UNITED STATES OF AMERICA

BEFORE THE

FEDERAL ENERGY REGULATORY COMMISSION

PREPARED DIRECT TESTIMONY OF

PETER CRAMTON

ON BEHALF OF

ISO NEW ENGLAND INC.

DOCKET NO. ER12-____-000; ORDER NO. 755 COMPLIANCE

FREQUENCY REGULATION COMPENSATION IN THE ORGANIZED WHOLESALE POWER MARKETS

30 APRIL 2012

SUMMARY OF DIRECT TESTIMONY OF PROFESSOR PETER CRAMTON

In Order No. 755, the Federal Energy Regulatory Commission (FERC) identified a number of problems with the frequency regulation markets operated in the US. The order calls for a redesign of the regulation markets to address the identified flaws. Professor Cramton examines the New England regulation market and proposes an alternative market design that would address the current problems and support an efficient regulation market.

Professor Cramton evaluates five alternatives:

1. ISO New England's current one-dimensional design.
2. A simple two-part bidding design that treats capacity and mileage as if they were separate products.
3. A linear scoring design that maps two-part bids into a score used for resource selection.
4. A sequential design, used in some reserve markets, in which resources are selected for regulation based on the capacity offer, and then selected resources are dispatched based on the mileage offer.
5. A Vickrey design, in which resources are selected to minimize total cost and then each selected resource is paid its system opportunity cost—the cost to the system were the resource unavailable.

He finds that each of the first four designs has problems that make the design ill-suited to New England's regulation market. In contrast, the Vickrey design has many virtues and is most consistent with the intent of Order No. 755.

The key properties of the Vickrey approach are:

- *Simple*: Suppliers bid costs and each resource is paid system opportunity cost.
- *Truthful*: Suppliers have incentives for truthful bidding that reveal actual costs.

- *Efficient*: The cost-minimizing set of regulation resources is selected and dispatched.
- *Nondiscriminatory*: Identical resources receive the same payment.

Most importantly, the Vickrey approach handles well the two main challenges of the regulation market in New England. The first is the bundled supply of capacity and service (mileage). The second is the lumpy selection of resources. The lumpiness challenge is especially severe in New England. Regulation is a small component—about 0.2% of the total energy value—in the relatively small New England market. In 28 percent of the hours (January 2010 to March 2012) only one or two regulation resources were required by the system and in 52 percent of the hours three or fewer resources were required.

The Vickrey approach selects regulation resources to minimize cost and then pays each selected resource the system opportunity cost—the additional cost that the system would incur if the particular resource were unavailable. This payment is also referred to as avoided cost.

The payment can be broken into two components: the realized cost (actual mileage cost plus capacity cost including energy opportunity cost) and the incremental cost savings to the system. The realized cost is calculated at settlement based on the resources actual performance, as-bid costs, and actual energy opportunity cost. The incremental cost savings is based on the information at the time of resource selection. This approach guarantees that actual costs of selected resources are recovered, reducing market risk and encouraging market participation and performance.

The Vickrey approach complies with Order No. 755. It allows full expression of actual costs via two-part bids and properly motivates suppliers to bid true costs and to perform as bid. It selects resources to minimize total cost and then pays selected resources a bundled payment equal to the system opportunity cost—the cost of the marginal resource. As a result of lumpy resources, the bundled payment is necessary to achieve efficiency (least-cost supply). The market-based payment is nondiscriminatory and guarantees recovery of the resource's actual costs.

Market transparency is achieved through the posting of the requirements—both capacity and mileage—in advance of the hour, then posting the realized capacity and mileage quantities and the total regulation payment after the hour. Also posted on an hourly basis are approximate prices for mileage and capacity. The mileage price is the system marginal cost of mileage—the increase in system cost were the mileage constraint increased by 1 MW. The capacity price is the residual payment per MW of capacity after deducting the mileage price:

Capacity price = (total regulation payment – total mileage $\times$ mileage price) / (total capacity).

These prices give an approximation of the compensation per MW of capacity and mileage. The approximation is better when there is greater competition and less lumpy resources. In any event the prices are an accurate measure of average compensation. After 90 days the masked offers are posted. Finally the Internal Market Monitor's regular reports will provide additional information and analysis of the performance of the regulation market. Taken together this information gives both market participants and other stakeholders ample information about the market outcomes and the market performance.

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ISO New England Inc. and	)	**Docket No. ER12-____-000**
New England Power Pool	)	

DIRECT TESTIMONY OF

PROFESSOR PETER CRAMTON

Q Please state your name, title, and business address.

A I am Peter Cramton, Professor of Economics at the University of Maryland. My business address is Economics Department, University of Maryland, College Park, MD 20742.

Q What are your qualifications?

A Since 1983, I have conducted research on auction theory and practice. This research appears in the leading economics journals. The main focus is the design of auctions for many related items. Applications include spectrum auctions, electricity auctions, and treasury auctions. On the practical side, I am Chairman of Market Design Inc., an economics consultancy founded in 1995, focusing on the design of auction markets. I have advised numerous governments on market design and I have advised dozens of bidders in high-stake auction markets. Since 1997, I have advised ISO New England on electricity market design and was a designer of New England's forward capacity auction. I led the design of electricity and gas markets in Colombia, including the Firm Energy Market, the Forward Energy Market, and the Long-term Gas Market. Since 2001, I played a lead role in the design and implementation of electricity auctions in France and Belgium, gas auctions in Germany, and the world's first auction for greenhouse gas emissions held in the UK in 2002. I led the development of the FAA's airport slot auctions for the New York City airports. I received my B.S. in Engineering from Cornell University and my Ph.D. in Business from Stanford University. My writings and vita are available at www.cramton.umd.edu.

Q What is the purpose of your testimony?

A I have been asked by ISO New England to advise them on the design of the frequency regulation market in New England. This testimony reports the results of my design work.

Q What is the objective of your design work?

A FERC Order No. 755 identifies problems with the existing regulation markets as operated in New England and in other restructured electricity markets. I was asked to evaluate design alternatives that address the problems. The goal is to identify the auction design that would be as effective as possible in providing frequency regulation in the New England electricity market. This objective includes both short-run efficiency—least-cost supply of regulation services—and long-run efficiency—price signals to motivate efficient investment in regulation capability.

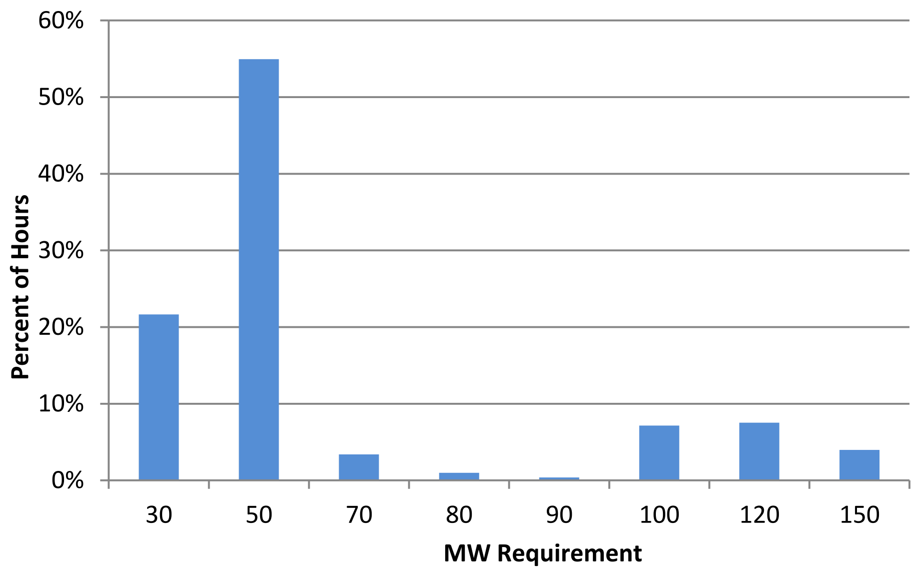
Q Are there special properties of the regulation market that are relevant in New England?

A Yes. There are four main properties: the small size of the market, the lumpiness of supply, the abundance of available capacity, and the tight bundling of the two key components of supply—capacity and mileage. I will consider each in turn.

The regulation market in New England is small. The total cost of regulation in 2011 was $13.3 million. By comparison, the total cost of wholesale electricity in New England was $7.3 billion in 2011, so regulation is a tiny fraction—just 0.2 percent—of the electricity cost. As such, the design should be implementable with no more than moderate expense for otherwise the improvement gains would likely be dwarfed by implementation costs. Further, it would be advantageous if the design allowed improvements to be implemented over time, so that the changes could be coordinated with changes to the energy and other markets to further reduce the implementation cost.

The small size of the market is seen in Figure 1, which shows the hourly regulation requirement for each hour of 2011. In 77% of the hours, the requirement was 50 MW or less. In each of these hours, it is possible to supply the entire requirement with a single resource. The requirement never exceeded 150 MW.

Figure 1. Hourly regulation requirement (2011)



The small size of New England's regulation market means that supply is lumpy. Few resources are selected for regulation in any hour. Figure 2 shows the frequency of the number of resources providing regulation in an hour from 1 January 2010 to 13 March 2012. In over one-quarter of the hours, only one or two resources provide regulation in the hour. In over one-half of the hours, there are three or fewer resources providing regulation. Figure 3 shows the cumulative frequency of the number of units providing regulation over the same period.

Figure 2. Frequency of number of units on regulation in hour (1 January 2010 to 13 March 2012)

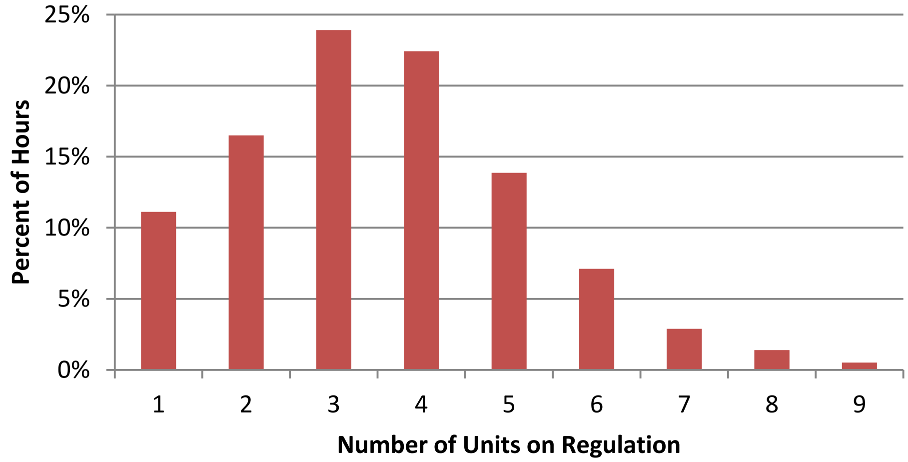
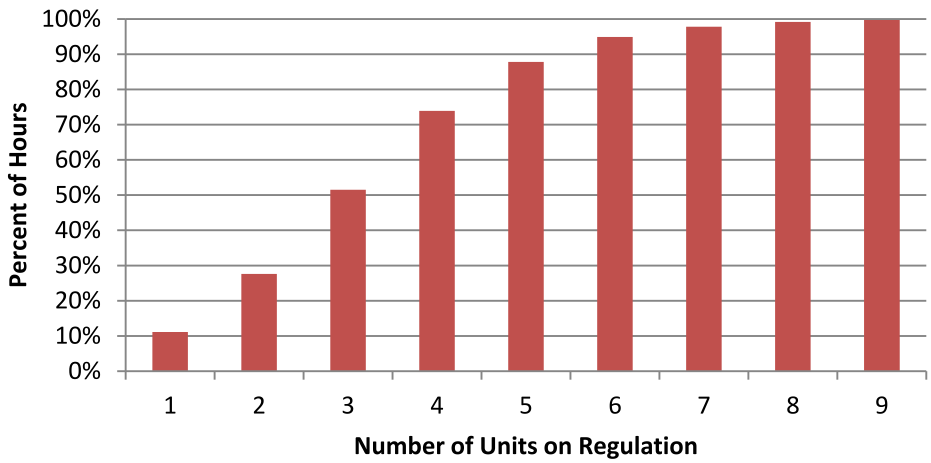


Figure 3. Cumulative frequency of number of units on regulation (1 January 2010 to 13 March 2012)



Given the lumpy nature of regulation supply, it will be important for the design to work well when only a small number of resources are required.

The abundance of supply is another important property. This is often expressed as the bid-to-cover ratio, the ratio of available capacity to the required capacity. Figure 4 shows the frequency of regulation surplus for the period from 1 January 2006 to 22 March 2012. The figure shows an average surplus of about 500 MW, compared with a requirement ranging from 30 to 150 MW. Most importantly in roughly 99% of the hours, the surplus exceeds the requirement. Thus, the bid-to-cover ratio is 2 or more in 99% of the hours, and typically the bid-to-cover ratio is between 2 and 20.

This is exceptionally high, suggesting that there is ample supply in the market in all but the most demanding hours. Auctions with a bid-to-coverage ratio of 2 or more are typically viewed as competitive. US Treasury auctions typically have a bid-to-cover ratio between 2 and 3.

Figure 4. Frequency of regulation surplus (1 January 2006 to 22 March 2012)

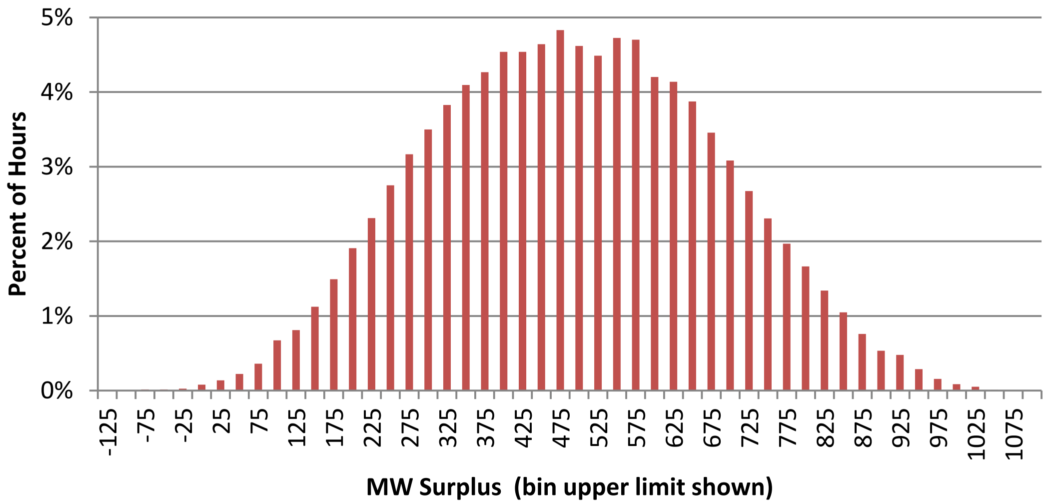
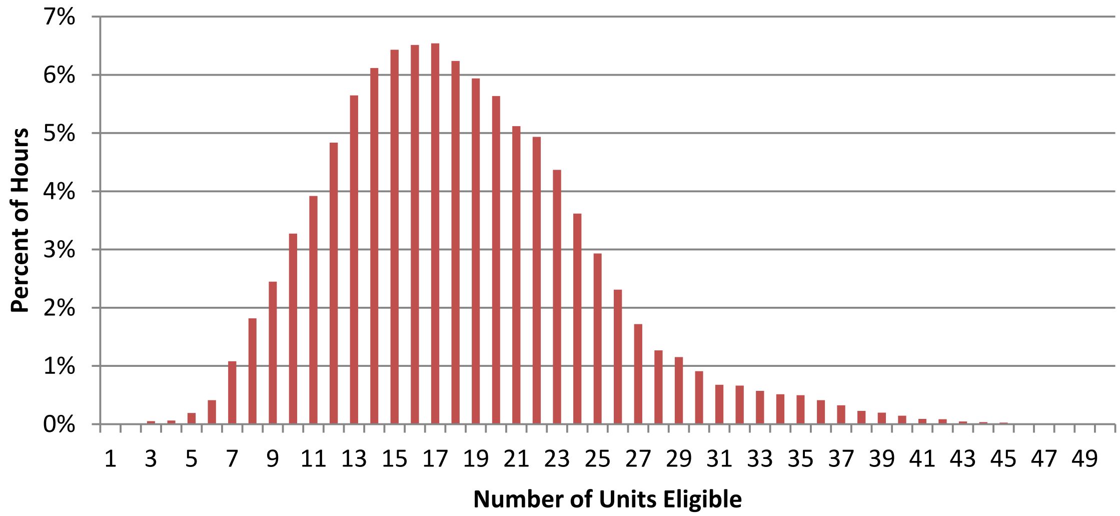


Figure 5 shows the frequency of the number of resources eligible to provide regulation for the period 1 January 2006 to 22 March 2012. Given that the regulation requirement typically is met with only a few resources, the figure suggests that the regulation surplus is coming from many eligible resources.

Figure 5. Frequency of number of units eligible to provide regulation (1 January 2006 to 22 March 2012)



The conclusion is that there is ample regulation capacity in New England. With a good market design that pays the cost of the marginal resource there should be plenty of participation and hence competition in the regulation market.

Finally, the two main components of regulation supply—capacity and mileage—are tightly bundled. Few units are selected and then each of the selected units is asked to supply significant quantities of both capacity and mileage. The chosen approach should handle well both lumpy and bundled supply.

Q What alternative designs did you develop and evaluate?

A I examined five alternative designs. They are:

1. A *one-dimensional design*. This is the current approach operated by ISO New England.
2. A *simple two-part bidding design*. Capacity and mileage are bid separately.
3. A *linear scoring design*. Demand and supply are expressed in terms of capacity. A linear scoring rule that depends on both capacity and mileage offers is used to rank resources for selection.

4. A *sequential design*. This design is similar to that used in some reserve markets. Resources are selected for regulation based on the capacity offer. Then resources are dispatched for mileage during the hour based on the mileage offer.

5. A *Vickrey design*. Resources are selected to minimize total cost. Each selected resource is paid its realized costs plus its incremental cost savings to the system. Equivalently, each resource is paid the system opportunity cost—the cost to the system were the resource unavailable.

Q Why did you focus on these five designs?

A The one-dimensional design is the starting point—where we are now. It is helpful to understand the current market and its limitations as a first step in identifying alternatives. The simple two-part bidding design is the simplest alternative that would appear to address FERC's concerns as expressed in Order No. 755. The linear scoring rule design is a standard approach in procurement when there are multiple components in a bid. The sequential design has proven successful in some settings such as reserve markets. Finally, the Vickrey design is a simple yet powerful approach that has good incentive properties and handles well both lumpy resources and bundled supply.

Based on my experience, these five alternatives span the set of desirable designs for the regulation market.

Q Can you describe the current one-dimensional design used in New England?

A Yes. The motivation for the current one-dimensional is that capacity and mileage are closely bundled. Demand is expressed in terms of capacity, since there is ample mileage when the capacity requirement is met. Also the current Automatic Generation Control (AGC) dispatch algorithm dispatches accepted resources to rapidly minimize Area Control Error (ACE). This means that all accepted resources are dispatched at relative response rates.

With this approach, there is no need for a separate mileage offer, since mileage is provided based on relative response rates. Instead the resource is asked to bundle its mileage cost and capacity cost into a single regulation offer.

Resources then are accepted in merit order based on the bundled offer, which determines the regulation clearing price. The compensation for each resource is determined by applying 100% of the regulation clearing price to the delivered capacity and 10% of the regulation clearing price to the delivered mileage. Thus, if the last resource accepted for regulation has an offer of $10, then the capacity price would be set at $10 and the mileage price would be set at $1. This 10-to-1 ratio was administratively determined such that a typical resource would receive roughly 50% of its compensation from capacity and 50% from mileage. However, a faster resource would receive a higher share of its compensation in mileage; whereas, a slower resource would receive a higher share of its compensation in capacity. In addition, each selected resource receives its energy opportunity cost.

Q Do you see problems with the current design?

A Yes, there are two main problems.

First, suppliers are unable to express capacity and mileage costs separately for each resource. With the bundled regulation offer it is not possible to dispatch resources based on the economics, nor is it possible to meaningfully decompose the regulation payment into capacity and mileage prices. As a result, the ISO makes the administratively determined 10-to-1 decomposition, which splits the compensation for a typical resource roughly 50-50. There is no economic basis for the 10-to-1 price decomposition.

Second, the regulation payment does not reflect the energy opportunity cost of the marginal resource. Rather, each resource is compensated for its own energy opportunity cost, but this cost is not included in the regulation clearing price.

Each of these problems makes the approach inconsistent with Order No. 755. The status quo is not an option.

Q **Can simple two-part bidding address the problems?**

A First let me define what I mean by simple two-part bidding. Then I can discuss the properties of the approach.

With simple two-part bidding, the supplier submits separate capacity and mileage offers for each resource. The capacity offers are adjusted to include each resource's energy opportunity cost. Resources are then selected for regulation to minimize total cost until the requirement is met. The capacity price is the highest accepted capacity offer (including the energy opportunity cost); the mileage price is the highest accepted mileage offer. Selected resources then receive the following payment:

Regulation payment = capacity price × capacity supplied + mileage price × mileage supplied.

This simple approach would appear to address the problems directly: (1) bidders can express capacity and mileage costs separately, and (2) the capacity price includes the market clearing energy opportunity cost. However, an analysis of the approach reveals that it performs poorly in both practice and theory as a result of the poor bidding incentives that it creates.

With this approach bidders have strong incentives to distort offers away from true costs. This was observed in the early California reserve markets, which had a similar structure.[1] There are at least two problems.

First, the pricing is logically flawed. Sensible clearing prices are the result of identifying the marginal resource and paying the cost of the marginal resource. That is not what is done with this simple approach. Neither the selected resource with the highest capacity cost nor the resource with the highest mileage cost may be on the margin. And regardless of whether they are, paying the highest accepted cost in both dimensions leads to excessive compensation if resources were to offer at cost. The reason is that the selected resource with the highest capacity cost likely was made economic as a result of a low mileage cost; similarly, the resource with the highest mileage cost likely has a low capacity cost. Clearing the two markets separately is inappropriate in a circumstance where the resource is selected based on its bundled capability for capacity and mileage.

Second, the pricing creates strong incentives for extreme offers. To see the problem, consider a resource with a high capacity cost and a low mileage cost. The resource knows that if it is selected for regulation it may well set the capacity price, but there is no chance that it will set the mileage price. The resource then can gain by raising its capacity offer and lowering its mileage offer so that its probability of selection does not change. The end result is skewed bids by those resources that are likely to set either the capacity price or the mileage price when selected.

In equilibrium, this approach leads to offers that are sharply distorted from actual costs. The result is inefficient selection and poor prices. The simple two-part bidding approach is not a viable option.

[1] See Hung-Po Chao and Robert Wilson, "Multi-dimensional Procurement Auctions for Power Reserves: Robust Incentive-Compatible Scoring and Settlement Rules," *Journal of Regulatory Economics*, 22(2), pages 161-83, September 2002.

Q Can you explain how the linear scoring design works?

A Yes. The linear scoring design is similar to the simple two-part bidding approach in that two-part bids are accepted, but it makes additional assumptions to maintain a simple one-dimensional structure. There are two key components to the approach, the scoring rule and the settlement rule.

The scoring rule takes the capacity and mileage offers and maps them into a score. The score is linear in the capacity and mileage offers:

Score = capacity offer + mileage-to-capacity ratio × mileage offer

In the calculation, each resource's capacity offer is adjusted to include the resource's energy opportunity cost. The mileage-to-capacity ratio is not bid but is set by the ISO. The simplest approach is to set the mileage-to-capacity ratio at the system-wide average. Then we can interpret the ratio as the expected mileage per MW of capacity. And the score is an approximation of system cost per MW of capacity.

Resources are accepted for regulation in order of increasing score until the regulation requirement is met.

The settlement rule takes advantage of the fact that the scoring rule made the problem one-dimensional. The market clearing score is the score of the last accepted resource. This market-clearing score is then decomposed into capacity and mileage prices. Unfortunately, there is no unique way to do this decomposition. One approach is to set the mileage price equal to the highest mileage offer among accepted resources. The capacity price then is calculated to be the residual, such that the total payment is equal to the market-clearing score times the total accepted capacity.

Thus, the approach begins with two-part bids, uses a linear scoring rule to select resources and determine a market-clearing score, and then decomposes the total payment into linear prices for capacity and mileage.

Q Are there any problems with this approach?

A Yes, there are three main problems.

First, selecting resources in order of score does not minimize total cost, since the score is only an approximation of the system cost. The approximation is problematic when resources differ. Fast resources may have a much higher mileage-to-capacity ratio than slower resources.

One response to address this heterogeneity would be to use a resource-specific mileage-to-capacity ratio. But this would penalize faster resources for their greater capability, which is nonsensical. The penalty is easy to see. If two resources have identical offers but one can ramp more quickly, the faster ramping resource will have the inferior score. The problem is that the score does not recognize the benefit of the mileage service, but in fact treats it as a cost—the more the resource does, the worse its score.

Second, the linear scoring rule together with a linear settlement rule creates strong incentives for skewed bids. A skewed bid puts much of the desired score in one factor and little in the other. This is a frequent problem in procurement auctions that have a linear scoring rule and a linear settlement rule. Intuitively, the best bidding strategy is to pick a desired score and then achieve the score in the most profitable way, which typically will be to put the entire score in either the capacity component or the mileage component, but not both.

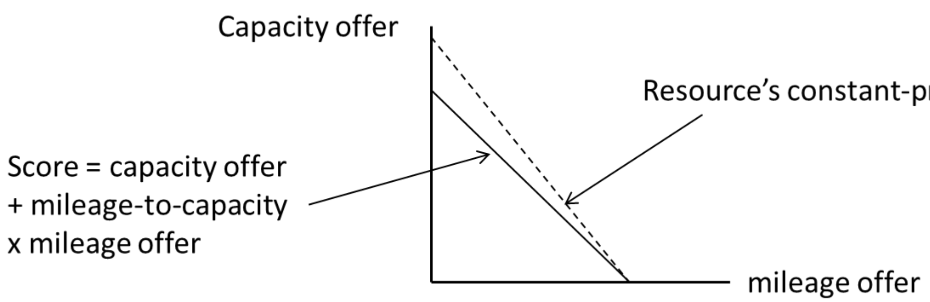
With the linear scoring approach, bidders have skewed bidding incentives whenever their bids can affect the split in the capacity and mileage payments. The argument is as follows. The probability of being selected depends on only the score and not on how the bidder divides the score between capacity and mileage. Thus, the supplier's decision can be broken into two steps: (1) to choose the optimal score for the resource and (2) to choose how to optimally split the score into capacity and mileage offers given the optimal score. The supplier thus seeks to select the capacity and mileage offers to maximize profit subject to achieving the optimal score, where

Score = capacity offer + mileage-to-capacity × mileage offer, and

Profit = capacity × capacity price + mileage × mileage price – cost(capacity, mileage).

Notice that the score is linear in the offers and that revenue is linear in the prices. By assumption, the resource can impact the split between capacity and mileage payments, and hence prices. The linear constraint and the linear constant-profit curve imply a corner solution: the entire score is best allocated to either the capacity offer or the mileage offer. Figure 6 shows the incentive for skewed bidding. In this example, the constant-profit curve is steeper than the score and so the supplier puts its entire score in the mileage offer.

Figure 6. The incentive for skewed bids with a linear scoring rule



With the AGC dispatch to rapidly minimize ACE, as is the current practice in New England, slower resources will prefer a high capacity price and have an incentive to put their entire score in the capacity offer; whereas, faster resources will prefer a high mileage price and so will put their entire score in the mileage offer. Unfortunately, the offers do not reflect costs.

Assuming that the mileage price is the highest accepted mileage offer, then the equilibrium split between the mileage and capacity payment will tend to favor the mileage payment. Indeed, when a resource that has its entire score in mileage is near the marginal score, the capacity payment will tend toward zero. This approach favors the faster resources that benefit from a larger mileage payment.

The third problem with this approach is that the decomposition of the payment into linear prices for capacity and mileage is arbitrary. Setting the mileage price equal to the highest mileage offer is one method, but there are many others, including the other extreme of setting the capacity price equal to the highest capacity offer. The method of decomposition has a large impact on the split of the regulation payment between capacity and mileage. Yet the choice of method is an administrative decision without an economic basis.

Thus, the approach provides two-part payments, one for capacity and one for mileage based on linear prices, but there is no reason to believe that the prices for capacity and mileage reflect the economic contribution coming from the two components. The approach sends clear price signals, but the price signals likely are wrong.

For these reasons, the linear scoring design is a poor choice in New England.

Q Please explain how the sequential design works.

A The sequential design is also based on two-part bids and a two-part pricing structure. The difference is the two markets are cleared in sequence. Capacity selection occurs first. Resources are accepted in order of increasing capacity offers (including the energy opportunity cost) until the capacity requirement is met. Then during the hour accepted resources are dispatched to minimize system costs subject to operational constraints. This design is outlined by Hung-Po Chao and Robert Wilson in "Multi-dimensional Procurement Auctions for Power Reserves: Robust Incentive-Compatible Scoring and Settlement Rules," *Journal of Regulatory Economics*, 22(2), pages 161-83, September 2002. The approach is used in some reserve markets.

The sequential design has excellent incentive and efficiency properties when applied to reserve markets. Essentially resources compete first to provide reserves and then the selected reserve resources compete to supply energy whenever reserves are needed for energy. When resources are small and there is ample competition in both markets, then the resulting linear prices support the efficient outcome. This is approximately the case in many actual reserve markets, where many resources are selected for reserve duty from among hundreds of units and these many reserve resources then compete to provide energy in those few instances when it is necessary to dip into the reserves.

Q Are there problems with the sequential approach in the New England regulation market?

A Yes. There are two problems.

First, the current AGC dispatch bundles products by dispatching selected resources at their relative response rates, rather than according to mileage cost. The sequential design requires the ability to dispatch resources by the mileage offer. Such a change to the real-time dispatch may only be practical at a later date.

The second problem has to do with the size and lumpiness of the New England regulation market. Lumpiness makes the unbundling of capacity and mileage problematic. More often than not, the New England market needs one, two, or three regulation resources. This is an extremely lumpy market. When only a single resource is needed, then there is no competition in the mileage market, and in a majority of hours the competition is quite limited.

Thus, although the sequential approach may work well in many settings, it is ill-suited to the New England regulation market because supply is too lumpy.

Q Your fifth and final approach is the Vickrey design. Please explain how it works and its properties.

A The Vickrey design is based on the Vickrey auction, but for simplicity I assume that each resource has a separate owner. The Vickrey design admits two-part bids, selects resources to minimize total cost, and then pays each resource the system opportunity cost, which can best be thought of as a "bundled clearing price."

The Vickrey approach has three key properties:

1. *Truthful*: suppliers have an incentive to bid the true costs of each resource.
2. *Efficient*: the total cost of regulation is minimized.
3. *Nondiscriminatory*: identical resources receive the same payment.

Importantly, each of these properties still applies in the New England setting with bundled products and lumpy supply. Indeed, the Vickrey design can be thought of as a generalization of the basic clearing-price ideas to settings with lumpy supply and products with multiple dimensions.

To clarify the strong connection between the Vickrey approach and the standard clearing price auction, it is helpful to consider an example. First consider the simplest case of a one-dimensional product. Suppose there are five 1-MW resources as shown in the table below and there is a requirement of 3 MW. In the Vickrey approach, the three least expensive resources, A, B and C, are selected. The Vickrey payment is the system opportunity cost—the increase in cost if the resource were not available. For each of the three selected resources, the system opportunity cost is $24. If any of A, B, or C is not available, then resource D is selected at a system cost of $24. Resource D is the marginal resource and the Vickrey payment is the cost of the marginal resource.

Resource	Capacity (MW)	Cost ($/MW)	Cost savings ($)	Payment ($)
A	1	10	14	24
B	1	14	10	24
C	1	21	3	24
D	1	24	-	-
E	1	30	-	-

In this simple case, the Vickrey auction is equivalent to the standard clearing-price auction. The payment is uniform and equal to the first-rejected offer. Each resource is paid the avoided cost—the cost of the marginal resource.

There is a second useful interpretation of the Vickrey payment. The resource is paid its cost plus the cost savings to the system—the resource's inframarginal rent. The cost savings of a particular resource is calculated as the difference between the minimal total cost when the resource is unavailable and the minimal total cost when the resource is available. Thus, the cost savings for resource A is $14, since not using A at a cost of $10 would require using D at a cost of $24, so costs would increase by $14. Paying the resource 100% of its cost savings induces each resource to offer true costs. Thus, full efficiency—least-cost supply—is achieved.

The key advantage of the Vickrey approach is that it generalizes nicely to a multi-dimensional problem with lumpy resources. To see this consider a second example with two-part bidding. There are three 5-MW resources as shown in the table below. Suppose the capacity requirement is 10 MW and the mileage requirement is 10 MW.

Resource	Reg. Capacity (MW)	Capacity + EOC offer ($/MW)	Mileage Offer ($/MW)	Response rate (MW/min)	Capacity bought (MW)	Mileage bought (MW)	Cost ($)	Cost savings ($)	Vickrey Payment ($)
A	5	1	10	1	5	5	55	5	60
B	5	10	1	1	5	5	55	5	60
C	5	6	6	1	-	-	-		

Regulation resources are selected to minimize total cost. Any two of the three resources will meet the requirements, so resources A and B are selected, since this has the lowest system cost of $110.

The Vickrey payment is equal to the system opportunity cost—the cost of the marginal resource. When resource A or B is removed, resource C must be selected. Resource C also provides 5 MW of capacity and 5 MW of mileage, but at a cost of $60, rather than $55. Thus, both A and B are paid $60, or equivalently their cost of $55 plus the cost savings for resource A or B, which is $60 – $55 = $5. Again, suppliers have an incentive to bid true cost and full efficiency is achieved.

Notice that the payment received is a bundled payment and no attempt is made to unbundle the payment. The reason as we will see in a moment is that with lumpy supply it generally is not possible to find linear prices that support the efficient outcome.

The example also illustrates the problem with the simple two-part bidding approach in which we set linear prices equal to the last accepted offer in each dimension. This would result in capacity and mileage prices of $10 each. Resources A and B would be happy to supply at these prices. The problem is that resource C would also be happy to supply at these prices.

Q What is the main difference between the Vickrey design and the standard clearing-price auction?

A The key difference between the Vickrey approach and the standard clearing-price auction is that the Vickrey approach properly handles lump supply. In particular, the properties of truthful bidding and efficiency are retained despite lumpy supply. To accomplish this, the Vickrey design must abandon linear pricing. The reason is that truthful bidding and efficiency require that the payment to a resource be equal to the system opportunity cost—the cost the system avoids as a result of the resource's availability. When resources are lumpy, the system opportunity cost is specific to the resource. A larger or faster resource typically has a different system opportunity cost, since different resources are needed to optimally replace it.

A general theoretical result is that the Vickrey payment is not only sufficient for efficiency (least-cost supply) but necessary. In the simplest cases, like our initial one-dimensional example, the Vickrey payment is equal to the linear payment in the standard clearing-price auction, so both approaches result in least-cost supply. However, when we have lumpy supply, this no longer is possible. No linear prices can replicate the Vickrey payment of system opportunity cost. Thus, with lumpy supply, one either must abandon linear prices or efficiency. In the context of New England's regulation market, which is extremely lumpy, my view is that it is better to focus on efficiency. Insisting on linear prices not only prevents efficiency, but requires arbitrary rules to determine linear prices. And then once constructed the linear prices necessarily send the wrong price signals.

Q Can you provide an example that illustrates the need for resource-specific payments with lumpy supply?

A Here is a simple example with four regulation resources: A, B, C and D. The capacity requirement is 10 MW and the mileage requirement is 10 MW. Resources are accepted for regulation all-or-nothing. Finally, assume that the AGC dispatch is optimized to minimize cost. The example would change only slightly if we instead dispatched selected resources at their relative response rates as is the current practice in New England.

The resources' offers and characteristics are shown in the table below.

Resource	**Capacity (MW)**	**Capacity + EOC offer ($/MW)**	**Mileage Offer ($/MW)**	**Automatic response rate (MW/min)**
A	5	1	1	1
B	10	2	3	2
C	15	3	5	3
D	20	4	7	4

The table below shows all 15 possible resource selections ($2^4 - 1$). Given each resource selection, mileage is bought to minimize mileage cost. The table also shows the mileage bought and the total cost of each resource selection.

Selection	Capacity bought (MW)					Mileage bought (MW)				Total cost ($)
	A	B	C	D	Total	A	B	C	D	
1	5	0	0	0	5	-	-	-	-	Infeasible
2 (B)	0	10	0	0	10	-	10	-	-	50
3	0	0	15	0	15	-	-	10	-	95
4	0	0	0	20	20	-	-	-	10	150
5 (A,B)	5	10	0	0	15	5	5	-	-	45
6 (A,C)	5	0	15	0	20	5	-	5	-	80
7	5	0	0	20	25	5	-	-	5	125
8	0	10	15	0	25	-	10	0	-	95
9	0	10	0	20	30	-	10	-	0	130
10	0	0	15	20	35	-	-	10	0	175
11	5	10	15	0	30	5	5	0	-	90
12	5	10	0	20	35	5	5	-	0	125
13	5	0	15	20	40	5	-	5	0	160
14	0	10	15	20	45	-	5	5	0	185
15	5	10	15	20	50	5	5	0	0	170

The Vickrey approach begins by selecting resources to minimize total cost. The least-cost solution is to select resources A and B yielding a total cost of $45. Resource A provides mileage at the lowest cost, but can only satisfy one-half of the mileage requirement. Resource B therefore provides the remainder. This selection is highlighted in green.

The next step is to determine the Vickrey payments for each resource. For this we need to calculate the system opportunity cost of the resource, which is found by re-optimizing the system without the resource. Without resource A, the best selection is B alone, which increases total cost from $45 to $50; without resource B, the best selection is A and C, which increases cost from $45 to $80. These alternative selections are highlighted in blue.

The system opportunity cost for a resource is the avoided cost. Without A, we shift to the selection of B alone. This requires an addition cost of $15 for having B increase its mileage by 5 MW. Thus, A's Vickrey payment is $15 as shown below.

Resource	Capacity (MW)	Capacity + EOC offer ($/MW)	Mileage Offer ($/MW)	Response rate (MW/min)	Capacity bought (MW)	Mileage bought (MW)	Cost ($)	Cost savings ($)	Payment ($)
A	5	1	1	1	5 → 0	5 → 0	10	5	15
B	10	2	3	2	10	5 → 10	35 + 15	35	70
C	15	3	5	3	-	-	-	-	-
D	20	4	7	4	-	-	-	-	-

An equivalent expression for the Vickrey payment is the resource cost plus the incremental cost savings to the system. Resource A's availability reduces the system cost from $50 to $45—a cost savings of $5. Thus, resource A is paid $10 + $5 = $15, its cost plus its cost savings to the system. A's payment is only slightly above its costs, since it is relatively inexpensive to replace A—all that is required is a little bit more mileage from resource B.

Now consider resource B's payment. Without B, the optimal selection is A and C. The additional system cost comes from C providing 15 MW of capacity and 5 MW of mileage for a replacement cost of $3 × 15 + $5 × 5 = $70. Thus, B's Vickrey payment is $70, as shown below.

Resource	Capacity (MW)	Capacity + EOC offer ($/MW)	Mileage Offer ($/MW)	Response rate (MW/min)	Capacity bought (MW)	Mileage bought (MW)	Cost ($)	Cost savings ($)	Payment ($)
A	5	1	1	1	5	5	10	5	15
B	10	2	3	2	10 → 0	5 → 0	35	35	70
C	15	3	5	3	0 → 15	0 → 5	0 +70	-	-
D	20	4	7	4	-	-	-	-	-

Alternatively, resource B is paid its cost of $35 plus the incremental cost savings stemming from B's availability. Were B not available, costs would increase from $45 to $80, so the cost savings is $35, and the Vickrey payment is $35 + $35 = $70. B's payment above cost is large because replacing resource B is so expensive. It requires selecting the large and expensive resource C.

Finally, consider the impossibility of linear prices to replicate the Vickery payments. Actually, in this example, since two resources are selected in the least-cost solution, we can replicate the Vickrey payments with linear prices. We have two equations (one for each selected resource) and two unknowns (the capacity price and mileage price):

5 × capacity price + 5 × mileage price = $15

10 × capacity price + 5 × mileage price = $70

The unique solution is a capacity price of $11 and a mileage price of –$8. However, there are two important points to make about these linear prices.

The first is that their existence depends on there being exactly two selected resources. If only one resource is needed the system of equations is under-determined and if more than two resources are needed the system of equations is over-determined—no linear prices exist.

The second more important point is that the linear prices calculated in this way have little meaning. They lose the interpretation of a shadow price: the additional system cost if the requirement is increased by 1 MW. The –$8 mileage price does not mean that system cost would be reduced by $8 if the mileage requirement were raised from 10 to 11 MW. Similarly, the $11 capacity price does not mean that system cost would increase by $11 if the capacity requirement is raised from 10 to 11 MW.

In fact, the shadow prices for both capacity and mileage can be calculated. The shadow price for capacity is $0. As a result of the lumpy purchase we are buying 15 MW of capacity, 5 MW more than the requirement. Thus, when we increase the capacity requirement by 1 MW from 10 to 11 MW, there is no change in cost. The shadow price for mileage is $3. The increase in cost when the mileage requirement increases by 1 MW from 10 to 11 MW is the cost of buying an addition MW of mileage from resource B: $3.

These shadow prices of ($0, $3) are much more economically meaningful than the linear prices of ($11, –$8). However, they cannot be used for payments, since they typically would grossly undercompensate resources.

Q Can you describe the steps of the Vickrey approach in greater detail?

A The market begins with each supplier submitting a regulation offer for each resource consisting of several components: a capacity offer, a mileage offer, the regulation range, and the ramp rate. In the simplest implementation, this regulation offer can be submitted at any time. The offer will remain in effect until it is replaced or cancelled.

Resource selection is the next step. This can be done periodically, such as every 60 minutes or every 15 minutes, or it can be done as needed in response to a system change. Regardless, the current offers from each resource are used in the selection and compensation until a new selection is run. Resources are selected to minimize expected cost subject to satisfying the regulation requirement.

The advantage of shorter selection intervals is that the estimate of expected costs, both the energy opportunity costs and mileage costs, will be more accurate. Fortunately, the implementation of the improvements to the regulation market likely will coincide with the implementation of the sub-hourly (5-minute) energy market settlement. This may allow for the cost-effective implementation of a shorter regulation interval, say 15 minutes rather than one hour, and selection on demand in response to system changes. Such an approach not only promises improved selection based on better estimates, but greater participation of limited energy resources that may be unable to sustain service for long intervals.

During the selection interval, resources are dispatched by AGC. Ideally, this dispatch is done to minimize cost subject to operational constraints. However, it may be necessary at least in the near term to continue to use the current AGC dispatch algorithm, which is to dispatch according to the relative response rates of the selected resources. The Vickrey approach can be used with either dispatch algorithm, but dispatching to minimize cost will result in lower costs and more efficient operation. A further advantage of the minimize-cost objective is that it simplifies the selection optimization.

The final step in the Vickrey approach is settlement. Recall that the Vickrey payment is the system opportunity cost—the avoided cost. In this application, it is desirable to split the Vickrey payment into its two components—the incremental system cost savings and the realized cost—and calculate each component at different times. In particular, each resource is paid the sum of:

1. The incremental system cost savings of the resource at the time of selection (before the regulation interval).
2. The realized cost of the resource, both the actual mileage cost and the capacity cost including the realized energy opportunity cost.

Calculating the cost savings at the time of selection, rather than ex post, guarantees that the cost savings is positive. The algorithm for calculating the cost savings is straightforward. First, resources are selected to minimize total cost subject to the regulation requirements. This yields the optimal total cost. Next, for each selected resource, we run the same optimization, but with the particular resource removed. This yields the (higher) optimal total cost with the resource removed. The system cost savings for the particular resource is just the difference between the minimal cost without the resource and the minimal cost with the resource.

Calculating the resource cost after the fact guarantees that the resource is fully compensated for all as-bid costs given the actual realizations of both mileage and energy opportunity costs. The ex post compensation of costs reduces risk and encourages resource participation.

The payment is a bundled payment including compensation for both capacity and mileage. Given the lumpy supply and the tightly bundled resource attributes it is neither possible nor desirable to unbundle the payment into separate payments for capacity and mileage. Attempting to do so with linear prices necessarily prevents efficient (least-cost) supply.

The expected bundled payment equals the system opportunity cost, or avoided cost. The actual payment will depend on the specific performance delivered by the resource. The payment is resource specific, since the avoided cost depends on the capacity and ramping capability of the resource. Nonetheless, the resource-specific payment is nondiscriminatory: identical resources that deliver identical performance receive the same payment.

Q Please explain why the Vickrey approach induces suppliers to bid true costs?

A For this result I need to assume that each resource is owned separately. As mentioned earlier, this simplifies the problem and also guarantees that the payments are nondiscriminatory. Later I will discuss how bidding incentives change when we relax this assumption.

The Vickrey result can be stated as follows: It is a dominant strategy for each supplier to offer the resource at true costs. Moreover, when each supplier follows this dominant strategy, the outcome is efficient (least-cost supply).

The efficiency result is obvious. If the offers are true costs and we select resources to minimize total as-bid cost, then the selection minimizes total cost.

Showing truthful bidding is a bit more work. First, notice that the Vickrey payment does not depend on the resource's capacity and mileage offers. The payment is the system opportunity cost and this only depends on the offers of the *other* resources. Thus, the resource's offers only affect when the resource is selected. The objective of the supplier then is to make offers such that the resource is selected whenever selection results in a positive profit. But bidding true costs does exactly that. Then the resource receives as payment its true cost plus the incremental cost savings, which is guaranteed to be positive when the resource is selected.

Were the supplier to offer above cost, the result would have no impact on the payment, but it would mean that the resource would not be selected in some instances when selection is profitable. Were the supplier to offer below cost, the result would be no impact on the payment, but the resource would now be selected in some additional instances in which selection is unprofitable. Only by bidding true cost is the resource guaranteed to be selected whenever selection is profitable.

The argument above is a dominant strategy argument (which means that it is the best strategy for the supplier regardless of how the other suppliers bid), since it makes no assumption about the offers of other resources. Truthful bidding is the best strategy regardless of how the other resources are bid. This result makes bidding especially easy. The supplier simply needs to properly calculate the cost of capacity (exclusive of the energy opportunity cost) and mileage.

Q How do bidding incentives change when some suppliers own many resources?

A The Vickrey payment, as described here, is calculated on a resource basis, which implicitly is assuming each resource is owned separately. This is done partly to simplify the payment calculation. Assessing ownership interest is complex in wholesale electricity markets as a result of extensive contracting intended to reduce risks. However, another important reason is to assure that the payments are nondiscriminatory: identical resources receive the same payment.

In practice we know it is common for suppliers to own and operate multiple resources. For those that own multiple regulation resources, this may create an incentive to offer above cost on one or more resources. However, the incentive to bid above cost only applies to a rejected marginal resource. Then the higher offer on the rejected resource will create a higher cost savings for the selected resource and therefore a higher payment. It, however, is difficult for the owner to know when a resource is apt to be marginal. Also the gain from the strategy is limited by the competitive bids of others. As I discussed earlier there currently appears to be ample supply in the regulation market.

An analogous way to exercise market power in the regulation market is to not offer a resource for regulation. This physical withholding has the same impact as an above cost offer that leads to non-selection. The mitigating forces are the same: it is difficult to know which resources to withhold and in any event the payment impact is limited by the competitive offers of others.

Certainly, it makes sense for the market monitor to analyze the regulation market for market power problems. The watchful eye of the market monitor provides a further incentive for large owners not to withhold supply from the regulation market.

Q What happens when there is insufficient competition?

A Insufficient competition appears to be an unlikely possibility. Since 2006, there were only 77 hours (0.1 percent of all hours) in which there was inadequate supply. Still it is a possibility and so it must be addressed in the design.

The simplest approach is with a penalty factor in the optimization that selects resources for the regulation interval. The penalty factor is equivalent to a reserve price in the auction, which is the standard approach to addressing insufficient competition.

The penalty factor for capacity needs to include the potential opportunity cost for energy. Thus, a reasonable penalty factor for capacity would be the estimated energy component of LMP (the shadow price on the New England power balance constraint) plus $100/MWh. The penalty factor for mileage could be set at $10/MWh. In the Vickrey design these factors would also be used in calculating a resource’s incremental cost savings in the event there is insufficient supply with the particular resource removed.

There are three tradeoffs that must be weighed in setting the penalty factors. Penalty factors that are too low discourage participation in the market and therefore may result in too high a frequency of insufficient supply. Penalty factors that are high encourage participation and thus reduce the chance of insufficient supply. However, penalty factors that are too high may increase the possibility that a large participant may withhold supply in circumstances when the market is especially tight, although typically it will be difficult for a large supplier to identify such opportunities and the chance that such opportunities arise is reduced by higher penalty factors.

Setting a penalty factor for capacity that moves with the energy price is highly desirable—a high penalty factor is needed when the energy price is high to account for the energy opportunity cost, and a low penalty factor is desirable when the energy price is low. Penalty factors equal to the estimated energy component of LMP plus $100/MWh for capacity and $10/MWh for mileage would appear to strike the right balance. These penalty factors are well above historic payment levels, except in a handful of hours over many years. Nonetheless, it will be important to do further analysis before finalizing the penalty factors, and these factors should be reviewed and revised as needed in light of experience.

Q How would the market assure transparency?

A Transparency would be provided by publishing information both before and after the event. The capacity and mileage requirements would be published before the event. Then after the fact the ISO would publish the actual hourly capacity purchased (in MW), the actual hourly mileage purchased (in MW of instructed movement), and the total hourly regulation payment (in $). Finally, in accordance with the ISO New England Information Policy as it applies to Bid and Offer data, the ISO would release after 90 days the masked offers for both capacity and mileage.

This data would provide potential participants with good information about expected compensation in the regulation market. Since payments are based on the cost of the marginal resource, seeing the aggregate payments and purchased services is a good indicator of likely compensation. The regulation payment is not broken down into separate mileage and capacity components. Doing so for each resource is not possible given the lumpy and bundled nature of supply.

However, as a substitute for separate capacity and mileage prices, the ISO can calculate and post *approximate* prices as follows. In each hour, the ISO calculates the hourly system marginal cost of mileage in $/MWh. This is the increase in system cost from a 1 MW increase in realized mileage. This mileage price provides excellent information about how mileage is valued on the margin and likely provides good information on how mileage is valued for resources that are not too large, and hence near the margin.

This same method does not work for capacity. Since capacity is purchased on a lumpy basis, typically the system cost of increasing the capacity requirement by 1 MW is zero. Instead, we can calculate a capacity price as the residual after subtracting the "mileage payment" assuming the mileage price above. That is,

Capacity price = (total regulation payment – mileage price $\times$ total mileage)/total capacity.

The mileage and capacity prices thus calculated are a reasonable approximate measure of the relative rewards to mileage and capacity. These hourly prices would be reported as well.

One important source of resource-specific information for any resource that is AGC capable is simply participation in the market. Gathering information in this way is easy and low cost, since the regulation payment guarantees that the resource will receive at least its ex post cost including its energy opportunity cost.

For long-term investment decisions, participants can study the history of hourly regulation payments, requirements, purchases, and approximate prices in assessing the opportunities in the regulation market. The market monitoring reports on the regulation market should also prove useful.

Q Do you believe that the Vickrey approach complies with Order No. 755?

A Yes. Order No. 755 requires "compensation based on the actual mileage provided, including a capacity payment that includes the marginal unit's opportunity costs and a payment for performance that reflects the quantity of frequency regulation mileage provided by a resource when the resource is accurately following the dispatch signal."

The Vickrey approach allows full expression of actual costs with two-part bids. It then determines the least-cost set of regulation resources. The expected payment is a bundled capacity and mileage payment equal to the system opportunity cost, which is the cost of the marginal resource including all components of cost—the capacity offer, the energy opportunity cost, and the mileage offer. The payment provides strong incentives for suppliers to offer each resource at true costs. The final settlement is also based on the actual capacity and mileage that the resource supplies.

The bundled payment, equal to system opportunity cost, is a necessary condition of least-cost supply in the New England setting with lumpy resources. Nonetheless, market transparency is supported with the posting of the requirements, purchases, and total payment. In addition, price transparency is supported with the posting of an approximate mileage and capacity price. The mileage price is based on the system marginal cost for mileage. The capacity price is then computed as the residual after deducting the mileage price. Actual payments are resource specific given the lumpiness, but these approximate prices still provide good information about likely compensation.

Importantly, the payment ensures recovery of the resource's actual mileage and capacity costs including its energy opportunity cost. This makes participation in the regulation market low-risk, encouraging competition. In addition to recovering full costs, each selected resource receives its incremental system cost-savings. This reward aligns the incentives of the supplier with the system, which is the source of the strong incentives to offer true costs and thereby achieve least-cost supply.

The payment also is nondiscriminatory: identical resources receive the same payment. To achieve this important property the Vickrey payment calculation has to be done on a resource basis rather than an owner basis. This greatly simplifies the calculation, but does introduce the possibility that an owner with multiple resources may benefit from withholding supply in certain circumstances. The size of this adverse incentive is limited by the owner's limited information about the circumstances, the competitive bids of other resources, and the penalty factors (reserve prices) for regulation services.

The payment is market based. The competitive (opportunity cost) pricing is simply the proper extension of the standard clearing-price methodology that is commonly used in a one-dimensional non-lumpy setting. The extension is necessary to achieve an efficient market outcome with lumpy resources. As always, the penalty factors (reserve prices) for regulation requirements are set administratively, but they only set the regulation price in the rare hours where there is no competition. In all other hours regulation payments are determined from the competitive offers.

Q Doesn't Order No. 755 require uniform payments?

A When Order No. 755 refers to uniform payments, my interpretation is that each resource must be paid the cost of the marginal resource, which is how uniform clearing prices are calculated in simple environments. The Vickrey payment is 100% consistent with this interpretation. The only difference is the Vickrey approach extends to settings like New England with lumpy resources. With this extension, the desirable efficiency property—least-cost supply—is retained despite the lumpiness.

My view is that FERC’s intent is to promote market rules that support efficient markets. Thus, nondiscriminatory payments that deviate from linear prices as a necessary condition to support efficient supply are consistent with the intent of Order No. 755.

It is the efficiency and transparency of uniform prices that causes FERC to favor them. The Vickrey approach fully supports efficiency. Transparency is addressed through the timely posting of ample information for potential suppliers to estimate compensation from the regulation market, including approximate prices for mileage and capacity.

Q Order No. 755 requires that the opportunity cost of the marginal resource be included in the capacity payment. Does the Vickrey payment do this?

A Yes, and it does so in a way that is economically correct in a setting where the components of supply are tightly bundled and lumpy. The selection of resources includes all components of costs including the energy opportunity cost. Then the payment is determined based on the appropriate marginal calculation—the system opportunity cost were the resource unavailable. Thus, the payment includes the cost of the marginal resource across both components of cost—mileage and capacity (including energy opportunity cost). Since the system cost includes the energy opportunity cost of each resource, the incremental cost savings includes these costs on the suitable margin. This is exactly what Order No. 755 requires.

Q Order No. 755 requires that resources be able to include inter-temporal opportunity costs in their offers. How is this allowed in the Vickrey approach?

A The Vickrey payment provides incentives for the supplier to express the true costs of the resource. Thus, the capacity offer would include any inter-temporal opportunity costs. The proposed approach lets suppliers adjust the capacity offer as circumstances change. This allows the resource's capacity offer to track its inter-temporal opportunity costs throughout the day.

Q Order No. 755 requires that the compensation be based on the actual service provided. Is the Vickrey approach consistent with this requirement?

A Yes. The Vickrey payment is based on the actual capacity and mileage supplied and is adjusted for actual performance. However, one component of the payment, the incremental cost savings, is based on estimates of both energy opportunity cost and mileage, since the selection occurs before energy opportunity cost and mileage are realized.

One could calculate the incremental cost savings based on the realized energy opportunity cost and mileage. The difficulty is that this would result in a negative incremental cost savings for some selected resources, whenever the selection of resources turns out to be suboptimal because of differences between the estimates and the realizations. This ex post approach would increase resource risk and tend to reduce resource compensation. The reason is that the proposed (ex ante) calculation of incremental cost savings determines the cost savings assuming the optimal selection of resources; whereas in the ex post calculation the selected resources may be suboptimal. The cost savings will tend to be higher on average when the resources are selected optimally.

Nonetheless it is important in the approach that the estimates of opportunity cost and mileage are unbiased and as accurate as possible. Better estimates will improve efficiency and lower total cost. One way to improve estimates is to shorten the regulation interval. The ISO should consider implementing a shorter regulation interval as part of the shift to a shorter settlement period for energy. My understanding is that this may be possible given the likely timing of implementation.

One potential concern is that a resource may end up providing more mileage than was estimated at the time of selection. The extra mileage is paid for but only at the resource's as-bid cost—the ex-ante cost savings in this case likely would be an underestimate of the ex post cost savings, and thus the resource is undercompensated in this scenario. But notice that there will be other hours in which the resource provides less mileage than was estimated at the time of selection. In this scenario, the resource is overcompensated. Provided the estimates of mileage are unbiased, the compensation discrepancies in the two scenarios will cancel and the resource will receive the right compensation on average. Moreover, as the estimates of mileage improve the hourly compensation discrepancies will become insignificant.

Q The Vickrey payment is resource specific as in a pay-as-bid auction. Is this a pay-as-bid auction?

A No. The incentives are quite far from a pay-as-bid auction. The payment is calculated from the offers of the other resources, excluding the bids of the particular resource. The supplier's incentive is to bid true costs, rather than to try to guess the clearing price as in a pay-as-bid auction. The Vickrey incentive encourages efficient least-cost supply; whereas the pay-as-bid incentive can undermine efficiency if bidders do not guess correctly. The reason for resource-specific payments is lumpy supply. Were resources small relative to the requirement, then the payments would approximate the clearing prices in non-lumpy markets.

Q Can the Vickrey approach create an incentive for a supplier owning two resources to submit offers with widely separated values in an effort to increase the payment of the selected resource?

A Yes, there may be an incentive to offer the first resource at cost and the second resource above cost, but the incentive is limited by three factors. First, offering both at cost may be better in circumstances when both resources are selected. Second, the gain is limited by the competitive offers of other resources. And third, absent competitive offers from others the gain is limited by the penalty factors for regulation services. Given the large number of resources with AGC capability relative to the requirement and the low risk of offering in the market, I anticipate that competition from others will greatly reduce any incentives to withhold supply.

Q Are there other market power issues?

A No. The only market power problem is the possibility of one or a few large owners facing inadequate competition from others. The exercise of market power then is to withhold supply either physically or economically in order to increase the regulation payment for the selected resources. This risk appears small in New England's regulation market and it is something that the market monitor can watch and take corrective action as needed. Another mitigating factor is that the gains from exercising market power are limited by the small size of the regulation market.

Q What are the expected benefits of the Vickrey design?

A The Vickrey design will benefit both short-run operations and long-run investment.

In the short run, the Vickrey approach promotes efficient, least-cost supply of regulation. Resources can fully express costs and have incentives to offer true costs. This makes the selection of resources efficient, especially since participation in the market is low risk.

Efficient operation and pricing in the short run also sends the right price signal for long run investment. Thus, a second benefit is improved long-run investment signals. The market transparency about payments and outcomes will encourage additional regulation investment when needed. Moreover the market information will motivate investments in the right types of resources.

Q How would the Vickrey approach impact new technologies?

A The Vickrey approach will promote efficient long-run investments. Thus, if a new technology is efficient in that it can supply the regulation services at the lowest long-run average cost, then the technology will be encouraged. In contrast, the entry of inefficient technologies will be discouraged.

This is an improvement from New England's current regulation market that administratively assumes a 10-to-1 ratio between capacity and mileage prices. This administrative price decomposition may under or over reward faster resources. In the Vickrey approach, the relative rewards for capacity vs. mileage are determined from the competitive offers and the demand for regulation services. In this way, the payments motivate investment in the types of resources that are most economic.

Q Is the Vickrey auction used elsewhere?

A Yes. Vickrey auctions are common-place and have been used for hundreds of years (well before Vickrey first studied them in 1961). The most common Vickrey auction seen today is eBay. eBay's second-price auction is the simplest case of a Vickrey auction: the high bidder wins and pays the second-highest price. This structure is what motivates bidders to bid full value in an eBay auction. The sponsored-search ad auctions used by Google, Yahoo, and Microsoft are another version of a Vickrey auction in a setting in which many products are offered simultaneously. Vickrey methods are also used in recent auctions for radio spectrum in the UK, Canada, Australia, the Netherlands, Austria, and Denmark, where complements and lumpiness are important. Elements of a Vickrey auction are used in current electricity markets. For example, pricing based on "avoided cost" or "replacement cost" is Vickrey pricing.

Q Why doesn't the Vickrey approach also suffer from bid skewing?

A The good incentive properties come from paying a resource its cost plus its incremental cost savings, or equivalently the system opportunity cost. This makes it a dominant strategy for the supplier to offer the resource at true cost. The first thing to note is that the supplier's offer only impacts the resource's selection, not its payment, which is the cost of the marginal resource. Thus, there is no marginal incentive to distort one's bid. The remaining step in the dominant strategy argument is to recognize that the payment is such that the resource wants to be selected for regulation whenever the incremental cost savings is positive. This is exactly what the Vickrey auction does when the supplier offers the resource at its true cost.

Further intuition for the truthful bidding result comes from recognizing that the Vickrey payment aligns the incentives of the supplier and the system by giving the supplier a reward above its cost equal to 100% of its incremental contribution to the system. The supplier gains nothing by offering above cost, since this distortion has no impact on its payment (the higher cost payment is offset dollar for dollar by a lower cost savings payment), but the distortion means that the resource will not be selected in some instances in which selection is profitable. Similarly, the supplier gains nothing by offering below cost, since the distortion does not impact its payment, but the resource ends up getting selected in some additional cases all of which result in a negative profit.

Q The scoring rule used to evaluate offers in the Vickrey approach appears linear, since total cost is capacity × capacity offer + estimated miles × mileage price. Why doesn't this lead to skewed bidding?

A There are two reasons. First, the scoring rule, minimize total cost, is not truly linear, since the estimated mileage likely depends on the mileage offer. Second, the bid skewing result comes from a linear scoring rule *and* a linear payment rule. When both are linear, then the cheapest way for the resource to attain a particular score is to skew its bid—putting the entire score in the capacity offer or in the mileage offer. The Vickrey payment rule is far from linear. Indeed, the payment does not depend on the resource's offers, but rather the offers of competing resources.

Q Suppliers get paid at their offer prices for capacity and miles. Why is this not pay-as-bid?

A The payment is the cost of the marginal resource, which is *independent* of the resource's bid. Yes, part of the payment covers as-bid costs, but the total payment is independent of the resources costs, just like a clearing price. The Vickrey payment indeed is best thought of as a resource-specific bundled clearing price. The "resource specific" aspect is made necessary because of the lumpiness of the selection problem. As the problem becomes less lumpy and competition increases, the payment converges to a clearing price.

Q If resources get paid their actual unit-specific opportunity cost, how does this ensure opportunity costs are reflected in the clearing price?

A Again, part of the payment is to cover the resources actual cost, but what is relevant is the total payment, just like in the energy market, where resources receive the cost of the marginal resource. Here we do the same thing: the resource receives the cost of the marginal resource (including energy opportunity cost). This is analogous to a clearing price calculation, and indeed the payment is independent of the resource's actual costs. The only difference is that the bundled clearing price is resource specific as a result of lumpiness—the cost of the marginal resource depends on what is required to optimally replace the resource.

Q Can you summarize why you believe the Vickrey approach is best in the New England market?

A There are five key properties of the Vickrey approach that make it especially well-suited for the New England regulation market.

1. *Simple*: Suppliers fully express the costs of each resource and are paid the system opportunity cost.
2. *Truthful*: Suppliers have excellent incentives for truthful bidding that reveals the actual costs of each resource.
3. *Efficient*: The cost-minimizing set of regulation resources is selected.
4. *Nondiscriminatory*: Identical resources are paid the same.
5. *Powerful*: The Vickrey approach easily handles multi-dimensional bids and lumpy resources.

The approach also guarantees that each selected resource receives at least its actual costs. This reduces risk and encourages participation in the market. Make-whole payments are unnecessary.

Importantly, the Vickrey design avoids the problems of the other approaches. There is no incentive for skewed bids, as in the linear scoring rule approach. With the Vickrey approach, each supplier offers actual costs. There is no thin market problem as in the sequential approach. With the Vickrey approach, all resources available for regulation simultaneously compete to supply in both the capacity and mileage dimensions.

The chief disadvantage of the Vickrey approach is a modest loss of price transparency. Rather than finding linear prices for each component offered, the Vickrey approach finds a bundled payment that rewards each resource based on its cost savings to the system. In a setting like New England's regulation market with tightly bundled products and lumpy resources, efficiency requires a bundled payment that is resource specific.

However, the loss of price transparency is modest, since participants can learn a great deal from the published requirements, the quantities purchased of both capacity and mileage, and the total regulation payment. In addition, approximate prices for mileage and capacity are posted. The mileage price is the system marginal cost of mileage—the increase in system cost from a 1 MW increase in the mileage requirement. The capacity price is the residual payment per MW of capacity after deducting the mileage component. Although approximate, these prices are indicative of the split between capacity and mileage payments for a typical regulation resource.

Finally, the Vickrey approach has implementation costs that are as low as possible given the requirements of complying with Order No. 755 and promoting an efficient market. All that is required is the ability to accept two-part bids and then optimize the selection to minimize system cost. Moreover, the approach easily accommodates improvements to the market as they become feasible with the introduction of changes to related markets. These improvements may include an improved AGC dispatch algorithm based on cost minimization and an improved estimation of mileage and energy opportunity costs as a result of a shortened regulation interval.

I declare under penalty of perjury that the foregoing is true and correct.

Executed on 30 April 2012

Peter Cramton