constructed from G as follows. Connect each $s_i \in S$ to a super-source s with edge capacity $M(s_i)$. Connect each $t_i \in T$ to a super-sink t with edge capacity $d(t_i)$. We call $G(S)$ the market graph of G.

Suppose the suppliers and the buyer in Example 2.1 are located in a network as in Figure 1. The production capacities and the demand are the same as before. The difference, however, is that the good needs to be delivered from the suppliers to the buyer through the capacitated network. Its corresponding market graph is shown in Figure 2.

The *maximum network flow* from s to t in the market graph $G(S)$ is equal to the amount that can be traded and delivered in the market subject to the network capacity constraints, supplier production capacity constraints and demand functions, i.e., the realizable exchange $E(S, T)$. In our example of Figures 1 and 2, $E(S, T) = 10$.

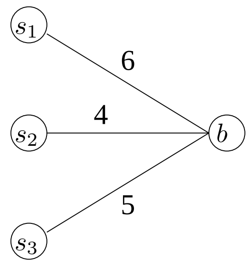

Figure 1: A market with network constraints.

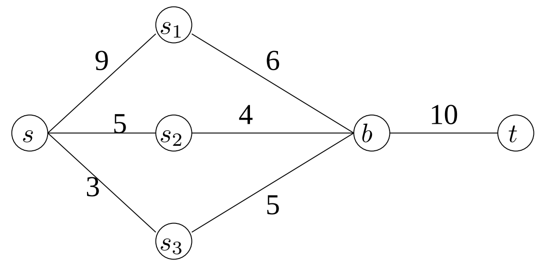

Figure 2: Market graph of Figure 1.

Similarly for any subset $S' \subset S$ of suppliers, we can construct the *submarket graph* of S' on G by connecting only $s_i \in S'$ to s with edge capacity $M(s_i)$ and connecting $t_i \in T$ to t with edge capacity $d(t_i)$. We denote this graph $G(S')$. Now we extend our market power definition to a network constrained market. Let $G(S)$ be the market graph of such a market. The market power of A is $P(A) = E(S,T) - E(S-A,T)$, where $E(S,T)$ is the maximum flow from s to t in $G(S)$ and $E(S-A,T)$ is the maximum flow from s to t in $G(S-A)$.

Figure 1 shows the previous example with network constraints. Each supplier has the same production capacity and each buyer has the same demand as before but the edge capacity constraints have now been added. Figure 2 is the corresponding market graph of the market in Figure 1. We show that the suppliers may have different market power when the market is network constrained. For supplier s_1, the maximum $s-t$ flow in the submarket graph $G(\{s_2, s_3\})$ is 7; so her market power $P(s_1) = 10 - 7 = 3$. Similarly supplier s_2 has market power $P(s_2) = 10 - 9 = 1$ and s_3 has market power 0. It essentially calculates the difference between the maximum flow on the network when all generators are online and the maximum flow when one or more generators are removed. If this difference is positive, it shows that how pivotal a supplier or coalition is in its ability to deliver the power on the network. Once a supplier has been determined to be pivotal, it can potentially extract the entire consumer surplus from the consumers.

Please note that the production capacity is one of the main sources of market power, however, network constraint may also create market power for suppliers at some particular locations in the network. For instance, the market power of supplier s_2 comes from the network capacity constraints and the network topology, rather than its production capacity. When there is no network, s_2 does not have any market power. In this paper our aim is to understand the emergence of market power due to network topology and capacity constraints.

The model of markets with network constraints at first may seem to be too specific, and only adaptable to markets over networks. A careful glance would show that a simple resource (production) constrained market can also fit this model. We can put the market in Example 2.1 on a network with infinite edge capacities as in Figure 3. Its corresponding market graph is in Figure 4. Clearly this market is equivalent to the original market without the network, i.e., they have the same market power functions.

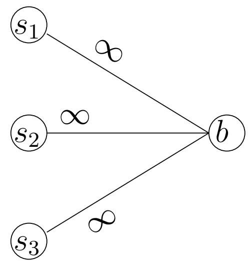

Figure 3: A normal market with a network.

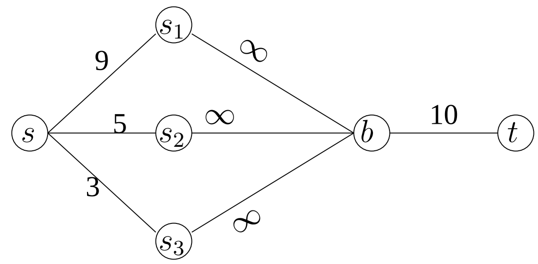

Figure 4: Market graph of Figure 3.

3 Supermodularity: An Incentive to Collude

We now prove several theoretical results about market power that show why suppliers have an incentive to merge. The analysis is based on our model of markets with a network. Note that these results are true for any market with a network. Normal markets without the network are a special case of our model, with infinite edge capacities, therefore the results of this section hold for normal markets too.

Theorem 3.1. *Market power is supermodular, that is, for any* $A, B \subset S$, $P(A \cup B) + P(A \cap B) \geq P(A) + P(B)$.

We first introduce some terms in the network flow theory. From the *maximum flow minimum cut theorem* of Ford and Fulkerson [5, Chapter 26], the maximum flow from s to t in a network is equal to the minimum cut between s and t. A cut is a partition of the nodes into two disjoint subsets such that s and t are in different subsets. The size of a cut is the total capacity of the edges connecting the two subsets, and a minimum cut (or min-cut) is a cut of minimum size. For example in Figure 2, the partition of the nodes into disjoint sets $\{s, s_1, s_2, \} \sqcup \{s_3, b, t\}$ is a cut of capacity 13. However, the min-cut is $\{s, s_1, s_2, s_3, b\} \sqcup \{t\}$ which has capacity 10. This equals the maximum flow from s to t. In general, there may be several min-cuts, though in this example the min-cut is unique.

For any $S' \subseteq S$, Let $f(S') = \text{mincut}(G(S'), s, t)$, that is, the maximum $s-t$ flow in submarket graph $G(S')$. Let $A, B \subset S$. For any min-cut of $G(A)$, let $X(A)$ be the set containing s. Likewise, for any min-cut of $G(B)$, let $X(B)$ be the set containing s. Finally, let $X(t) = G(S) \setminus (X(A) \cup X(B))$. For simplicity of notation, let $x(A) = X(A) \setminus (X(A) \cap X(B))$, and $x(B) = X(B) \setminus (X(A) \cap X(B))$. Let a denote the set of edges in $G(A)$ between $x(A)$ and $X(t)$, and α their cut capacity in $G(S)$. Let b denote the edges in $G(B)$ between $x(B)$ and $X(t)$, with cut capacity β, and let c be the edges between $X(A) \cap X(B)$ and $X(t)$, with capacity γ. Denote the set of edges in $G(S)$ between $x(A)$ and $x(B)$ by d, with cut capacity δ. Finally, let e be the edges in $G(S)$ from $x(A)$ to $X(A) \cap X(B)$ with capacity ϵ, and let f be the set of edges in $G(S)$ between $x(B)$ and $X(A) \cap X(B)$, with capacity ϕ. To summarize, the edge sets a, b, c, d, e and f of the graph $G(S)$, which are shown in Figure 5, have respective capacities α, β, γ, δ, ϵ, and ϕ.

It is important to realize that though the sets of edges defined above are fixed, their capacities may be different in a submarket graph as opposed to in $G(S)$, because submarket graphs are subgraphs of $G(S)$. We will denote capacity of an edge set in a submarket graph by a subscript.

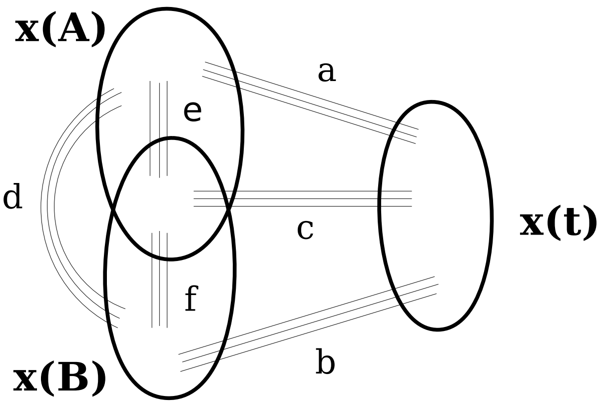

Figure 5: A picture of the notation in the proof of Theorem 3.1.

For example, for any set $S' \subset S$ of sellers, $\gamma_{S'}$ is the capacity of the edges in c, in the graph $G(S')$. We will often omit the subscript where this distinction is irrelevant. For example, $\alpha = \alpha_{S'}$ for any S' because none of the "dynamic" edges $\{s, s_i\}$ can lie in a. Next, we prove two lemmas.

Lemma 3.2. *For any $A, B \subset S$, we have $\gamma_A + \gamma_B = \gamma_{A\cup B} + \gamma_{A\cap B}$.*

Proof: We can partition the edges in c into four categories:

(I) $\{s, s_i\}$, $s_i \in A \setminus B$,

(II) $\{s, s_j\}$, $s_j \in B \setminus A$,

(III) $\{s, s_k\}$, $s_l \in A \cap B$,

(IV) all other edges.

By definition, γ_A is the capacity of the edges in (I), (III), and (IV), and γ_B is the capacity of the edges in (II), (III), and (IV). In contrast, $\gamma_{A\cup B}$ is the capacity of the edges in (I), (II), (III), and (IV), and $\gamma_{A\cap B}$ is the capacity of the edges in (III) and (IV). The lemma now follows. ■

Lemma 3.3. *The function f is submodular, i.e., $f(A) + f(B) \geq f(A \cup B) + f(A \cap B)$.*

Proof: Observe that $f(A) = \alpha + \gamma_A + \delta + \phi_A$ and $f(B) = \beta + \gamma_B + \delta + \epsilon_B$. Because $a + b + c$ is a cut of $G(A \cup B)$, though not necessarily the minimum cut,

$$f(A \cup B) \leq \alpha + \beta + \gamma_{A\cup B}.$$

Similarly, $c + e + f$ is a cut of $G(A \cap B)$, and so $f(A \cap B) \leq \gamma_{A\cap B} + \epsilon_{A\cap B} + \phi_{A\cap B}$. Using Lemma 3.2, and the facts that $\epsilon_{A\cap B} \leq \epsilon_B$, and $\phi_{A\cap B} \leq \phi_A$, we conclude that

$$\begin{aligned} f(A) + f(B) &= \alpha + \beta + \gamma_A + \gamma_B + \epsilon_B + \phi_A + 2\delta \\ &\geq \alpha + \beta + \gamma_A + \gamma_B + \epsilon_B + \phi_A \\ &\geq \alpha + \beta + \gamma_{A\cup B} + \gamma_{A\cap B} + \epsilon_{A\cap B} + \phi_{A\cap B} \\ &\geq f(A \cup B) + f(A \cap B). \end{aligned}$$

■

Proof of Theorem 3.1: We first write market power as

$$
\begin{aligned}
P(A) &= \mathrm{mincut}(G(S), s, t) - f(S \setminus A) \\
P(B) &= \mathrm{mincut}(G(S), s, t) - f(S \setminus B) \\
P(A \cup B) &= \mathrm{mincut}(G(S), s, t) - f(S \setminus (A \cup B)) \\
P(A \cap B) &= \mathrm{mincut}(G(S), s, t) - f(S \setminus (A \cap B))
\end{aligned}
$$

By Lemma 3.3,

$$
\begin{aligned}
&P(A) + P(B) - P(A \cup B) - P(A \cap B) \\
&\qquad = -f(S \setminus A) - f(S \setminus B) + f(S \setminus (A \cup B)) + f(S \setminus (A \cap B)) \\
&\qquad \leq 0,
\end{aligned}
$$

and hence the theorem. ■

In the field of coalition game theory, a superadditive function on the power set $\mathcal{P}(\mathcal{S})$ is called a *characteristic function.*

Corollary 3.4. *If $A, B \subset S$ and $A \cap B = \emptyset$, then $P(A \cup B) \geq P(A) + P(B)$. In other words, market power is superadditive.*

This follows from the fact that if A and B are disjoint, then $P(A \cap B) = 0$, and is the main practical result of the theorem. It simply says that a coalition of suppliers has at least as much power as the sum of the individuals' market power, or in other words, P is a characteristic function. Notice that in particular, if $i \neq j$, then $P(\{i, j\}) \geq P_i + P_j$, i.e., two suppliers never have incentive not to merge.

4 Experimental Setup and Methodology

Our study uses the power grid of Portland, Oregon. It includes the topological locations of generators (suppliers) and consumers, and the transmission lines along with their capacities. The Portland grid has 776 lines and 662 nodes. Of these nodes, 319 are load serving (consumer) nodes and 41 are generator nodes. The maximum flow in the market graph $G(S)$ or in the submarket graph $G(S')$ for a subset S' of generators is computed using Goldberg's implementation of the push-relabel algorithm [13].

The demand data is generated from the consumer peak demand for the summer of year 1999 available from the FERC website. The total peak demand for Portland is 6986.62MW. We use the US Department of Energy (DOE) website to obtain capacity data on the generators. Even though the EIA-860A Database provides data on all power plants, it is not easy to identify which generators in the database correspond to the 41 Portland generators. We use the following method to assign capacities to the generators used in this study. We randomly select generator capacities from the database to assign to Portland generators such that the sum of all the Portland generators' capacities is at least 110% of the total Portland demand. This technique ensures that the assigned generator capacity is large enough to meet the city's demand.

In order to analyze the role of price elasticities of supply and demand on the market power of the generators, we consider four different scenarios with different combinations of demand and supply elasticities: (i) inelastic demand and inelastic supply (ii) inelastic demand and elastic supply, (iii) inelastic supply and elastic demand, and (iv) elastic demand and elastic supply. In case of price elastic demand and supply, we allow the price to vary between \$20 and \$30 in increments of one.[1]

For the constant demand case, we use the peak demand data from FERC to assign demand to each of the consumer nodes. For assigning the constant supply amount to generators, we use the methods described above for assigning capacities.

In case of the elastic demand, we use $q = a - bp$ to represent the elastic demand function where q is the quantity demanded, p is the price, a is the inelastic demand and b represents the elastic coefficient of the demand. For p_{min} i.e. \$20, the quantity demanded is maximum which we know is equal to the peak demand. Based on this relation, for each consumer node, we determine the corresponding value of a after we pick b from

$$\{\tfrac{1}{10}, \tfrac{1}{9}, \ldots, \tfrac{1}{2}, 1, 2, \ldots, 10\}$$

uniformly at random. This linear demand function for each consumer node is used to measure the price responsiveness of consumers. The average elasticity of demand in our experiments is about 0.01.

In case of the elastic supply, we use $q = c + dp$, a linear function where q is the quantity supplied, p is the price and c is the inelastic supply. We pick the supply function coefficients in such a way that total supply is more than total demand at any price. It is sufficient to ensure this at the minimum price \$20. For each generator node, we take values of d between 0 and 40 uniformly at random and determine c such that at price \$20, q is equal to the generator capacity value selected in the constant supply case. The average price elasticity of supply in our experiments is about 0.19. Interested readers can find exact values of variables b and d on the web at http://staff.vbi.vt.edu/chenj/pub/JEBO.Market.Power.Slope.txt.

For each of the four scenarios, we first compute the locational market power of each supplier as defined in Section 2. We then create supplier coalitions of size 2 through 6. For each coalition size, we compute the market power of each possible combination in the coalition. For instance, if there are 3 generators and the coalition size under consideration is 2, we would calculate the market power of coalition between suppliers 1,2; 2,3; and 3,1. We compare and analyze the market power distributions of these different coalition sizes. For the inelastic supply and inelastic demand case, we tabulate the results and provide quantitative details but for the price elastic demand and supply cases, we report the mean and maximum market power against coalition size and market clearing price along with the graphical analysis. Showing the result for each price increment for the price elastic cases would make the paper very repetitive and long.

[1] This price range is chosen because it represents the likely average wholesale marginal cost per MWh of electricity. http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html

Rank	*Capacity*		*Market Power*		*Topological Property*	
	% Total Capacity	ID	% Total Flow	ID	Degree	ID
1	15.68	98	22.40	83	11	83
2	14.69	306	14.23	39	8	108
3	10.77	122	13.64	98	7	114
4	10.08	445	8.33	356	6	39
5	9.96	83	7.80	445	5	356
6	9.74	475	7.26	60	4	89
7	8.90	60	4.56	475	4	40
8	6.32	39	3.47	493	4	130
9	3.70	356	3.02	130	3	98
10	2.16	220	2.52	122	3	70
11	1.54	493	2.41	601	3	55
12	1.34	130	1.67	306	3	487
13	1.07	601	1.11	487	3	479
14	0.70	328	0.75	220	3	122
15	0.66	67	0.69	348	2	60
16	0.49	487	0.69	328	2	47
17	0.44	348	0.69	100	2	453
18	0.31	100	0.60	17	2	445
19	0.27	17	0.54	310	2	310
20	0.24	310	0.50	514	2	100

Table 1: Twenty largest generators and their capacities.

5 Discussion of Results

5.1 Inelastic Demand and Inelastic Supply

In this subsection we examine the market power of the generators assuming that both demand and supply are constant and not responsive to price. The demand is fixed at the peak demand level and the supply is set based on the method described in Section 4.

The *Capacity* column of Table 1 identifies the twenty generators who own the largest generation capacity. The top 4 generators own more than half of the total market generation and the top 10 generators own almost 92% of the total generation capacity. This implies that the rest of the 31 generators together have only 8% of the capacity. The *Market Power* column identifies the twenty generators who have the maximum market power, and the *Topological Property* column identifies those who have the largest degree. The degree of a node (generator) in a network is the number of links (transmission lines) the node is connected to. The purpose of this table is to compare the correlations between capacity, degree and market power of the generators.

Intuitively, one would expect high generation capacity generators to be the ones with high market power. From Table 1, it is clear that the highest capacity generators are not necessarily the ones with the maximum market power. The second largest capacity generator (with ID 306) which controls about 15% of the generation capacity has less than 2% of market power. On the other hand, generator ID 83 has less than 10% of the total generation capacity but has more than 20% of the market power. Similarly, generator ID 39 has only 6.32% total generation capacity but has 14.23% of the market power. These observations naturally suggest that factors other than production capacity are responsible in determining the market power of the generators.

In this study we find that a generator's topological degree can play a dominant role in determining its control on the total flow of the network. If we compare the list of top twenty generators with the largest degree and those with the maximum market power, we find 11 out of the 20 IDs are the same, indicating a strong positive correlation between the degree of a generator and its market power. Generator with ID 83 has both the maximum market power and the largest degree. Five out of the top nine generators in these two lists completely overlap. These observations strongly suggest that market power of a generator is determined at least partly by its location in the network. If it is located at a high-degree node, then it is likely to have large market power. The economic consequences of the degree of a generator have never been studied before.

Tables 2, 3 and 4 show the market power of generators under different coalition sizes. Columns 1 and 4 of these tables show the generator IDs of the coalitions. Columns 2 and 5 show the actual market power (in MW) each coalition can have and columns 3 and 6 show the market power of the coalition in terms of the percentage of the total flow. We report only the top twenty coalitions in terms of their market power. To calculate the market power of each coalition, we first calculate the total network flow with all generators on the network. Then we exclude the members of the coalition i.e. no flow is supplied from those members on the network. The new network flow excluding the members is calculated. The difference in the two network flows is the market power of the coalition. Table 2 shows that the biggest coalition can be made between generators 83 and 39 who independently also control the most flow. It is clear from column 5 of Table 2 that nineteen of the top twenty coalitions include generator number 83 which alone controls almost 22.4% of the total network flow. In fact, our results shows that the generators that belong to the most powerful size k coalition are also members of the most powerful size $(k+1)$ coalition.

Table 3 shows results of coalition sizes 3 and 4. Note that all of the top 20 size 3 coalitions lead to over 37% of market power. Similarly, all of the top 20 size 4 coalitions can have over 50% of the market power. The best size 4 coalition can control almost 60% of the market. Table 4 shows the market power of size 5 and size 6 coalitions. Market power consistently increases with the coalition size. It is alarming to see that all top 20 size 6 coalitions can control 67% or more of the market.

Figure 6 shows that the average market power of the coalition goes up with the coalition size. The average market power of a size 1 coalition is 86MW whereas for size 6 coalitions the average market power goes up to 520MW. Figure 7 shows that the maximum market power also monotonically increases with the coalition size. It increases from 806MW to 2651MW as coalition size increases from 1 to 6. This result shows that in the absence of price responsiveness of demand, the mergers between generators can lead to higher exploitation of the consumers. As coalition size increases, the generators' control on the network flow increases, resulting in higher incidence of market power.

Gen ID	Mktpow (MW)	%Total	Gen ID	Mktpow (MW)	%Total
83	806.40	22.40	39,83	1318.49	36.63
39	512.09	14.23	83,98	1297.40	36.04
98	491.00	13.64	83,356	1106.40	30.74
356	300.00	8.33	445,83	1087.35	30.21
445	280.95	7.80	60,83	1067.58	29.66
60	261.18	7.26	39,98	1003.09	27.87
475	164.00	4.56	83,475	970.40	26.96
493	125.00	3.47	83,493	931.40	25.87
130	108.70	3.02	83,130	915.10	25.42
122	90.62	2.52	83,122	897.02	24.92
601	86.70	2.41	83,601	893.10	24.81
306	60.00	1.67	83,306	866.40	24.07
487	40.04	1.11	83,487	846.44	23.51
220	27.00	0.75	220,83	833.40	23.15
348	25.00	0.69	83,348	831.40	23.10
328	25.00	0.69	83,328	831.40	23.10
100	25.00	0.69	83,100	831.40	23.10
17	21.50	0.60	17,83	827.90	23.00
310	19.60	0.54	83,310	826.00	22.95
514	18.00	0.50	514,83	824.40	22.90

Table 2: Market power of generators with coalition size 1 and 2.

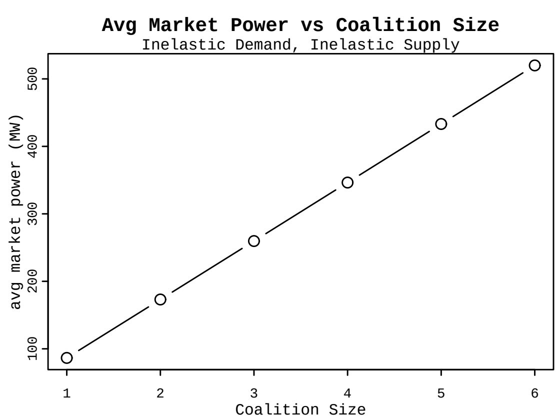

Figure 6: Average market power for different coalition size under inelastic demand and inelastic supply.

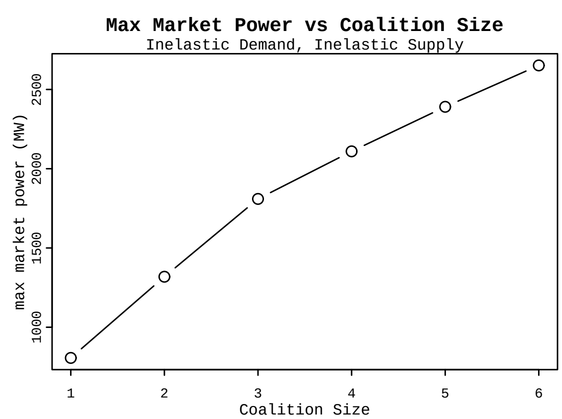

Figure 7: Maximum market power for different coalition size under inelastic demand and inelastic supply.

Gen ID	Mktpow (MW)	%Total	Gen ID	Mktpow (MW)	%Total
39,83,98	1809.49	50.27	39,83,98,356	2109.49	58.60
39,83,356	1618.49	44.96	445,39,83,98	2090.44	58.07
445,39,83	1599.44	44.43	39,60,83,98	2070.67	57.52
83,98,356	1597.40	44.38	39,83,475,98	1973.49	54.82
39,60,83	1579.67	43.88	39,83,98,493	1934.49	53.74
445,83,98	1578.35	43.85	39,83,98,130	1918.19	53.29
60,83,98	1558.58	43.30	39,83,98,122	1900.12	52.78
39,83,475	1482.49	41.18	445,39,83,356	1899.44	52.77
83,475,98	1461.40	40.60	39,83,98,601	1896.19	52.68
39,83,493	1443.49	40.10	39,60,83,356	1879.67	52.22
39,83,130	1427.19	39.65	445,83,98,356	1878.35	52.18
83,98,493	1422.40	39.51	39,83,306,98	1869.49	51.93
39,83,122	1409.12	39.14	445,39,60,83	1860.62	51.69
83,98,130	1406.10	39.06	60,83,98,356	1858.58	51.63
39,83,601	1405.19	39.04	39,83,98,487	1849.53	51.38
83,98,122	1388.02	38.56	445,60,83,98	1839.52	51.10
445,83,356	1387.35	38.54	39,220,83,98	1836.49	51.02
83,98,601	1384.10	38.45	39,83,98,348	1834.49	50.96
39,83,306	1378.49	38.29	39,83,98,328	1834.49	50.96
60,83,356	1367.58	37.99	39,83,98,100	1834.49	50.96

Table 3: Market power of generators with coalition size 3 and 4.

Gen ID	Mktpow (MW)	%Total	Gen ID	Mktpow (MW)	%Total
445,39,83,98,356	2390.44	66.41	445,39,60,83,98,356	2651.62	73.66
39,60,83,98,356	2370.67	65.86	445,39,83,475,98,356	2554.44	70.96
445,39,60,83,98	2351.62	65.33	39,60,83,475,98,356	2534.67	70.41
39,83,475,98,356	2273.49	63.16	445,39,60,83,475,98	2515.62	69.88
445,39,83,475,98	2254.44	62.63	445,39,83,98,356,493	2515.44	69.88
39,60,83,475,98	2234.67	62.08	445,39,83,98,356,130	2499.14	69.42
39,83,98,356,493	2234.49	62.07	39,60,83,98,356,493	2495.67	69.33
39,83,98,356,130	2218.19	61.62	445,39,83,98,356,122	2481.07	68.92
445,39,83,98,493	2215.44	61.54	39,60,83,98,356,130	2479.37	68.88
39,83,98,356,122	2200.12	61.12	445,39,83,98,356,601	2477.14	68.81
445,39,83,98,130	2199.14	61.09	445,39,60,83,98,493	2476.62	68.80
39,83,98,356,601	2196.19	61.01	39,60,83,98,356,122	2461.29	68.37
39,60,83,98,493	2195.67	60.99	445,39,60,83,98,130	2460.32	68.35
445,39,83,98,122	2181.07	60.59	39,60,83,98,356,601	2457.37	68.26
39,60,83,98,130	2179.37	60.54	445,39,83,306,98,356	2450.44	68.07
445,39,83,98,601	2177.14	60.48	445,39,60,83,98,122	2442.24	67.84
39,83,306,98,356	2169.49	60.27	445,39,60,83,98,601	2438.32	67.74
39,60,83,98,122	2161.29	60.04	39,60,83,306,98,356	2430.67	67.52
445,39,60,83,356	2160.62	60.02	445,39,83,98,356,487	2430.48	67.52
39,60,83,98,601	2157.37	59.93	39,60,67,83,98,356	2423.97	67.34

Table 4: Market power of generators with coalition size 5 and 6.

5.2 Inelastic Demand and Elastic Supply

We now consider the case when demand is inelastic or constant but the supply is linear in price. With price being yet another variable, the market power results become trickier to report. In this paper we report the average and the maximum market power with respect to the price and the coalition size. Interested readers can go to the website at

http://staff.vbi.vt.edu/chenj/pub/JEBO.Market.Power.All.Plots.pdf

for a complete set of plots and histograms. Figure 8 and Figure 9 display the average market power of the size 2 coalition and size 6 coalition generators respectively for different levels of prices. Here the generators have linear supply functions. Our study finds that the market power of a supplier is higher for larger coalition size. For coalition size 6, the average market power goes up about 720KW as price increases from \$20 to \$30 whereas for size 2, it goes up about 240KW. If the price is kept constant at \$30, just the increase in coalition size from 2 to 6 increases the market power from 170MW to 520MW, a difference of about 350MW. This shows that the difference in market power due to change in price is much less compared to the difference due to the change in the size of coalition. Figure 10 and Figure 11 show the change in the average and maximum market power due to change in the coalition size and market clearing price.

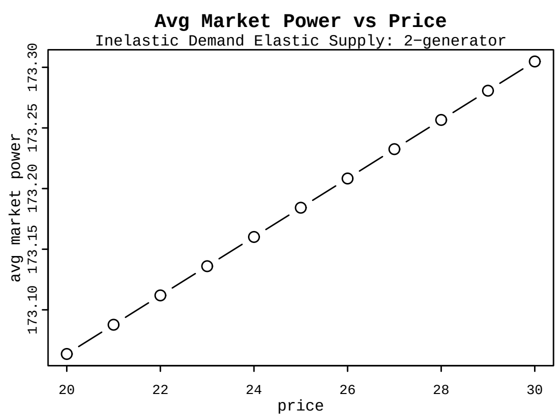

Figure 8: Average market power for size 2 coalitions under inelastic demand and elastic supply.

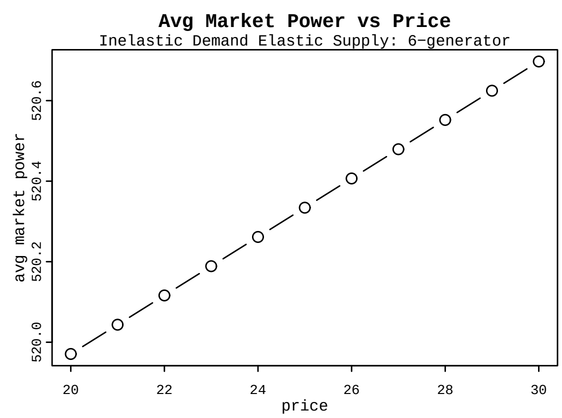

Figure 9: Average market power for size 6 coalitions under inelastic demand and elastic supply.

5.3 Elastic Demand and Inelastic Supply

In Figure 12 and Figure 13 we observe the role played by the elasticity of demand. A linear demand function is used to show the price responsiveness of demand. Intuitively, one would expect that the generators have smaller market power if the demand is more elastic. Figure 12 and 13 show that, given the elastic demand, as the price goes up, the average market power goes down for both size 2 and size 6 coalitions. This is an important result since it shows how increase in demand

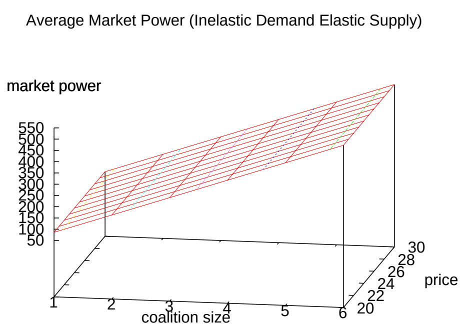

Figure 10: Average market power vs. coalition size and price under inelastic demand and elastic supply.

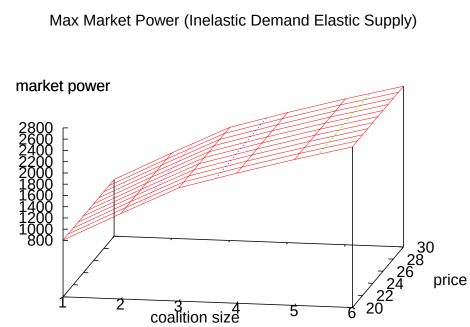

Figure 11: Maximum market power vs. coalition size and price under inelastic demand and elastic supply.

responsiveness by consumers can mitigate exercise of market power by the suppliers. In case of the size 6 coalitions, an increase in price by \$10 reduces the average market power by over 36KW whereas in case of the size 2 coalitions, it goes down by about 9KW. Here again, if the price is kept fixed at \$30, an increase in coalition size from 2 to 6 can increase the market power by almost 350MW. If we compare these results with the inelastic demand case, it is easy to see the impact demand elasticity has in mitigating market power. If elastic demand can create disincentives for collusion among suppliers, it can lead to a significant drop in the average market power. Figure 14 and Figure 15 show that the average and maximum market power increase with the coalition size and the market clearing price when demand is elastic and supply is held constant.

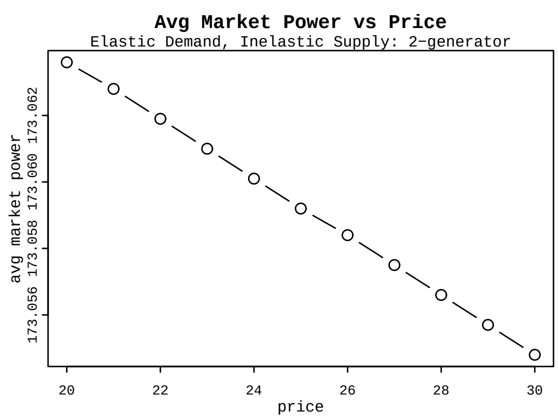

Figure 12: Average market power for size 2 coalition under elastic demand and inelastic supply.

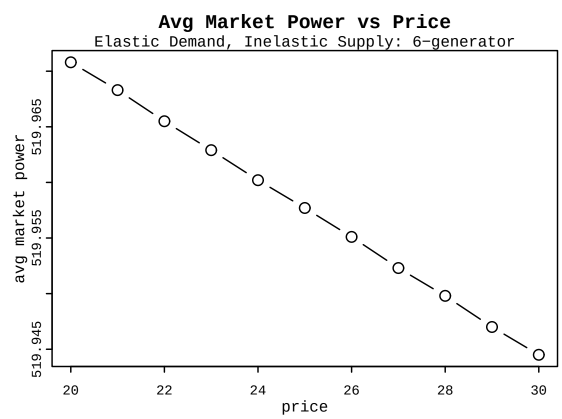

Figure 13: Average market power for size 6 coalition under elastic demand and inelastic supply.

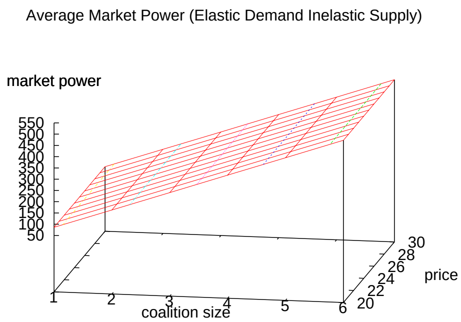

Figure 14: Average market power vs. coalition size and price under elastic demand and inelastic supply.

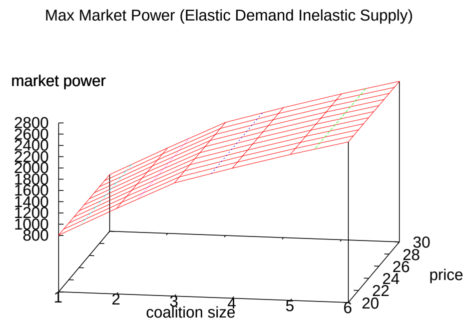

Figure 15: Maximum market power vs. coalition size and price under elastic demand and inelastic supply.

5.4 Elastic Demand and Elastic Supply

Figure 16 and Figure 17 show the results of change in price on market power when supply and demand are both elastic. With both supply and demand being price responsive, the effect of price on market power will be determined by the relative elasticities of the two curves. The exact shapes of the supply and demand curve along with the topology of the grid will determine whether the average market power will increase, decrease or stay constant with changes in price. In our experiments the elasticity of demand (0.01) is much less than the elasticity of supply (0.19) which implies that the demand is relatively less responsive to changes in price compared to the supply. This causes the market power to go up with increase in price.

It is interesting to compare Figures 16 and 17 with Figures 12 and 13, and with Figures 8 and 9. It shows that the elastic supply brings more market power to the suppliers and elastic demand mitigates generators' market power. If supply elasticity is higher than the demand elasticity as is the case in our experiments, it can overshadow the mitigating effect of the elastic demand. Figure 18 and Figure 19 show that the average and maximum market power increases with the coalition size as well as the market clearing price.

6 Summary of Results

The findings of our study are summarized below.

1. The large capacity generators do not necessarily have the locational advantage and hence locational market power. In the presence of transmission constraints, opportunities exist even for small suppliers to exercise market power and be price makers, especially if they are located at high-degree nodes. This also suggests that adding just a few transmission lines could have a powerful effect on the total market power. In future work, we plan to explore the implications of this study on the growth of the electrical infrastructure.

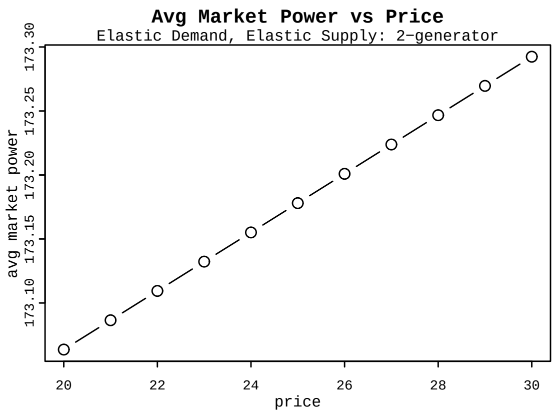

Figure 16: Average market power for size 2 coalition under elastic demand and elastic supply.

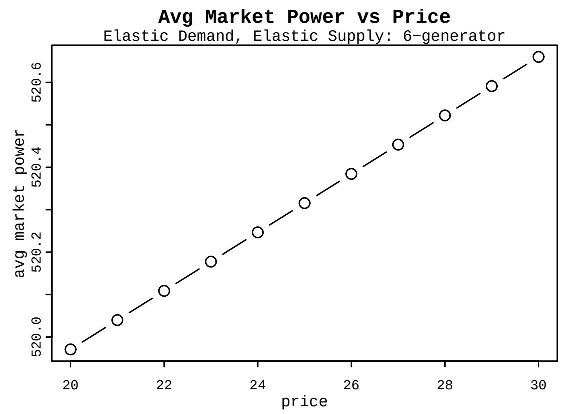

Figure 17: Average market power for size 6 coalition under elastic demand and elastic supply.

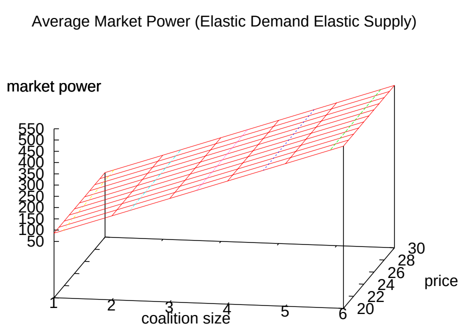

Figure 18: Average market power vs. coalition size and price under elastic demand and elastic supply.

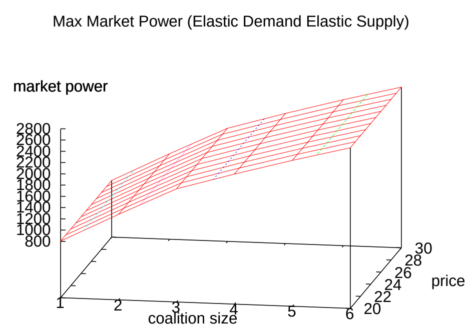

Figure 19: Maximum market power vs. coalition size and price under elastic demand and elastic supply.

2. The market power is supermodular which implies that supplier always have incentive to collude.
3. In our experimental setup, it is shown that generators that belong to the most powerful size k coalition are also members of the most powerful size (k+1) coalition where k varies from 1 to 5.
4. Strategic collusion between generators can significantly increase the size of market power. The empirical results show that in the case of Portland, a strategic coalition of just 2 generators can result in control of about 36% of the transmission flow. A coalition size of 6 generators can result in control of almost three quarters of the market. Our analysis shows that a merger of even a small number of generators, none of them being very large in terms of its production capability, can create significant non-competitive conditions in the market.
5. Our experiments show that the mean market power and the maximum market power of the coalitions always go up with the increase in the coalition size.
6. Elasticity seems to significantly affect market power. The demand elasticity is found to be negatively correlated with market power; while the supply elasticity is positively correlated with market power.
7. When demand and supply both are elastic, the mean and maximum market power go up with the market clearing price because supply is more elastic than demand in our experiment. However, this may not be true for an arbitrary grid topology and an arbitrary market configuration.

For interested readers, a complete set of plots and histograms have been made available at http://staff.vbi.vt.edu/chenj/pub/JEBO.Market.Power.All.Plots.pdf

7 Conclusions and Policy Implications

This research studied the issue of locational market power as caused by the transmission network and its physical constraints. Using a computable definition of market power, we show the importance of the location of different suppliers and their influence in determining the total flow on the network. The role of demand and supply elasticity is examined along with the locational attributes of the suppliers.

The results obtained in this study show that the high capacity suppliers are not the only ones likely to exercise market power. In case of network based markets, locational market power is also significantly important. Significant economic consequences can result from the non-competitive behavior of small generators with locational advantage. Hence, policy makers need to be cognizant of this important attribute when physical constraints in a market are involved. Strategic alliances among small suppliers can also result in market power.

Regardless of the level of the elasticity of demand and supply, a bigger coalition always results in higher market power. With elastic demand, market power can be curtailed as consumers react to higher prices and reduce consumption. This work supports the view that efficient markets require active participation from consumers [10, 11] and it may be worth investing in the infrastructure that enables consumers to be price responsive. The strong connection between market power and network topology suggests that strategic placement of new generation plants and transmission lines can also increase the competitiveness of the market and mitigate market power of the generators.

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