Electricity Markets: How Many, Where and When?*

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Abstract

Most markets compromise the economist's ideal of matching the marginal benefits to consumers with the marginal cost of supply for incremental purchases because individual buyers and sellers are aggregated over space, time and/or other product attributes like quality or reliability. These aggregations into discrete market segments are designed to facilitate transactions by reducing search and distribution costs, and they may enhance the competitiveness of each market segment by encompassing a larger number of buyers and sellers, but at some loss of precise efficiency matches. Furthermore, as individual market segments grow in size, the price differences across their boundaries may also increase which can raise the transactions costs associated with increased arbitrage.

These are important considerations for electricity markets since significant physical, operational and capacity barriers separate and define these markets over space and time. Thus principles for the optimal structure of these markets are developed, and in particular, it is shown that forward markets with lead times longer than the gestation period required to construct new generation capacity are essential to insure efficient subsequent spot markets. By comparison, if these forward markets occur only after new construction is begun, as with existing installed capacity markets, spot market prices may be higher. Similarly, the extent of separation and spacing of markets across regions and control areas, particularly in the face of transport congestion or operational boundaries, is important for enhanced efficiency.

1. Introduction

Because of important components of cost that are neglected and/or other considerations, nearly all markets fall short of the economist's theoretical ideal for efficiency that requires marginal benefits to equal marginal costs for all incremental transactions. One example is where substantial search and transactions costs are incurred with each trade or where the costs of serving each buyer vary by individual. Rather than assigning a different price to each buyer, the costs are frequently "averaged" over some market segment in which a uniform market price is assessed in order to reduce administrative costs. This averaging can be across a variety of dimensions: space, where typically transportation costs are averaged; product quality, where for most mass-produced products every customer does not receive a unique customized version; and time, although if the product is storable those timing costs may be individualized if each customer provides their own storage.

Furthermore with the current trend toward just-in-time manufacture in order to reduce the cost of inventories, if the product's availability on-demand is essential for some customers, then the existence of forward markets may be important if they increase the likelihood that delivery will take place when required. Under these circumstances, the frequency and

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duration of these forward markets may also have substantial efficiency implications.

These considerations are particularly important when a new type of commodity or service is marketed for the first time. In contrast, long-established markets for traditional goods and services that have evolved over many years through repeated "experiments of the whole" may incorporate many of these efficiency-enhancing considerations in their market structure. But a clear example of the difficulties that can arise when structural details of markets for similar (but slightly different) commodities are applied to a new product is provided by the many problems that arose in the early years of operating electricity markets in the U.S. As examples, commercial deals were attempted across congested interfaces because price spreads existed, but the delivery of the product was impossible because of the congestion. Similarly, Kirchhoff's laws that govern electricity flows were ignored in establishing point-to-point contracts despite the out-of-state loop flows that delivered power back to the starting point.

Other market enthusiasts have proposed eliminating regulatory standards for reliability and substituting market-determined levels. But these proposals overlook the fact that most electricity customers receive their power over a network, so everyone in the vicinity receives the identical voltage, frequency and number of unannounced outages, regardless of differences in individual preferences. Thus although the components for providing reliable electricity service can be assembled through a market, the determination of the level to be provided is a public good and must be established and enforced by a regulatory body.[1] Finally, since it takes many years to construct electricity supply facilities, and since electricity is not storable in large quantities, buyers want some assurance that they will receive their electricity when they want (need) it and as much of it as they want. Can markets be used to ensure adequate facilities are completed in time, and if so, what should be the structure of those forward markets?

The general principle to be considered when devising the optimal structure ("grain") of any new market is balancing four different costs: 1) the inefficiencies of not precisely matching marginal benefit with marginal cost for incremental transactions as the market segments become larger, 2) the greater transactions costs incurred by having a large number of market segments (both price-posting and marketing costs for suppliers and decision costs for buyers), 3) increased costs of arbitrage across the borders of market segments where substantial price-differences may exist (generally these differences become greater as the market segments become larger), and 4) the effect of the size of market segments on the ability of buyers and/or sellers to behave strategically and exercise market power (generally, the smaller the segments, the fewer the number of buyers and sellers in each). Implicit in this analysis are applications for large industrial economies that are characterized by some scale economies and therefore where production is concentrated at finite locations for discrete product groups. In a locally "self-sufficient" society, by contrast, every buyer would provide everything they required so there would be no spatial markets; although if those individuals couldn't produce all of the goods that they required instantaneously on-demand and the commodities were not storable, markets would still spring up. Add the impact of transportation costs when the buyers and producers are spread across the landscape and the question of market-grain again becomes relevant.

In fact, many market boundaries are defined by physical constraints that limit transactions. In the spatial context, geographic barriers like mountains, deserts, rivers and oceans define many market, as well as socio-political boundaries, but over time, technological advances have allowed us to span many of these barriers. Indeed, in many cases it was the price/quality differences across those boundaries that provided the incentive to breach them. As an example, spatial markets for electricity are often defined by a series of junctions where congested transmission lines limit flow across these boundaries. These physical barriers have been used to define pricing zones, and it is thought that the differences in locational marginal prices (LMP) across these zones provides an incentive for locating new production efficiently, as well as providing a signal for the needed construction of additional transmission facilities. So too where there are physical constraints on the ability of suppliers to meet demand and/or on the ability of buyers to adjust their usage, a proper spacing of forward markets over time may enhance efficiency. In the case of electricity supply, there are a number of decisions ranging from the short-run choice of committing a unit for the next hour (or day) that results in start-up costs, to decisions on scheduling prolonged maintenance, on through the long-term choice of building additional capacity. Since each of these decisions has some minimum lead time before electricity is actually generated, the existence of a forward market within a similar time-frame should provide additional information to assist in the decision, as well as offering opportunities to

[1] See Mount, Schuler and Schulze [9] for a theoretical analysis of the public and private good aspects of electricity markets.

hedge risks and/or engage in strategic posturing. But the emphasis in structuring market segments is to identify these physical limits on transactions as the starting point for establishing market boundaries.

This analysis will be applied primarily to the electricity industry and its emerging markets, but it begins with a review of market structure over space and how that might be applied to the spatial grain of electricity markets. Then a model is presented that examines the optimal structure of forward markets which is particularly relevant for commodities produced by highly capital-intensive technologies whose creation requires substantial lead-times. Since electricity cannot be stored economically, getting the inter-temporal market structure correct is particularly important if demand is to equal supply in real time; otherwise the probability of precipitating the "public-bad" of a blackout is greatly increased.

2. Markets over space

When customers arrange for a product's transportation, as an example by driving to the shopping mall to make purchases, the price is customarily quoted at the supply location and all buyers pay the same price at the same time (Mill Pricing (MP)). In this case, each buyer who utilizes the product somewhere other than at the store incurs the transportation cost and effectively considers and pays a different delivered price at the point of utilization. However, when it is most effective to have the supplier deliver the product to each buyer, usually for technological reasons like with electricity supply – particularly where there are large scale economies in hauling as well as in production and/or production and transportation are vertically integrated – then spatial discriminatory patterns of pricing (SDP) may emerge, or uniform delivered pricing (UDP) may be employed as a simplified variant. Under both SDP and UDP pricing structures, few customers pay the actual marginal cost of manufacture plus delivery. Note, "postage stamp" pricing used by the U.S. postal service is an example of UDP where cost differences are not reflected in the prices paid by customers, but by using UDP the postal service reduces greatly the administrative cost of transactions when compared to assessing individualized prices by origin-destination, weight and volume for every letter and parcel sent as under MP or SDP. In fact parcel post (packages) does incur these substantial transactions costs by requiring all items to be sized, weighed and charged individually, usually adding a customer trip to the post office.

Because there are substantial physical barriers to transporting electricity where inadequate transmission line capacity exists, it is reasonable to have spatial price differences. Typically, different prices are allowed to emerge in locations that are separated by congestion (e.g. location-based marginal pricing (LMP)), but within an un-congested region all buyers may face the identical wholesale price even though line-losses might differ slightly depending upon location (UDP within an un-congested zone). Furthermore, where different regions have different operating entities (Independent System Operators (ISO) or Regional Transmission Organizations (RTO)) that are responsible for maintaining service reliability within each of their separate regions, their operators and markets dispatch and price power to minimize cost, subject to reliability constraints, within their own jurisdictions. The physical necessity of coordinating operations within a set geographic area in order to maintain reliability creates boundaries that might inhibit buyers and sellers who attempt to transact electricity across the borders of those jurisdictions. In fact electricity buyers and sellers confront many of the same problems encountered in international trade, but with the compounding problem of just-in-time delivery. Until the entire nation (or continent) can be served reliably with confidence by one entity, an enormous technological challenge at present, it makes sense to separate markets in accordance with this overriding physical constraint. Nevertheless, mechanisms also need to be established to facilitate exchanges across these boundaries (efficient arbitrage) and reduce what are called "seams" issues.

As an example, consider two un-congested power systems as shown in Figure 1 where there are line losses that result in different transportation costs to serve the customers distributed throughout each system. Furthermore suppose each ISO contains generators having different marginal costs, but their customers are distributed uniformly across space with identical demand curves. Under UDP, but without trade across the border, generator #1 might charge P1A in its region and generator #2 might charge the slightly higher UDP of P2B in its own ISO-B jurisdiction. Now, open the borders to bi-lateral transactions. In this case generator #1 might offer a lower price across the border, P1B, and try and serve all of B's customers up to point R1 while still charging P1A in its home, ISO-A region, since generator #2 cannot undercut P1A because of its higher delivered costs. In fact, generator #2 may be induced to lower its UDP below P2B between R1 and R2 in order to forestall further incursions into its market by generator #1. Note, supplier #2 also cannot compete against #1 between the border and R1 because of its higher marginal production and delivery costs. Furthermore if ISO-B were likely to require generator #2 to charge the same price throughout ISO-B's territory if there is no internal congestion, then generator #2 may be reluctant to compete with generator #1 between R1 and R2 since that could lead to lower overall profits.[2]

Note, as described this initial cross-border transaction proposed by supplier #1 is beneficial to some customers in ISO-B, but has no effect on those in ISO-A. Second, the flow at the border runs from a high to a low price area after the exchange takes place; yet this counter flow has improved efficiency (obviously regulators in ISO-A would like to force their own price down to P1B as well if generator #1 could still recover its fixed costs). Similar patterns of flow from high to low-priced regions have been frequently observed in un-regulated international markets for a variety of commodities where producers like generator #1 would be accused of "dumping" [10]. In fact, this commodity counter-flow from high to low-price areas is a normal pattern under spatial price discrimination where there is competition at the borders (See Holahan and Schuler [5] for a comprehensive discussion of competitive spatial pricing practices).

One key attribute that determines the borders of segmented markets is the existence of some physical barrier that might be modified by an additional expenditure. Thus, a congested transportation network can always be improved by building more facilities (e.g. roads, terminals, or transmission lines, etc.), and those price differences across the boundary provide a clear signal of the benefits to be derived by reducing that congestion. But, the market boundary needs to be specified at the point of congestion. Similarly, if for managerial and reliable operation purposes, the entire U.S. is not operated as a single power grid, then it may make sense to have separate markets in each operating jurisdiction, and to the extent that price differences exist across those "seams", they may be warranted in particular if internal congestion costs might increase substantially were large transfers across those boundaries to be arranged. And, to the extent that price differences do exist, they provide powerful incentives to make the arrangements and investments to reduce those physical and operational procedure barriers.

Likewise, where physical impediments restrict commodity flows over time, as in capital intensive industries where a long gestation period is required between the time when a capacity addition is begun and it is available to produce, then the timing of forward markets around that decision point to commit physical resources may be helpful in promoting economic efficiency.

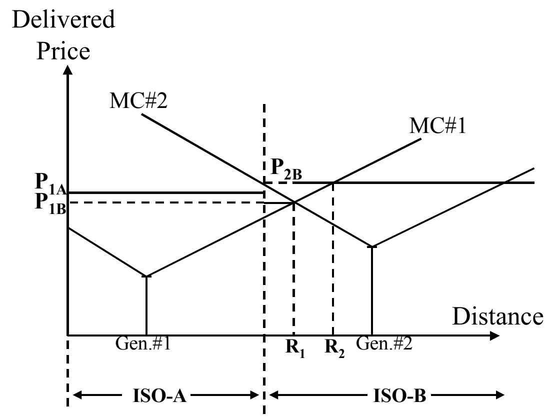

Figure 1. Competition at border under uniform delivered pricing

2 See Schuler and Hobbs [11] for detailed examples of spatial price competition under UDP.

3. Markets over time

3.1. Model

The existence of forward markets has been explained in the economics literature by market participants' unwillingness to take risks. However, Allaz and Vila [2] suggest strategic reasons for the existence of forward markets and argue that firms with market power engage in forward contracts to enhance their market share in spot markets. Allaz and Vila conclude that more frequent forward markets make firms worse off and drive the spot prices down. Models that adopt the Allaz and Vila framework suggest that forward markets decrease spot prices and enhance efficiency as well.[3] A crucial assumption in their analyses is that firms are underutilizing their capacity levels in the absence of forward markets or that firms can adjust their production levels costlessly. In what follows, we present a model that endogenizes firms' investment in capacity levels and study the effects that the timing of forward markets has on competition and efficiency.[4]

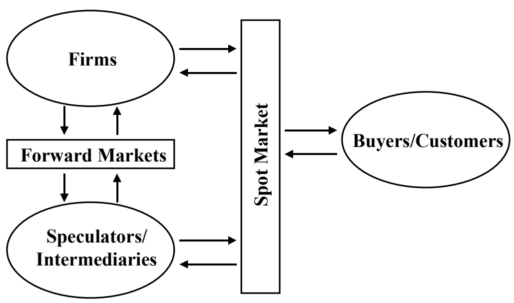

Figure 2. Market structure and market participants

There are three types of players in the market: firms, an intermediary and buyers (see Figure 2). Firms produce and sell the product in forward and spot markets. There is a finite number of firms, and thus the firms have some market power. In the electricity markets, firms are represented by generators that produce and sell electricity. The firms have constant marginal cost production functions. The intermediary buys forward contracts from firms in forward markets and resells the product in the spot market. It is assumed that the intermediary earns zero profits due to free entry and exit. In a regulated electricity industry, an Independent System Operator that buys forward contracts and effectively sells the electricity at a spot market price in the spot market can represent the intermediary.

Buyers purchase the product in spot markets for consumption purposes. It is assumed that buyers are infinitesimal, always bidding their marginal valuation. In the electricity markets, buyers are represented by residential and industrial electricity consumers. Due to its analytical simplicity, the choice of linear demand is conventional in forward markets and supply function equilibria models. Therefore, we assume that demand is stochastic and linear in all periods, i.e., $D_t(P_t) = a_t/b - P_t/b + \varepsilon_t/b$. Where P_t denotes the spot market price at time t, a_t and b denote demand parameters, and ε_t denotes random demand shocks. In the electricity markets, changing weather conditions is the major contributor to demand fluctuations. Cold winters and hot summers correspond to high demand for electricity. We also assume that the expected demand is non-decreasing over time, i.e., $a_{t+1} \geq a_t$.

We partition forward markets into shorter-term and longer-term forward markets based on their "length" relative to the physical lead time required to complete investment. Forward market length denotes a time frame between when the forward market takes place and the spot market opens. Investment length denotes a minimum time frame between when the investment in capacity begins and that newly installed capacity becomes operational. In other words, shorter-term forward markets take place after investment decisions, and longer-term forward markets take place before investment decisions and the commitment of capital.

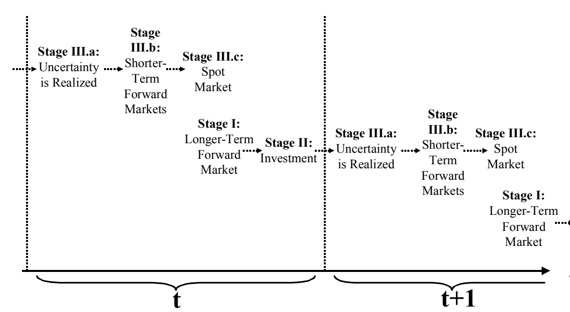

Figure 3. The timing of events

The game consists of three repetitive stages. Graphical representation of these stages is given in

[3] See Green [4], Ferreira [3], Lien [8], Le Coq and Orzen [7], Newbery [10].

[4] More technical version of the model is given in Adilov [1].

Figure 3. In stage I, the firms and the intermediary simultaneously present their longer-term forward market supply functions and longer-term forward market demand schedules, respectively. The forward market price and quantities are determined. In stage II, after observing forward market price and quantities, the firms simultaneously choose their new capacity levels. In stage III.a, demand uncertainty is realized. In stage III.b, the firms and the intermediary simultaneous choose shorter-term forward market supply functions and shorter-term forward market bid schedules. Shorter-term forward market price and quantities are determined. In stage III.c, the firms and the intermediary simultaneously choose spot market supply functions. The spot market price and firms' profits are realized. Note that the firms compete in spot and forward markets by choosing price-quantity schedules, i.e., supply functions. An equilibrium price in the forward (spot) market is determined by the intersection of forward (spot) market supply and demand. Firms' maximum quantity sales in the spot market are subject to capacity constraints that are chosen simultaneously by the firms prior to the spot market.

Although it is realistic to assume that the firms compete by selecting supply functions, supply function competition yields multiple equilibria. Without restricting the set of equilibria or without allowing for some selection mechanism, it is difficult to make analytical conclusions. One of the plausible solutions to this problem is to restrict the set of equilibria to a single outcome that maximizes the firms' joint profits. This would imply that the firms select the highest possible price among equilibrium price levels. We take a more general approach and restrict the set of equilibria to "consistent steady state" type equilibrium outcomes. In other words, we allow the firms to choose any equilibrium among multiple equilibria in a given period but then, we assume that the firms consistently choose similar equilibrium points in future periods. In what follows, we presents the results. Technical derivation of these results is given in Adilov [1].

3.2. Implications of longer-term forward markets

Longer-term forward markets decrease spot market prices and enhance efficiency. This result is consistent with the existing literature because capacity levels are flexible in the long run. The intuition here is similar to that underlying the two-period durable goods monopolist's problem and the Stackelberg leader game. In the durable goods monopolist's problem, higher product sales in the first period reduce the price in the second period. In our model, after longer-term forward market commitments are signed, firms compete for residual demand in the spot market (see Figure 4). Since forward market prices are fixed, firms behave aggressively and are more inclined to cut the price in the spot market. Firms cannot keep spot prices high by restraining themselves from participating in forward markets although firms are jointly better off by not participating in longer-term forward markets. Similar to the Stackelberg leader logic, each firm is trying to increase its market share by increasing its forward market commitment levels. Thus, higher longer-term forward market commitments reduce spot market prices by encouraging more aggressive spot market behavior, which, in turn, encourages higher capacity choices.

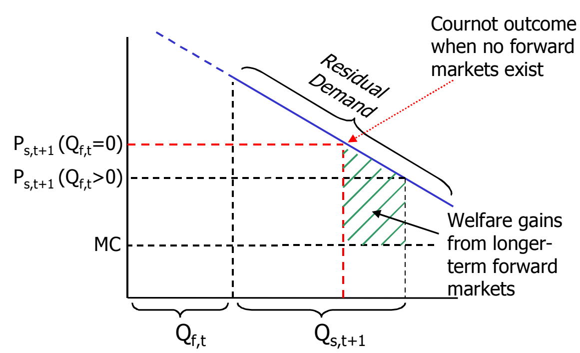

Figure 4. Residual demand competition

3.3. Implications of shorter-term forward markets

Similar to longer-term forward markets, shorter-term forward markets push spot markets prices down, however, firms can respond to this price pressure by altering their capacity investments. The overall effects of shorter-term forward markets on prices and efficiency depend on the degree of demand uncertainty. When the *demand uncertainty is small or absent*, spot price-reducing effects of shorter-term forward markets disappear because capacity investment serves as a commitment device. The firms commit to capacity levels that fully eliminate the firms' possible undercutting behavior in the spot market. The intuition behind this result is similar to Kreps and Scheinkman [6] in that if firms simultaneously choose quantity production levels before engaging in Bertrand competition, then the

Cournot outcome prevails. In our model, firms choose capacity levels before engaging in shorter-term forward markets. Introducing shorter-term forward markets puts downward pressure on spot market prices subject to the capacity constraints. This implies that the firms' total capacity levels determine the spot market price. Therefore, the unique outcome for optimal capacity choices in the absence of demand uncertainty is the Cournot outcome.

Under uncertainty, the investment in capacity choice becomes an imperfect commitment device because the firms might choose to underutilize their capacity levels during the periods of low demand. Similar to the certainty case, shorter-term forward markets induce more aggressive behavior in the spot market, forcing the firms to decrease spot market prices. However, spot market price decrease has a lower bound that is determined by the firms' overall capacity levels. Thus, from the firms' perspective, the introduction of shorter-term forward markets imply that the firms utilize their capacity levels more often at lower spot market prices. To counteract this spot market price-reducing effects of shorter-term forward markets during excess capacity periods, the firms decrease capacity investments more in the presence of shorter-term forward markets. In sum, shorter-term forward market under uncertainty increase capacity utilization, but decrease capacity investment. The overall effect of the two factors – higher capacity utilization and lower capacity investment – on social welfare depends on the shape of demand and the firms' marginal cost curves. With linear demand and constant marginal costs, the presence of shorter-term forward markets results in a Pareto inferior outcome reducing both consumer and producer surplus. The intuition why shorter-term forward markets might decrease social welfare can be explained by observing the spot market prices. Lower capacity levels and high spot market price volatility in the presence of shorter-term forward markets contribute to lower expected social welfare because social welfare is concave with respect to spot prices.

3.4. Forward versus futures contracts

The implications of the model are the same whether one considers forward contracts for a physical delivery of the commodity at a specified time in the future or futures contracts that are solely financial transactions with no physical commitments. The intuition behind this is following. Consider a firm that holds one unit of a futures contract to buy, i.e., "short" futures contract. If the spot price is above the futures price, then the firm suffers a financial loss equal to the price difference from holding this futures contract. When the amount of financial loss is subtracted from the revenue received from the physical delivery of one unit of commodity in the spot market, the net revenue equals the futures price. On the other hand, if the spot price is below the futures price, then the firm has a financial gain equal to the price difference from holding one unit of a futures contract. When this financial gain is added to the revenue received from physical sales of one unit of commodity, the net revenue for that unit equals the futures price. Thus, from the firm's perspective, holding one unit of a futures contract to buy is just like selling one unit of a forward contract. Similarly, holding one unit of a futures contact to sell, i.e., "long" futures contract, is just like buying one unit of a commodity in the forward market.

3.5. Policy implications

The existing literature on strategic use of forward markets suggests that forward markets either enhance efficiency or make producers better off if they collude. While these welfare-enhancing effects of longer-term forward markets are well known, the effects of shorter-term forward markets in relation to firms' investment decisions have not been analyzed in depth previously. Our findings imply that under some circumstances, a regulator can make both consumers and firms better off by eliminating shorter-term forward markets. In existing electricity markets in the United States, all forward markets take place one day to six months prior to the spot market, whereas investment commitments are made at least three years in advance. Therefore, it is crucial to develop longer-term forward markets in the electricity industry to maintain adequate investment levels and to sustain low spot market prices. One of the difficulties a regulator faces when introducing longer-term forward markets is the inability of some market participants to commit to specific long-term physical consumption levels. Then, a regulator might develop financial futures markets, since the analysis indicates that financial futures markets have the same effects on prices and social welfare as forward markets do.

It is realistic to assume that firms choose supply schedules in forward and spot markets, yet the findings hold for both supply function and Cournot quantity competition. This implies that the Cournot framework is a good approximation for studying analytical implications of forward markets. The multiplicity of equilibria under the supply function competition, however, yields a rich variety of outcomes. Our results are robust to various equilibrium selection mechanisms as long as the firms consistently choose similar equilibria over time. Also note that our analytical results hold both for risk-neutral and risk-averse market participants.

4. Conclusions

In structuring markets for new commodities and services, it is important to identify barriers that might impede transactions and to consider establishing separate markets spanning intervals that have few of these restrictions. Examples of these barriers in electricity are congested lines or the definition of operating jurisdictions charged with maintaining reliability, both of which delineate markets over space. Under some circumstances, it may be efficient to allow spatial differences in prices to persist if the investment costs required to eliminate those barriers is greater than the short-run efficiency improvements. And an illustration has been provided where a perverse flow (from high to low price region) may be efficiency-enhancing.

In addition, the same principles apply to the physical limitations of the lengthy construction period required to plan and complete new generation capacity that should define market segments over time. Even without risk aversion, it is shown that in markets where suppliers have the potential to exercise market power, it is important for efficient spot markets to have forward markets scheduled prior to the date necessary to schedule the construction of new generating capacity. Otherwise, it is of strategic interest for sellers to limit available capacity. But with markets scheduled forward of the time needed to develop new capacity, the suppliers face a prisoners' dilemma-type demonstration effect. Similar considerations apply to structuring separate markets within significant barriers if appreciable costs arise for distributing the product over space, time or varying quality.

In addition to their applicability to electricity markets, these principles are becoming ever more relevant to the globalizing economy to the extent it is characterized by scale economies and therefore discrete locations in production, appreciable transportation costs and competitive pressures to maximize just-in-time delivery (minimal inventories). In those circumstances, the support of modern societies requires a continual balancing in real time of production and consumption, and lessons learned in the efficient supply of electricity through markets might be extended to the efficient structuring of markets in the rest of the economy.

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