

Locational Market Power in Network Constrained Market

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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 [4][7]. Generators can exert monopoly power over the local load if network topology allows no other suppliers to serve the load. Strategically placed generators or phase shifters can be operated to deliberately congest lines that are needed by the competitors [2][1].

In this paper, we focus on the issue of locational market power arising out of transmission constraints in the electricity market. 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 imply higher market power? (ii) Can strategic collusive behavior by the generators result in higher market power? (iii)

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Does average market power of the generators increase with the increase in coalition size? (iv) How do the results differ for elastic demand and supply versus inelastic demand and supply curves? (v) What can the policy maker do to limit the market power of the suppliers?

2 Market Power in a Network Constrained Market

In the most general setting, we say that a supplier i has P_i units of market power if the total amount of the demand that can be fulfilled in the absence of supplier i decreases by P_i . It is often convenient to speak of market power as a fraction of the total quantity sold, $0 \leq p_i \leq 1$. To illustrate this with a simple example, consider a market with one consumer 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. 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 have market power because the entire demand can be fulfilled if either one was absent. However, 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 a central topic of this paper.

Since we are interested in studying markets over a network, we need to apply the previous definition to such a setting. Let $G = (V, E)$ be a graph with edge capacities $c : E \rightarrow \mathbb{R}^+$. There is a set of suppliers $S \subset V$ and consumers $T \subset V$. 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 consumers over a network must be delivered as a feasible network flow. Therefore, we may assume without loss of generality that G contains a super-source s with infinite production capacity and edges $\{s, s_i\}$ for all $s_i \in S$, each with capacity $M_i := M(s_i)$. Moreover, there is a super-sink t with demand D and edges $\{t_i, t\}$, each with capacity $d(t_i)$. We shall call such a graph G a *market graph*. To satisfy as much demand as possible, one needs to find a maximum network flow from s to t . We define the maximum power flow as the maximum amount of power flow that can be traded and delivered in the market subject to the network capacity constraint, generator capacity constraint, supply functions and demand functions.

Though the above model at first may seem to be too specific, and only adaptable to markets over networks, we may view a simple resource constrained market as a market over a network. Consider the example above, with suppliers

$\{s_1, s_2, s_3\}$ who have production capacities $\{9, 5, 3\}$, and a consumer with a total demand $D = 10$. This can be modeled as a network, as seen in Figure 1. We now define what market power is over a network.

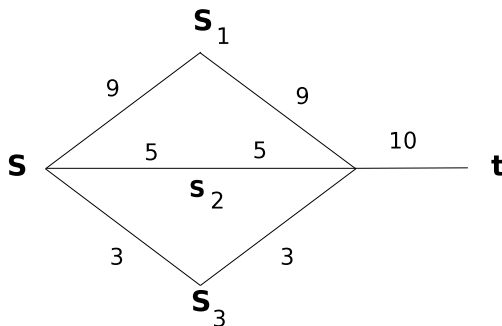


Figure 1: A network model of a simple market with resource constraints.

Definition For any subset $S' \subset S$ of suppliers, let $G(S')$ denote the market graph G , except $c(\{s, s_j\}) = 0$ for all $s_j \notin S'$. In other words, $G(S')$ is the market graph when all suppliers not in S' are off-line. We shall call $G(S')$ the *submarket graph* of S' .

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 realized exchange in the market if only S' and T' participate. For any supplier s , its 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 a market subject to network constraints, the realizable exchange $E(S', T)$ is the maximum flow from s to t in the submarket graph $G(S')$. Note that from the maximum flow minimum cut theorem of Ford and Fulkerson [3], 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. Size of a cut is the total capacity of the edges connecting the two subsets, and a minimum cut is a cut with the minimum size.

The special case when $S' = \{s_i\}$ is of particular interest, because it describes how much of the good supplier i is guaranteed to provide, which will likely affect

his selling price. The quantity $p(S')$ when $|S'| > 1$ is important as well because it signifies how much market power the suppliers in S' have if they were to merge into a single entity.

3 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. Portland grid has 776 lines and 662 nodes. Of these nodes, 319 are load serving nodes and 41 are generator nodes. To compute the realizable power delivery for a subset S' of generators, we connect each participating generator from S' to a source node s with link capacity equal to its generating capacity, and connect each consumer to a sink node t with link capacity equal to its demand. We then compute the maximum possible flow from node s to t .

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. The DOE EIA-860A Database provides generator capacity data on all existing US power plants. Even though the database provides data on all power plants, it is not easy to identify which generators in the EIA-860A 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 generators' capacities is at least 110% of the total Portland demand. This technique will ensure that the assigned capacity is large enough to meet the city's demand.

We study four different scenarios; (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 elastic demand and supply, we allow the prices to vary between \$20 and \$30 in increments of one. 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 demand, p is the price, a is the inelastic demand and b represents the elastic portion 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 a random value of b . This linear demand function for each consumer is used to measure the price responsiveness of consumers. The average elasticity of demand in our experiments is 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 the minimum possible supply should be able to meet the peak level demand. The minimum supply occurs at the lowest price so we set the supply q to be equal to the peak demand at \$20. Then, for each generator node, we take random values of d and determine the corresponding values of c . The average elasticity of supply is 0.20.

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 1 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 coalition size under consideration is 2, we would calculate the market power of coalition between suppliers 1 and 2, 2 and 3, 3 and 1. We compare and analyze the market power distributions of these different coalition sizes. We determine the mean and maximum market power and analyze how they change with the coalition size and market clearing price.

4 Inelastic Demand and Supply

In this section we discuss the inelastic demand and inelastic supply case in detail. The demand is fixed at the peak demand level and the supply is set based on the method described in the Section 3.

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 ten 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 in a network is the number of links that are connected to the node. 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

<i>Rank</i>	<i>Capacity</i>		<i>Market Power</i>		<i>Topological Property</i>	
	% Total Capacity	ID	% Total Flow	ID	Degree	ID
1	15.68	98	59.79	83	11	83
2	14.69	306	10.16	130	8	108
3	10.77	122	9.02	356	7	114
4	10.08	445	7.98	487	6	39
5	9.96	83	3.59	514	5	356
6	9.74	475	3.43	445	4	89
7	8.90	60	1.43	100	4	40
8	6.32	39	0.96	114	4	130
9	3.70	356	0.60	477	3	98
10	2.16	220	0.57	122	3	70
11	1.54	493	0.27	47	3	55
12	1.34	130	0.25	108	3	487
13	1.07	601	0.20	55	3	479
14	0.70	328	0.18	39	3	122
15	0.66	67	0.15	60	2	60
16	0.49	487	0.14	17	2	47
17	0.44	348	0.12	70	2	453
18	0.31	100	0.12	89	2	445
19	0.27	17	0.11	479	2	310
20	0.24	310	0.10	40	2	100

Table 1: Twenty largest generators and their capacities.

largest capacity generator (with ID 98) which controls over 15% of the generation capacity has less than 0.1% of market power (hence does not even appear in the *Market Power* column). On the other hand, generator with ID 83 which has only about 10% of the total generation capacity, has almost 60% of the market power. Similarly, generator with ID 130 has only 1.34% total generation capacity but has 10.16% of market power.

A natural question to ask is what other factors affect market power. In this study we find that a topological property of the generator i.e its degree, plays a big role in determining how much control it has on the total flow of the network. In the list of top twenty generators with the largest degree and those with the maximum market power have, 17 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 and the largest degree. And the top eight generators in these two list 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.

Tables 2, 3 and 4 show the market power under different coalition sizes. The fourth column in Table 2 shows coalitions of size two. Column 5 shows the market power each size 2 coalition can have. 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 flow is the market power of the coalition. The biggest coalition can be made between generators 83 and 130 who independently also control the most flow. It is clear from column 5 of Table 2 that the top twenty coalitions always include generator number 83 since it alone has almost 60% of the flow under control. In fact, 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 any coalition size of 3 among the top 20 generators leads to over 70% of market power. Similarly, any size 4 coalition among the top 20 generators can have over 79% of the market power. The best size 4 coalition can control almost 72% 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 more than 90% of the market.

Figure 2 shows that the average market power of the coalition goes up with the coalition size. The average market power of size 1 coalition is 10MW whereas for

Gen ID	Mktpow (MW)	%Total	Gen ID	Mktpow (MW)	%Total
83	299.934	59.79	83,130	350.901	69.95
130	50.9672	10.16	83,356	345.183	68.81
356	45.2485	9.02	83,487	339.965	67.77
487	40.0314	7.98	514,83	317.943	63.38
514	18.0091	3.59	445,83	317.141	63.22
445	17.2065	3.43	83,100	307.108	61.22
100	7.17354	1.43	83,114	304.75	60.75
114	4.8158	0.96	83,477	302.944	60.39
477	3.00988	0.60	83,122	302.794	60.36
122	2.85938	0.57	47,83	301.289	60.06
47	1.35444	0.27	83,108	301.188	60.04
108	1.25412	0.25	55,83	300.937	59.99
55	1.00329	0.20	39,83	300.837	59.97
39	0.902963	0.18	60,83	300.687	59.94
60	0.752469	0.15	17,83	300.636	59.93
17	0.702304	0.14	70,83	300.536	59.91
70	0.601975	0.12	83,89	300.536	59.91
89	0.601975	0.12	83,479	300.486	59.90
479	0.551811	0.11	40,83	300.436	59.89
40	0.501646	0.10	83,98	300.436	59.89

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

Gen ID	Mktpow	%Total	Gen ID	Mktpow	%Total
83,356,130	396.15	78.97	83,356,130,487	436.231	86.96
83,130,487	390.933	77.93	514,83,356,130	414.159	82.56
83,356,487	385.214	76.79	445,83,356,130	413.406	82.41
514,83,130	368.91	73.54	514,83,130,487	408.942	81.52
445,83,130	368.108	73.38	445,83,130,487	408.139	81.36
514,83,356	363.192	72.40	83,100,356,130	403.323	80.40
445,83,356	362.389	72.24	514,83,356,487	403.223	80.38
83,100,130	358.075	71.38	445,83,356,487	402.471	80.23
514,83,487	357.975	71.36	83,356,114,130	400.966	79.93
445,83,487	357.172	71.20	83,477,356,130	399.16	79.57
83,114,130	355.717	70.91	83,356,122,130	399.009	79.54
83,477,130	353.911	70.55	83,100,130,487	398.106	79.36
83,122,130	353.761	70.52	47,83,356,130	397.554	79.25
83,100,356	352.356	70.24	83,108,356,130	397.404	79.22
47,83,130	352.256	70.22	55,83,356,130	397.153	79.17
83,108,130	352.155	70.20	39,83,356,130	397.103	79.16
55,83,130	351.905	70.15	60,83,356,130	396.902	79.12
39,83,130	351.804	70.13	17,83,356,130	396.852	79.11
60,83,130	351.654	70.10	70,83,356,130	396.752	79.09
17,83,130	351.604	70.09	83,89,356,130	396.752	79.09

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

Gen ID	Mktpow	%Total	Gen ID	Mktpow	%Total
514,83,356,130,487	454.19	90.54	514,445,83,356,130,487	471.447	93.98
445,83,356,130,487	453.438	90.39	514,83,100,356,130,487	461.364	91.97
83,100,356,130,487	443.355	88.38	445,83,100,356,130,487	460.611	91.82
83,356,114,130,487	440.997	87.91	514,83,356,114,130,487	459.006	91.50
83,477,356,130,487	439.191	87.55	445,83,356,114,130,487	458.203	91.34
83,356,122,130,487	439.041	87.52	514,83,477,356,130,487	457.2	91.14
47,83,356,130,487	437.586	87.23	514,83,356,122,130,487	457.05	91.11
83,108,356,130,487	437.435	87.20	445,83,477,356,130,487	456.448	90.99
55,83,356,130,487	437.235	87.16	445,83,356,122,130,487	456.247	90.95
39,83,356,130,487	437.134	87.14	514,47,83,356,130,487	455.595	90.82
60,83,356,130,487	436.934	87.10	514,83,108,356,130,487	455.444	90.79
17,83,356,130,487	436.884	87.09	514,55,83,356,130,487	455.194	90.74
70,83,356,130,487	436.833	87.08	514,39,83,356,130,487	455.093	90.72
83,89,356,130,487	436.833	87.08	514,60,83,356,130,487	454.943	90.69
83,479,356,130,487	436.783	87.07	514,17,83,356,130,487	454.893	90.68
40,83,356,130,487	436.733	87.06	514,70,83,356,130,487	454.792	90.66
83,98,356,130,487	436.683	87.05	514,83,89,356,130,487	454.792	90.66
19,83,356,130,487	436.633	87.04	445,47,83,356,130,487	454.792	90.66
83,356,485,130,487	436.633	87.04	514,83,479,356,130,487	454.742	90.65
152,83,356,130,487	436.583	87.03	514,40,83,356,130,487	454.742	90.65

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

size 6 coalition the average market power goes up to 70MW. Figure 3 shows that the maximum market power also monotonically increases with the coalition size. It increases from 300MW to 470MW 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.

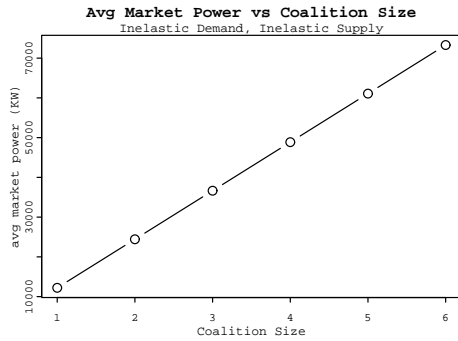


Figure 2: Average market power for different coalition size under inelastic demand and inelastic supply.

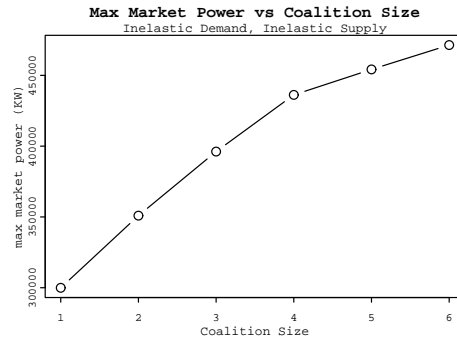


Figure 3: Maximum market power for different coalition size under inelastic demand and inelastic supply.

5 Elastic Demand and Supply

In Figure 4 and Figure 5 we 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 250KW as price increases from \$20 to \$30 whereas for size 2, it goes up about 80KW. If the price is kept constant at \$30, just the increase in coalition size from 2 to 6 increases the market power from 24500KW to 73550KW, a difference of about 50MW! 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 6 and Figure 7 show that the average and maximum market power increase with the coalition size and decrease with the market clearing price.

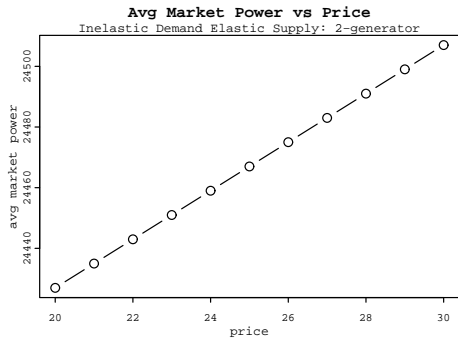


Figure 4: Average market power for size 2 coalition under inelastic demand and linear supply.

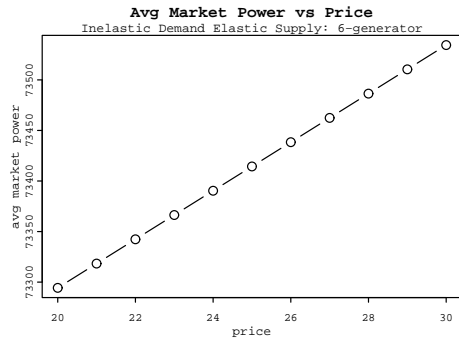


Figure 5: Average market power for size 6 coalition under inelastic demand and elastic supply.

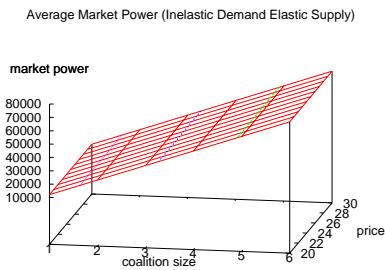


Figure 6: Average market power vs. coalition size and price under inelastic demand and elastic supply.

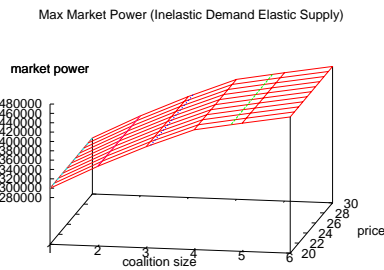


Figure 7: Maximum market power vs. coalition size and price under inelastic demand and elastic supply.

In Figure 8 and Figure 9 we observe the role played by the elasticity of demand. Note that with a linear demand function, the demand elasticity increases with price. Intuitively, one would expect that the generators have smaller market power if the demand is more elastic. Figure 8 and 9 show that 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 responsiveness by consumers can mitigate exercise of market power by the suppliers. In case of size 6 coalition, an increase in price by \$10 reduces the average market power by over 30KW whereas in case of size 2 coalition, it goes down by about 15KW. 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 49MW. 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.

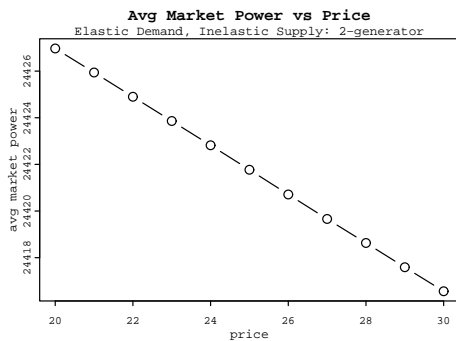


Figure 8: Average market power for size 2 coalition under elastic demand and inelastic supply.

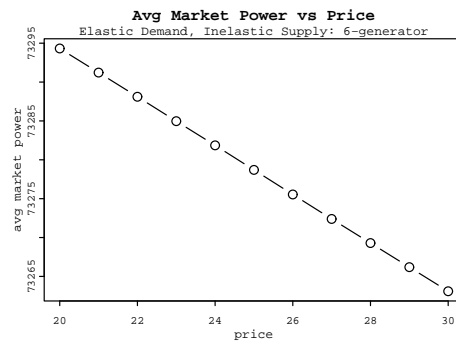


Figure 9: Average market power for size 6 coalition under elastic demand and inelastic supply.

Figure 10 and Figure 11 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 and Figure 13 show the results of change in price on market power when supply and demand both are 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

Average Market Power (Elastic Demand Inelastic Supply)

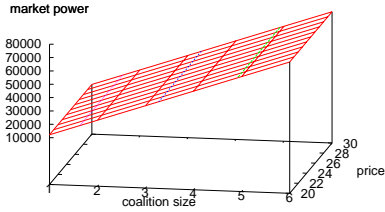


Figure 10: Average market power vs. coalition size and price under elastic demand and inelastic supply.

Max Market Power (Elastic Demand Inelastic Supply)

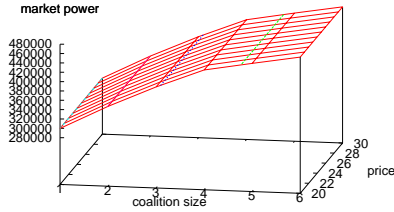


Figure 11: Maximum market power vs. coalition size and price under elastic demand and inelastic supply.

our experiments the elasticity of demand is much less than the elasticity of supply 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.

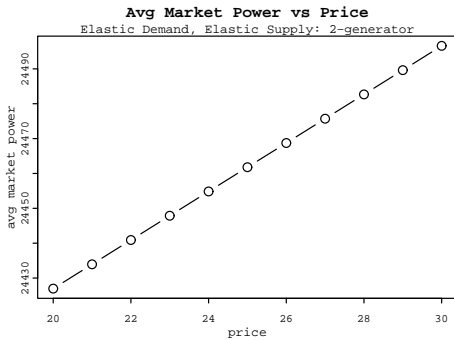


Figure 12: Average market power for size 2 coalition under elastic demand and elastic supply.

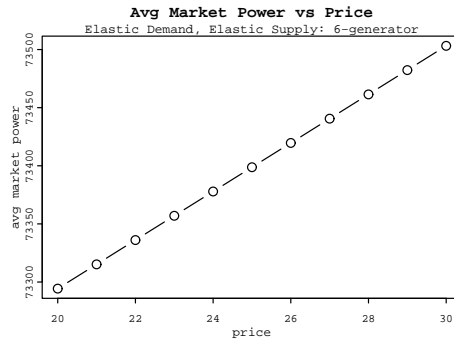


Figure 13: Average market power for size 6 coalition under elastic demand and elastic supply.

Figure 14 and Figure 15 show that the average and maximum market power increases with the coalition size as well as the market clearing price.

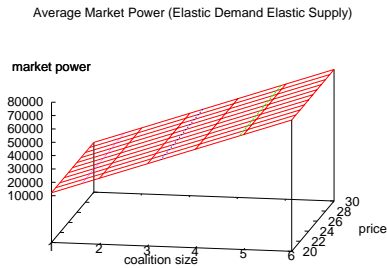


Figure 14: Average market power vs. coalition size and price under elastic demand and elastic supply.

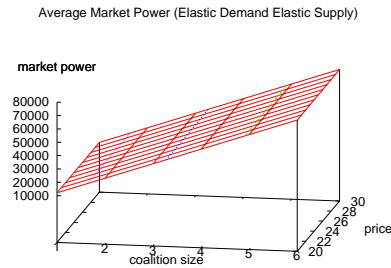


Figure 15: Maximum market power vs. coalition size and price under elastic demand and elastic supply.

6 Summary of Results

The findings of our study are summarized below.

1. The large sized 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.
2. 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 almost 70% of the transmission flow. A coalition size of 6 generators can result in control of over 90% 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.
3. The mean and maximum market power always go up with the increase in coalition size.
4. Elasticity seems to significantly affect market power. The demand elasticity tends to be negatively correlated with market power; while the supply elasticity tends to be positively correlated with market power. In our experiment, supply is more elastic than demand, as a result, the mean and

maximum market power go up with the market clearing price. However, this is not proven true for an arbitrary grid topology and an arbitrary market configuration.

5. Generators that belong to the most powerful size k coalition are also members of the most powerful size $(k+1)$ coalition.

For interested readers, a complete set of plots and histograms have been made available at <http://staff.vbi.vt.edu/chenj/market.power.plot.pdf>

7 Conclusions and Policy Implications

The results obtained in this study have many policy implications. First, the high capacity suppliers are not the only ones likely to exercise market power. In case of network oriented markets, locational market power is equally important. Significant economic consequences can result from the non-competitive behavior of small generators with locational advantage. Second, whether the demand and supply are elastic or inelastic, a bigger coalition will always result in higher market power. This implies that the policy makers should look out for strategic alliances even among small suppliers to curb market power. Third, collusive behavior among suppliers leads to higher incidence of market power when the demand is inelastic. The increase in market power is the highest (from 300MW to 470MW) when coalition size increases to 6 and the demand does not change at all. Fourth, 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 [5][6] and it may be worth investing in the infrastructure that enables consumers to be price responsive.

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