Market Design in Energy and Communications

Peter Cramton[1]

April 2015

Abstract

I discuss market design issues in two important regulated industries—energy and communications. In both industries auction markets have transformed monopoly utilities into competitive markets. Restructured electricity markets are based on a portfolio of markets that allow contracting to take place in the short-, medium-, and long-term. Many challenges, especially with long-term markets, have been solved only recently. In communications, spectrum auctions largely have succeeded in efficiently pricing and assigning the scarce spectrum resource among competing carriers. However, going forward, it will be important for governments to encourage the development of short- and medium-term markets for spectrum. This is the best way for regulators to support innovation and competition in wireless services. Good market design does not just happen. It requires the engagement of experts and regulators focused on social welfare maximization who resist capture by special interests.

Introduction

The use of auctions in important regulated industries, such as energy and communications, is having a large positive impact on the global economy. Governments should welcome this innovation, but do so with proper care. Effective auction programs reduce costs, stimulate competition, and promote innovation. Here I briefly discuss market design issues in energy and communications—two infrastructure industries that provide a foundation for today's economy.

In energy, my focus is electricity market design. Beginning in the 1990s, many countries replaced monopoly utilities with competitive wholesale electricity markets that are based on a variety of interrelated auctions. I describe the types of auctions and how they fit together to support an efficient electricity market—one that provides reliable electricity at least cost to consumers. I emphasize some of the important lessons that were learned from often quite costly mistakes. Still the overall message is that when properly designed, these markets work well.

In communications, my focus is spectrum auctions. Spectrum is an essential input to wireless communications, especially mobile broadband, which today relies almost exclusively on auctioned spectrum. Our ever improving smart phones use mobile broadband for communications together with an ample use of Wi-Fi (unlicensed spectrum) wherever available to greatly expand capacity. Spectrum auctions were first introduced in the United States in 1994. Since then they have grown in both

[1] Peter Cramton is Professor of Economics at the University of Maryland; since 1983, he has conducted widely-cited research on auctioning many related items, and has applied that research to major auctions of radio spectrum, electricity, financial securities, and other products. This policy brief is based on a talk I gave at an OECD hearing on government auctions, 15 December 2014.

effectiveness and popularity around the world. I present a brief discussion of the spectrum auction experience and make recommendations to countries designing spectrum auctions.

The auction settings of both energy and communications are among the most complex of any industry. As such my presentation will only highlight key themes rather than dive into details. The references at the end of this paper provide a starting point for a more in-depth treatment.

Objective

In any market design application, it is best to start with the objectives of the market. The market designer evaluates alternative market designs with respect to these objectives, choosing the rules of market interaction to best meet the objectives given the details of the setting. The most common objectives in government auctions are efficiency, transparency, simplicity, and fairness. I describe each.

Efficiency

Efficiency is the most basic objective for economists. A market design is efficient if it yields outcomes that maximize social welfare. In a trading environment, this means that all gains from trade are realized. In the case of electricity market design, efficiency can be broken down into two components:

- Short-run efficiency—current demand is satisfied at least cost given existing resources.
- Long-run efficiency—the ideal quantity and type of resources are provided to meet economic electricity demand at least cost.

Achieving short-run efficiency is relatively straightforward with a well-designed spot market that prices electricity in real-time at every node in the system. A locational marginal price is determined that represents the system cost of generation at the node at that time. There are complicating details such as lumpiness of supply and the need to address contingencies, such as when a generator or network element must be taken offline. An effective design for short-run efficiency is presented in the "standard market design" that developed in the US (see FERC proposed rule 2002).

Long-run efficient is the more challenging of the goals as it requires in addition to short-run efficiency that the market provide the right incentives for long-run investment, so that the right set of resources stand ready to balance supply and demand. In what follows, I focus on this investment market.

In communications, I also focus on the investment market, and in particular spectrum auctions for wireless communications. Here efficiency is about putting spectrum to its best use. Spectrum auctions are the preferred instrument. These auctions are readily designed to award spectrum to those who value it most highly. However, there often are issues of competition in the downstream communications market that creates a divergence between highest private value (as bid in the auction) and highest social value (reflecting the benefits of improved competition in downstream markets). Competition policy is often needed to make sure that the auction maximizes social value, rather than private value.

In spectrum auctions, a common mistake that governments make is to put too much emphasis on revenue maximization rather than efficiency. As I discuss in Cramton (2013, p. 3),

> The goal for the government should be efficiency, not revenue maximization. The government should focus on ensuring that those who can put the spectrum to its highest use get it. Focusing simply on revenue maximization is short-sighted. Many steps such as technical and service flexibility, and license aggregation and disaggregation, improve efficiency and thereby improve revenues. But short-run revenue maximization by creating monopolies, which would create the highest profits before spectrum fees, and therefore would sustain the largest fees, should be resisted. Indeed, competition, which ultimately will lead to greater innovation and better and cheaper services, will likely generate *greater* government revenues from a long-run perspective. The government can best accomplish this objective with an efficient auction that puts the spectrum to its best use.

Simplicity

The auction should be as simple as possible, but not simpler. The settings in both energy and communications are complex; hence, it should not be surprising that some level of complexity is needed in an efficient design. Nonetheless, it is important that the market be made as simple as possible to solve the economic problem of the setting.

Simplicity is best measured in terms of the simplicity of participating in the auction. Clear rules that make it straightforward to develop an effective bidding strategy get high marks for simplicity. Simpler auction designs tend to avoid guesswork. For example, ascending or descending clock auction designs that facilitate outcome discovery, both with respect to clearing prices and the prospects for winning, are simpler for bidders, especially when auctioning multiple interrelated products. These designs help bidders avoid substantial guesswork and speculation in bidding strategy.

Simpler designs also limit risks to bidders. Again dynamic designs with good outcome discovery often let the bidder better manage budget and portfolio constraints. Executing a particular business plan is often more straightforward in such designs.

Simpler designs tend to promote efficiency by letting the bidder express preferences more simply and effectively.

Transparency

A first requirement of transparent auctions is clear and unambiguous rules that map bids into outcomes. With a transparent design bidders know why they won or lost and understand why their payments are what they are. Bidders are able—at least after the event—to confirm that the auction rules were followed.

Higher levels of transparency are achieved in auction designs that have excellent outcome discovery—both with respect to prices and prospects for winning. These are dynamic auctions, such as clock auctions, in which substantial information is provided to bidders to understand prices and winning prospects during the auction. Still the auction designer must recognize that the release of some information could potentially be used to foster collusion or improper coordination among bidders. For this reason it is common to release anonymous information that is relevant to understanding demand in a forward auction or supply in a reverse auction. Transparent auctions have an information policy that reveals information that is most helpful in understanding demand and supply. Such designs promote outcome discovery, which generally promotes auction participation and competition.

Fairness

Equal opportunity is a basic requirement of fairness. All potential participants have access to the market rules and the rules do not inappropriately discriminate among parties. In the context of auctions, this means that identical bids are treated the same way.

Discussion

Now that the four objectives have been defined, it is helpful to view them in combination. To a large extent, the objectives are complementary. The market designer can choose a design that gets high marks with respect to each objective. This is most easily seen when we abstract from details and consider the auction of a single divisible good.

Consider a single-price descending clock (reverse) auction in a competitive setting in which aggregate supply is reported after each round. My claim is that this auction gets high marks with respect to all four objectives. First, the auction is a simple price discovery process. Bidding strategy amounts to figuring out what the spectrum is worth to the bidder and then exiting when that reservation value is reached. Second, the auction is highly transparent. The rules are clear and it is easy to see why a bidder won or lost at a particular price. The revelation of aggregate supply promotes excellent outcome discovery, both about the market price and also the prospects for winning. Third, the auction is fair. Every potential bidder faces the same rules and all trade takes place at the market-determined clearing price. And finally, the auction is efficient. Given the straightforward and effective bidding strategy of exiting when reservation values are reached, the auction is fully efficient, maximizing total surplus.

Electricity markets

Electricity markets worldwide are restructuring from a monopoly utility model to a competitive market for wholesale electricity. We briefly highlight some of the key issues from a market design viewpoint.

Electricity markets face many challenges. The setting is extremely complex. The market must balance supply and demand at every instant and every location, while respecting all physical constraints of the network. Another challenge is that the demand side generally does not participate fully in the market. Although demand response is an increasing segment of the market, most consumers still neither see nor respond to the real-time electricity price.

Finally, many countries as part of national climate policy are transitioning much of their fossil-fueled generation to renewable energy. Since most renewable supply is intermittent, a substantial amount of capacity must be standing ready to supply energy when demand is high, yet the supply from solar and wind is low. As an example, Germany intends to replace all of its nuclear resources and much of its fossil generation with renewable energy. Indeed, Germany plans for 80 percent of its energy to be renewable, mostly wind, by 2050. Yet there is a significant probability of multiple days with wind production less than 5 percent of capacity. This intermittent energy must be backed up with substantial gas capacity, for example, requiring an additional 30 GW of gas turbines by 2030. The market must provide incentives for this capacity to be build.

To meet these challenges, wholesale electricity markets are structured around markets of three durations.

- *Short term* (5 to 60 minutes). The spot market provides the foundation of the electricity market. In the standard market design, the main two markets are for energy—the day-ahead market and the real-time market. In the day-ahead market, participants offer and bid energy for 24 one-hour blocks, one day-head. The system operator then commits units for the next day to clear the market. Then during the day (in real time), the system operator makes adjustments as needed to balance the market. The real-time energy market is a 5-minute market. To assure that the system operator has sufficient flexibility to balance the system throughout the day, say in response to a supply disruption of a generator or line, the system operator procures a number of ancillary services: 30-minute non-spinning reserves, 30-minute and 10-minute spinning reserves, and frequency regulation, which provides balancing capabilities on a second-by-second basis. All the markets are based on single-price auctions. That is, the price is determined to balance supply and demand, and all supplying resources are paid the clearing price for product supplied. In the case of the energy markets (day-ahead and real-time), the price is a *locational* marginal price; that is, the price depends on the contribution of the resource at its particular location in the network. In a system without congestion, prices are the same at all locations, but when lines become congested, the prices separate to reflect the congestion in the system. In this way, the market sends the right price signals for supply and demand (and transmission planners) to motivate participants both in the short-run and long-run. There are other complicating details as a result of lumpy resources and other non-convexities that require combinatorial optimization and make difficult the determination of clearing prices—which are guaranteed to exist only with convex costs.
- *Medium term* (1 month to 3 years). To better manage risk, the vast majority of energy is traded in medium-term markets. Here product durations range from one-month to three-years. The products may be for variable quantity that depends on load or for fixed quantity. The medium-term market may be a formal forward energy market with standard products in which supply is procured in regular auctions typically for small regulated customers. Large customers in contrast typically procure their own supply as bilateral contracts via either auction or negotiation. In well-functioning markets, roughly 90 percent of energy is traded in these medium term markets. However, the spot market plays an essential and enabling role by allowing the efficient settlement of deviations. Parties are able to sign risk-reducing medium-term contracts, knowing that in the event plans or capabilities change the parties can efficiently settle any deviations in the spot market.
- *Long term* (4 to 20 years). It often is desirable to have a market for long-run investments of more than three years. In simple settings characterized by low load growth, high income, and plenty of storable energy—such as Nord Pool—a long-term market is not necessary. However, in other settings, where these simplifying features are not present, a long-term investment market may further reduce risk, coordinate investment, and improve the operation of the spot market during

periods of stress. The long-term market typically takes the form of a capacity market in thermal systems, such as New England, and a firm energy market in hydro systems, such as Colombia.

In addition to our basic objectives of efficiency, transparency, simplicity, and fairness, these markets are organized to address risk, mitigate market power, and encourage cost-effective investment. The markets work as a complementary portfolio of opportunities for participants to manage their resources, obligations, and needs. The California energy crisis of 2000-2001 is a vivid and costly example of the importance of the medium- and long-term markets. California's excessive reliance on the spot market cost Californians roughly $40 billion (Borenstein 2002).

Long run investment markets

The most challenging component of the wholesale electricity market has proven to be the long-run investment market. Early versions of this market had fatal flaws (Cramton 2003). Improvements in the market design addressed these problems (Cramton and Stoft 2005, 2006, 2007, 2008; Cramton and Ockenfels 2012). The improved designs were adopted initially in New England (2007) and Colombia (2006); however, a full adoption of the design did not take place in New England until 2013. Most recently this design, based on strong performance obligations, has been adopted in PJM (2014), one of the largest electricity markets in the world.

The development of these markets illustrates some important lessons of market design. The primary motivation of a capacity market is to address a market failure in energy-only markets—the absence of robust demand-side participation. Most consumers neither see nor feel the spot energy price. This makes the demand curve too steep and leads to the possibility of shortage situations in which the market cannot set the price. The capacity market sets a high scarcity price to motivate supply and demand response during periods of shortage.

The long-term investment can be summarized in four words: *buy enough in advance*. The purpose of the market is to induce just enough *investment* to maintain adequate resources. Since investments in new generation take time—typically several years—it is important that the market clear well in advance of the commitment period. In this way, the costs of new investment are properly reflected in the capacity bids. The forward market also makes the market contestable; new capacity can compete with existing capacity.

In addition to making sure there are enough resources, the market has four other goals:

- Induce an efficient mix of resources.
- Reduce market risk.
- Mitigate market power in the spot market during scarcity.
- Pay suppliers no more than necessary.

As is often the case in market design, the critical step in a successful market is defining the product correctly. Early capacity markets defined the capacity product based on the nameplate capacity of a unit slightly discounted based on the unit's outage history. This definition effectively rewards nameplate capacity (iron in the ground), but not what consumers need—energy during scarcity periods. The distinction is fundamental.

Consider the decision of a gas-fueled generator on whether to buy firm or non-firm gas. When capacity is rewarded based on “iron in the ground”, the owner is motivated to buy non-firm gas. It costs significantly less and the gas is available in all but a handful of hours each year. Unfortunately, many gas units will make the same choice, so during a severe cold-snap these gas units find they have no gas and cannot generate energy—a shortage of energy results. Customers are deprived energy from these “capacity” units at precisely the time the capacity is needed to produce energy.

The flaw in the early designs are seen in the fact that the product based on nameplate capacity has no value to the buyer (consumers). In contrast, the correct product definition—an obligation to deliver energy during scarcity periods—is valuable to consumers. To enhance substitution, the product is defined in a technology neutral way. All types of resources compete on an equal basis. Also, price separation across zones only occurs in response to binding transmission constraints. Thus, to the extent possible all resources irrespective of type or location compete on an equal basis. Finally, to reduce risk, new resources are able to lock in a price for a longer period of time.

By far the most important attribute of the product is strong performance incentives. With the exception of New England’s pay-for-performance design adopted in 2014, all capacity markets suffer from performance incentives that were too weak. PJM is scheduled to adopt a similar design in its 2015 auction. With poor performance incentives, the market gets what it demands: unreliable resources. The non-firm gas example is one of hundreds of ways weak performance incentives lead to reliability problems. This clearly is an instance of a serious market flaw, because the whole point of the capacity market is to properly address reliability.

Strong performance incentives are actually quite simple. Here is how the pay-for-performance market works. The system operator establishes a capacity target for the year being auctioned (typically three or four years ahead) that satisfies the reliability standard (for example, “one day in ten years”). The system operator then procures the target capacity in an annual auction. Absent binding transmission constraints, each selected resource receives the same capacity price—the market clearing price that balances supply and demand. Each winning resource has an obligation to supply energy during scarcity events, defined as hours in which the system has a reserve shortage. The obligation follows load. For example, a supplier that is supplying 10 percent of the target capacity would have an obligation to serve 10 percent of the load during the scarcity event. Deviations are settled at the administratively set scarcity price (say $5000/MWh). If the supplier supplies less than the 10 percent share, the supplier pays a penalty of $5000 per MWh for underperformance; if the supplier supplies more than the 10 percent share, the supplier receives a reward of $5000 per MWh for overperformance.

Notice the simplicity of mechanism. It is simply a standard option contract with obligations triggered by scarcity events and efficient settlement at the scarcity price for deviations.

One remaining question is the scarcity price. How is it set? The reliability standard implies a particular expected number of scarcity hours. The scarcity price is set to cover the costs of an efficient peaker that earns the scarcity price during the expected scarcity hours. This is about $5000/MWh in the New England market. The scarcity price is adjusted periodically.

Both the capacity target and the scarcity price are readily calculated from the reliability standard and the cost of an efficient peaking unit. These are standard economic/engineering calculations.

For hydro-dominated systems, such as Colombia, there is one essential difference in the market. The scarcity event is not a lack of capacity, but a lack of firm energy during the dry season. These scarcity events occur much less frequently, roughly once every ten years, than reserve shortages in a thermal system, but last much longer, often weeks or months. As a result the triggering event is a high energy spot price, but much lower than the scarcity price in a thermal system, given the long duration of scarcity events in a hydro system.

So why have performance incentives been too weak in every early capacity market? The reason is the market design is a result of a stakeholder process. Although the system operator can provide leadership in establishing a good design, special interests push for exceptions with respect to performance. The nuclear owners argue that they need to have a long scheduled maintenance, so an exception is introduced that units do not have to perform during scheduled maintenance. Owners of coal units argue that they are slow to start-up. They are happy to supply energy when given sufficient warning, so an exception is introduced that slow units do not have to perform without sufficient notice. Owners of gas units argue that they should not be penalizes if gas is not available. The list goes on and on. It is very much a slippery slope. Each of these exceptions makes the market more complex as the product loses the simplicity of a standard forward contract. Worse yet, the exceptions cause the market to fail in satisfying its primary objective, reliability.

Spectrum auctions

I now turn to a second important industry, communications. Here I focus on one critical regulatory task, the allocation of spectrum, and in particular on spectrum auctions. Spectrum auctions are used to price and assign the spectrum that enables wireless communications. Given the exponential growth in demand for mobile broadband, spectrum auctions have become an increasingly important regulatory tool.

Spectrum auctions began in the US in 1994. Although economists argued for spectrum auctions for many decades, most notably Coase (1959), it was not until 1993 that Congress finally granted the FCC the authority to conduct spectrum auctions. The motivation for auctions, was not so much a recognition that economists were right, but rather a realization that all of the FCC's earlier approaches had failed, first beauty contests and then lotteries. Beauty contests were too slow and lotteries led to too many applications and obvious windfalls to the lottery winners. Auctions were the only remaining choice and these had the handy residual benefit of generating government revenues.

Spectrum auctions are long-run investment markets, analogous to capacity auctions in electricity. However, unlike electricity markets, spectrum auctions are not supported with short-term or medium-term markets, an issue I will address later.

In the typical spectrum auction, a small number of incumbent carriers and possibly a few potential entrants compete for spectrum licenses. The licenses often are nationwide, although regional licenses are common in countries with large geographic footprints, such as the US, India, Canada, and Australia. Terms are long—typically, 10 years or more—to motivate the substantial specific investment in network infrastructure. In the US, although the nominal license term is 10 years, there is a presumption of renewal without significant fee for perpetuity. Such a framework provides significant property rights, enabling network investments.

Some spectrum auction settings are relatively simple. In a typical simple case the carriers are competing for a number of lots of highly substitutable nationwide licenses. The spectrum is incremental to existing holdings and all carriers intend to use the same technology, such as LTE. In this case, a simple clock auction can be used to determine how many lots of contiguous spectrum are won by each bidder, and each bidder pays the same clearing price for lots won.

Other spectrum auctions have one or more complicating issues such as:

- Competition policy is needed to limit excessive concentration of licenses (Cramton et al. 2011).
- Carriers compete on a regional basis so it is necessary to offer regional, rather than nationwide licenses.
- Bidders have substantially different business plans or intend to use different technologies that require the spectrum to be organized in different ways (Cramton 2013).
- Interference from adjacent bands limits the substitutability of the spectrum lots.
- Some of the spectrum currently is held by incumbents who will need to relocate or clear. These may be government users, such as the defense department, or private users, such as microwave users (Cramton et al. 1998).

These complicating issues mean that it is important to customize the spectrum auction design to the particular setting. Consistent with the simplicity objective, it is desirable to use an auction design that is as simple as possible given the economic setting. In many settings a simple clock auction works well, but in other settings much more complex designs are required. Here I describe two, the simultaneous ascending auction and the combinatorial clock auction, which are now the two leading spectrum auction designs.

Two-sided auctions, such as the broadcast incentive auction in the US to repurpose television broadcast spectrum for mobile broadband, are beyond the scope of this paper. These two-sided auction designs are being developed as I write this and are much more complex than the typical one-sided auction (Milgrom et al. 2012; Milgrom and Segal 2014; FCC 2014; Cramton et al. 2015).

Simultaneous ascending auction

The workhorse of spectrum auctions has been the simultaneous ascending auction. The simultaneous ascending auction is a natural extension of the English auction when selling many interrelated items. The key insight is that all items are on the trading block at the same time. Each item has a price, which is initially low. The auction proceeds in a series of rounds. In each round, each bidder can raise the bid on any of the items if the bidder is not happy with her provisional winnings. The auction continues until no bidder is willing to bid higher for any item. At that point the provisional winners become final winners.

An important detail is the activity rule that motivates price and assignment discovery by preventing bidders from hiding demand until late in the auction. Before the auction starts bidders submit a deposit, the size of which determines the quantity of spectrum the bidder is eligible to bid on. Then in each round the bidder has an activity requirement to be active on (at least) a specified percentage of her eligibility. Activity means the bidder either places a new bid or is the provisional winner on the item. The activity requirement typically starts at 80% and then increases in stages to 100%. If a bidder's activity is below the requirement, then the bidder's eligibility is proportionally reduced in future rounds.

In early auctions, all bids and bidder identities were revealed after each bidding round, an information policy of full transparency. Such a rule maximized price and assignment discovery, but it also enabled bidders to signal with the trailing digits of their bids, which in cases of weak competition could support low-price and other collusive outcomes (Cramton and Schwartz 2002). Most recent auctions are anonymous (bidder identifies are not revealed) and bids are allowed only in large discrete steps to avoid these problems.

Another important improvement in the evolution of the simultaneous ascending auction is the use of clock auctions and generic lots to further simplify the auction and improve substitution among close substitutes. For example, suppose the regulator is auctioning 100 MHz of spectrum in 5+5 MHz lots as is best for the current LTE technology. Ten highly substitutable lots are available. With the clock methodology, the lots are treated as generic. There is a single product with 10 lots available in this case, and therefore one price. In the clock auction, the auctioneer announces a price and asks the bidders how many lots they would like at that price. If there is excess demand, then the auctioneer raise the price. The bidders respond with any reductions in demand at the higher price. The price is continues to rise until supply and demand balance. This determines the number of lots won by each bidder and the price per lot.

The clock methodology simplifies the bidding and has two other desirable properties. It guarantees that all generic lots sell for the same price and it guarantees that each bidder wins contiguous spectrum, which yields technical efficiencies.

Bidders typically care at least a little bit about where in the band their lots are located. To address this issue, an assignment stage is run in which winners bid for particular locations. This is done with a simple sealed-bid. Notice that there are not too many possibilities at this stage. In our example, if there were three winners, there are at most 3! = 6 different ways to organize the winners.

The clock methodology easily extends to instances where there are many different products as in a multi-band auction or an auction with regional licenses (Ausubel and Cramton 2004).

The chief limitation of the simultaneous ascending auction is that bidders are not able to bid on packages of licenses. This is a useful simplification when licenses are substitutes, but can cause problems when licenses are complements. Then bidders may want to bid for a complementary package of licenses. Unfortunately, allowing package bids greatly complicates the auction.

Combinatorial clock auction

The combinatorial clock auction was introduced as a way of retaining many of the desirable features of the simultaneous ascending auction, such as good price and assignment discovery, within an auction that allows package bids (Ausubel et al. 2006). The auction format has now been used in many European countries, Australia, and Canada. It is especially well-suited to settings where complementarities are strong and differ across bidders, for example when bidders intend to use different technologies that require the spectrum to be organized in different ways. The combinatorial clock auction enables the auction to determine how much spectrum is allocated to each use.

The combinatorial clock auction begins with a clock stage, just like the clock implementation of the simultaneous ascending auction. The auctioneer names prices for each product and the bidder names its preferred package at those prices. Prices increase for every product with excess demand. The process is repeated until there is no excess demand. Then there is a supplementary round in which bidders may improve their clock bids or bid on any other relevant packages. At this point, an optimization of all the bids submitted is run to determine the value maximizing assignment and prices.

This approach handles complementarities well as it is a true package auction. Two important elements are the pricing rule and the activity rule. The pricing rule is a second price rule to encourage truthful bidding. The activity rule is based on revealed preference: bidders can only shift demands to packages that have become relatively less expensive. See Cramton (2013) and Ausubel and Baranov (2014) for details.

Discussion

My one word of advice to regulators is *prepare*. Spectrum auction design and implementation is something that requires time, effort, and engagement of experts. There are many instances of problems in spectrum auctions as a result of inadequate preparations. For example, the Italy 4G auction, conducted in September 2010, had procedures that failed in the first day. The auction was conducted on-site with pen and paper and lasted 470 rounds. The engagement of experts would certainly have improved the process and likely the outcome in this 4 billion euro auction.

The engagement of experts also can help avoid major mistakes that arise when the regulator makes political decisions about the design in the stakeholder process. The loudest voice in the process is that of the incumbents and their interests are generally not aligned with the government—incumbents do not like competition in the wireless market and do not like paying competitive prices for spectrum. Without expert advice the stakeholder process is apt to produce an outcome that undermines competition. This happened in the India 2G auction—the disaster was so great it ultimately led to a change of government.

Fortunately, expert advice is both readily available and inexpensive, so that even the smallest countries can conduct spectrum auctions ideally customized for their setting on a state-of-the-art auction platform.

Future wireless markets

It is interesting to contrast the current spectrum markets with the electricity market design discussed earlier. In today's spectrum markets, there is essentially only a long-term market. Opportunities to balance supply and demand in the medium- and short-term are largely lost. This is undesirable from an efficiency perspective, but it also creates competition problems in the market for wireless services.

The main reason for the absence of shorter-term markets for spectrum is inflexible devices. Historically, handsets could be built more cheaply with less weight and longer battery life if the handsets sacrificed flexibility. However, the ability to produce more flexible devices without sacrificing cost, weight and battery-life is now here. Regulators should take advantage of this new capability to promote short-term spectrum markets. These technology advances are not something that will come in the decades ahead; the technology is here today and simply has to be harnessed. Regulatory leadership likely is required, because the development of these short-term markets is pro-competitive and incumbents generally dislike competition.

What would the wireless market of the future look like? Much like the electricity markets of today, there would be multiple opportunities to contract. We would have the long-term investment market like existing spectrum auctions. There would be medium-term markets in which mobile operators contract for spectrum on a one-month to three-year duration. And there would be a spot market in which mobile operators buy and sell capacity on a real-time basis. To some this may sound like science fiction, but it is not. The technology is here today. It simply is a matter of overcoming the inertia of the status quo.

One area of opportunity is spectrum that is set aside for public safety use, such as the FirstNet spectrum in the 700 MHz band in the US. Historically public safety spectrum has been underutilized for two reasons: (1) public safety has lacked the funds to build a state-of-the-art network and (2) public safety use is characterized by high-value use during emergencies and emergencies are rare. A public-private partnership between public safety and a private system operator, who builds and manages the network, is ideally suited to solve both problems. Public safety retains priority use of the spectrum in emergencies, but the system operator manages real-time and longer-term markets for spectrum, assuring that the capacity is used efficiently and providing funds for building and operating the network. Since capacity on the network would be available to all parties on an equal basis (aside from the rare emergency uses by public safety), the network provides an easy entry point for companies that have innovative ideas for using the spectrum but are currently excluded because of the difficulties of negotiating contracts with incumbent carriers. Negotiations are difficult because incumbent carriers are protective of their networks. This is not surprising given that the carriers have spent many tens of billions of dollars building their networks.

With time, this same public-private model can be expanded to other government spectrum. The gains in terms of more efficient use of the spectrum, expanded opportunities for innovation, and improved competition in the wireless services market are large.

Conclusion

Governments play a critical role in establishing the rules under which market interactions occur. I have discussed this role in the context of two important infrastructure industries, energy and communications. In both cases, good market design can lead to dramatic improvements in social welfare. These gains come from more efficient allocation of scarce resources, improved price formation, reduced risk, enhanced competition, and the mitigation of market failures.

Good market design does not just happen. It is something that requires leadership at the highest levels, dedicated regulators focused on the market design problem, and the engagement of experts in several disciplines, especially economics, computer science, operations research, and other relevant engineering fields, to determine how to best meet objectives in the particular setting. Finally, and perhaps most important, it requires regulatory agencies ruthlessly focused on social welfare maximization, rather than captured by special interests.

References

Allaz, B. and J.L. Vila (1993), "Cournot Competition, Forward Markets and Efficiency," *Journal of Economic Theory*, 59: 1-16.

Ausubel, Lawrence M. and Oleg Baranov (2014), "Market Design and the Evolution of the Combinatorial Clock Auction," *American Economic Review: Papers and Proceedings*, 104:5, 446-451.

Ausubel, Lawrence M. and Peter Cramton (2004), "Auctioning Many Divisible Goods," *Journal of the European Economic Association*, 2, 480-493, April-May.

Ausubel, Lawrence M., Peter Cramton, and Paul Milgrom (2006), "The Clock-Proxy Auction: A Practical Combinatorial Auction Design," in Peter Cramton, Yoav Shoham, and Richard Steinberg (eds.), *Combinatorial Auctions*, Chapter 5, 115-138, MIT Press.

Ausubel, Lawrence M., Peter Cramton, Marek Pycia, Marzena Rostek, and Marek Weretka, "Demand Reduction and Inefficiency in Multi-Unit Auctions," *Review of Economic Studies*, forthcoming, 2014.

Boiteux, M. (1960), "Peak Load Pricing," *Journal of Business*, 33:157-79 [translated from the original in French published in 1951.]

Boiteux, M. (1964), "The Choice of Plant and Equipment for the Production of Electric Energy," in James Nelson, ed. *Marginal Cost Pricing in Practice*, Englewood Cliffs, N.J., Prentice-Hall.

Borenstein, S. (2002). "The Trouble with Electricity Markets: Understanding California's Restructuring Disaster" *Journal of Economic Perspectives*, 16(1), 191-211.

Borenstein, S., J. Bushnell und F. Wolak (2002). "Measuring Market Inefficiencies in California's Wholesale Electricity Industry" *American Economic Review*, 92(5), 1376-1405.

Chao, H.P. and R. Wilson (1987), "Priority Service: Pricing, Investment and Market Organization," *American Economic Review*, 77: 89-116.

Chao, H.P. and R. Wilson (2002). "Multi-Dimensional Procurement Auctions for Power Reserves: Robust Incentive-Compatible Scoring and Settlement Rules," *Journal of Regulatory Economics*, 22(2), 161-183.

Chao, H.P. and R. Wilson (2004), "Resource Adequacy and Market Power Mitigation via Option Contracts," EPRI, Palo Alto, CA.

Coase, Ronald H. (1959), "The Federal Communications Commission," *Journal of Law and Economics*, 2, 1-40.

Cramton, Peter (1995), "Money Out of Thin Air: The Nationwide Narrowband PCS Auction," *Journal of Economics and Management Strategy*, 4, 267-343.

Cramton, Peter (1997), "The FCC Spectrum Auctions: An Early Assessment," *Journal of Economics and Management Strategy*, 6:3, 431-495.

Cramton, Peter (2003). "Electricity Market Design: The Good, the Bad, and the Ugly," *Proceedings of the Hawaii International Conference on System Sciences*.

Cramton, Peter (2004). "Competitive Bidding Behavior in Uniform-Price Auction Markets" Proceedings of the Hawaii International Conference on System Sciences.

Cramton, Peter (2013), "Spectrum Auction Design," *Review of Industrial Organization*, 42:2, 161-190, March 2013.

Cramton, Peter, Evan Kwerel, Gregory Rosston, and Andrzej Skrzypacz (2011), "Using Spectrum Auctions to Enhance Competition in Wireless Services," *Journal of Law and Economics*, 54, 2011.

Cramton, Peter, Evan Kwerel, and John Williams (1998), "Efficient Relocation of Spectrum Incumbents," *Journal of Law and Economics*, 41, 647-675.

Cramton, Peter, Hector Lopez, David Malec and Pacharasut Sujarittanonta (2015), "Design of the Reverse Auction in the FCC Incentive Auction," Working Paper, University of Maryland.

Cramton, Peter and Axel Ockenfels (2012) "Economics and Design of Capacity Markets for the Power Sector," *Zeitschrift für Energiewirtschaft*, 36:113-134.

Cramton, Peter and Axel Ockenfels (2014) "Germany's 4G Spectrum Auction: Design and Behavior," Working Paper, University of Maryland.

Cramton, Peter and Jesse Schwartz (2002), "Collusive Bidding in the FCC Spectrum Auctions," *Contributions to Economic Analysis & Policy*, 1:1, 1-17.

Cramton, Peter, Yoav Shoham, and Richard Steinberg (2006), *Combinatorial Auctions*, Cambridge, MA: MIT Press.

Cramton, Peter and Steven Stoft (2005). "A Capacity Market that Makes Sense" *Electricity Journal*, 18, 43-54.

Cramton, Peter and Steven Stoft (2006), "The Convergence of Market Designs for Adequate Generating Capacity," white paper for the California Electricity Oversight Board, March 2006.

Cramton, Peter and Steven Stoft (2007), "Colombia Firm Energy Market," *Proceedings of the Hawaii International Conference on System Sciences*.

Cramton, Peter und Steven Stoft (2008). "Forward Reliability Markets: Less Risk, Less Market Power, More Efficiency" *Utilities Policy*, 16, 194-201.

Crew, Michael A. and Paul R. Kleinforder (1976), "Peak Load Pricing with Diverse Technology," *Bell Journal of Economics*, 7(1): 207-231.

DG Competition (2007a). "Structure and Performance of Six European Wholesale Electricity Markets in 2003, 2004 and 2005." DG Comp 26th February 2007, Prepared by London Economics in association with Global Energy Decisions.

DG Competition (2007b). "Energy Sector Inquiry der Europäischen Kommission." (2007). Available at: http://ec.europa.eu/comm/competition/antitrust/others/sector_inquiries/energy/#final

Federal Communications Commission (2014), "Comment Sought on Competitive Bidding Procedures for Broadcast Incentive Auction 1000, Including Auctions 1001 and 1002," FCC 14-191, released 17 December 2014.

Hart, Oliver (1995). *Firms Contracts and Financial Structure*. Oxford: Clarendon Press.

Hogan, William W. and Scott M. Harvey (2000), "California Electricity Prices and Forward Market Hedging," Working Paper, Harvard University.

Joskow, Paul L. (1987). "Contract Duration and Relationship Specific Investments," *American Economic Review*, 77:168-75.

Joskow, P.L. (2005). "The Difficult Transition to Competitive Electricity Markets in the United States." *Electricity Deregulation: Where To From Here?* (J. Griffin and S. Puller, eds.), Chicago, University of Chicago Press.

Joskow, P.J. (2006). “Markets for Power in the United States: An Interim Assessment.” *The Energy Journal*, 27(1), 1-36.

Joskow, P. L. (2007). “Competitive Electricity Markets and Investment in New Generating Capacity.” *The New Energy Paradigm* (Dieter Helm, Editor), Oxford University Press.

Joskow, P.L. and J. Tirole (2006), “Retail Electricity Competition,” *Rand Journal of Economics*, 37(4), 799-81.

Joskow, P.L. and J. Tirole (2007). “Reliability and Competitive Electricity Markets.” *Rand Journal of Economics*, 38(1), 68-84.

Klemperer, Paul (2004), *Auctions: Theory and Practice*, Princeton University Press.

Milgrom, Paul (2004), *Putting Auction Theory to Work*, Cambridge: Cambridge University Press.

Milgrom, Paul, Lawrence M. Ausubel, Jonathan Levin, and Ilya Segal (2012), “Incentive Auction Rules Option and Discussion,” NPRM Appendix FCC-12-118A2.

Milgrom, Paul and Ilya Segal (2014), “Deferred-Acceptance Auctions and Radio Spectrum Reallocation,” Working Paper, Stanford University.

Müsgens, F. (2006). “Quantifying Market Power in the German Wholesale Electricity Market Using a Dynamic Multi-Regional Dispatch Model.” *Journal of Industrial Economics*, 54 (4), 471.

Ockenfels, Axel, Felix Müsgens and Markus Peek (2011). Observations on the Economics and Design of Power Reserve Markets. Working Paper, University of Cologne.

Oren, Shmuel S. (2005), “Generation Adequacy via Call Option Obligations: Safe Passage to the Promised Land,” *Electricity Journal*, November.

Parkes, David C. (2006), “Iterative Combinatorial Auctions,” in Peter Cramton, Yoav Shoham, and Richard Steinberg (eds.), *Combinatorial Auctions*, Chapter 2, 41-78, MIT Press.

Stoft, Steven (2002), *Power System Economics*, IEEE Press.

Turvey, R. (1968), *Optimal Pricing and Investment in Electricity Supply: An Essay in Applied Welfare Economics*, Cambridge, MA: MIT Press.

Vazquez, Carlos, Michel River, and Ignacio Perez Arriaga (2002), “A Market Approach to Long-Term Security of Supply,” *IEEE Transactions on Power Systems*, 17 (2): 349-357.

Williamson, Oliver (1979). “Transaction-cost Economics: The Governance of Contractual Relations,” *Journal of Law and Economics*, 22:3-61.