**HARVARD ELECTRICITY POLICY GROUP**

**VIRTUAL SESSION**
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**Rapporteur's Summary***

## Looking Ahead: Price Formation and Multi-Period Dispatch

The basic model of bid-based, security-constrained, economic dispatch with locational prices is well understood and provides the foundation for efficient pricing. The most common analysis is for a single period with well-behaved bids and offers without uncertainty. With independent dispatches, serial application of this approach produces efficient prices. The real dispatch system requires some degree of look-ahead with intertemporal constraints. The expansion of intermittent resources increases the importance of efficient multi-period pricing. In principle, the same model applies for the multi-period dispatch. Relaxing any of the assumptions, however, presents new challenges for efficient pricing. Rolling dispatches must adjust to uncertain conditions inducing changes over time. Bids and offers with start-up, shut-down, and multi-period operating constraints require some form of extended locational marginal pricing and associated uplift requirements. Current practices differ across organized market. How important are efficient multi-period prices? What approaches might balance the current competing requirements to deal with efficiency, uncertainty and computational feasibility? What new modeling and software innovations are on the horizon?

*Introductory remarks, introduction of the panel and the beginning of the first presentation are missing from the recording. In this session, Speaker 1 often refers to charts and graphs from his presentation, which can be found within our research library.*

**Speaker 1.**
In the strictly convex case, you don't need to do anything. There's a paper by Biggar and Hesamzadeh that you can read which goes through that. But since almost all applications involved something which violates the strictly convex case, it's the general case that's really relevant here for our purposes.

So here's an illustration, which I'm not going to spend too much time on. I know it's hard to read the graphic, but I wanted to get it on one page. This is an example of a case where we have dependent multi-period prices. So there's ramping constraints. So this is a three-period model. There's two generators and then there's fixed loads, for the sake of discussion. You solve this optimization problem for the three periods, and you get market-clearing prices and their prices are shown and reported in the text there.

You observe something which sometimes worries people about these dynamic problems or these multi-period problems—which is, if you look on the right there with the unit B and the red supply curve, you find a situation where the market clearing price in the second period is below the bid-in marginal cost of the generator at the optimal generators' solution.

So it looks like the generators' solution is out of the money and this is going to create uplift requirements, and we're going to have to do all kinds of things in order to deal with that. But that is actually not correct. And the prices

* HEPG sessions are off the record. The Rapporteur's Summary captures the ideas of the session without identifying the discussants. Participant comments have been edited for clarity and readability.

from the LMP are correct, in the sense that they support the solution.

What's going on here is the generator is solving its own dynamic problem, and, given the prices, it recognizes that it has to run up its generation in period two in order to be ready for period three, to get up to the period where it's going to make extra money. All this is captured by the shadow price of the ramping constraints. So you get locational marginal prices, which are the marginal costs from the optimization problem. But they're the marginal costs that occur for the full intertemporal optimization problem, not just the bid-in cost in that period.

So that's an interesting problem. Then we go to the more general problem that I talked about before, where we have startup costs. I'm going to focus here on both that problem, and then what's the integer relaxation version of this problem. The integer relaxation, meaning that we take all of these startup and unit commitment variables and just relax those constraints. The ramping constraints turn out to make this problem complicated in very important ways. But under the right situation, in particular this work comes out of MISO and Hung-po Chao. If you formulate the problem correctly, and I'm going to talk a little bit about that, and the LMP, if you don't have intertemporal constraints, then the LMP prices from the relaxed problem give you the same thing as the convex hull pricing when you have ramping constraints and other intertemporal constraints that may not be true. The advantage of the integer relaxation problem, of course, is that it's easy to solve. And whereas the convex hull pricing problem is not going to be so easy to solve in practice.

So I'm going back to my table and then trying to fill in the bottom line here. And if we go across for the integer relaxation and a single period, which is what the Hung-po Chao wrote about, if you have a certain condition on the objective function, which I'm going to illustrate to the moment, then it turns out the integer relaxation gives you the same thing as the convex hull pricing. So it's a minimum uplift story. And it's really nice because you can exploit the computational simplicity of the integer relaxation problem.

The convex hull problem produces the prices and minimal uplift that we've talked about before. The independent multi-period case is essentially the same story because it's just a sequence of static problems. But when you get into the dependent story then it's quite a different situation and the interdependence between periods can upset this relationship. And in that case, the integer relaxation is both model dependent, as we'll see, and creates an uplift which is different and different prices than the convex hull**.** If you go into the truncated rolling process—I'll skip the independent multi-period, it just repeats.

The dependent multi-period problem is a little bit different. The integer relaxation problem is something that we could solve using, and we could apply the same principle that came from the case with the general convex case for this constrained integer relaxation, and that would deal with the difficulties in the prices. If you don't want to use the integer relaxation and you want the full convex hull story, then you have to have a look back there. Let me say I think you have to have. I think it's actually necessary, but certainly it's sufficient if you have a look-back mechanism to produce convex hull prices that go forward. This look-back mechanism means that when you're rolling forward, you have to treat previous decisions as variable. Not as some decisions that can't be changed. I think I will fear to say that this is a controversial position, but I think it's necessary for the pricing model.

So here's something which many people in the room know, but when it was first explained to me by Hung-po Chao a few years ago, and I've been teaching this to my students, I think this is really interesting. So I just repeat it for your benefit. You can read other papers that have made similar points.

But the basic idea is, if you start out with a non-convex problem. Here, the problem is caused by the fact that there's a startup cost so that if you produce nothing than the cost is zero. And if we produce something then the cost jumps. Then, you get stepwise increases in the total cost function and marginal costs.

If we take that problem and we solve the integer relaxation for that problem. And what I would consider to be the standard formulation, then you get the dotted line shown in this picture here, which is interesting and not so bad, but not exactly perfect.

If you solve the convex hull problem for that story, you get this picture. And that, in general, is a harder problem to solve. But it gives you the best convex approximation that you could have and, at the lowest, it minimizes the uplift in the way that we've talked about before.

What's interesting about this is that if you take the original model and you reformulate it in a way that is illustrated here, which, frankly, to me the first time I saw it didn't seem at all intuitive to me. But you can verify that the reformulation produces, where you're changing the intervals and you're scaling all of the intervals by the scale commitment variable, that that actually is still fine because it preserves the same dispatch problem. But it turns out that the integer relaxation of this case reproduces the convex hull story. So depending on how you formulate the model, the integer relaxation gives you different answers. And in the case Chao investigated, the different answers, if you satisfy certain assumptions on the objective function, then the convex hull and integer relaxation are the same. If you don't satisfy those conditions, then not necessarily true.

There is a series of issues that still remain, that are left out, that we could have opportunity to discuss later. One of them is in the general problem, this doesn't come up into convex problem, but in the general problem there is a choice that has to be made. This is for the purpose of the pricing model, but also for the dispatch.

So one way to think about this is that we should have a real-time quantity anchor. So that if we make decisions in period one and then we roll forward, that those decisions in period one still apply for the rolling forward story.

The other thing we'd like to have is real-time price consistency, which we've already defined. Now, for the actual commitment and dispatch, that the past decisions are sunk, and real-time quantity anchors are necessary, and they apply. It’s just physics. That's not controversial, but when you get to the pricing model that's a different matter. And we could have more flexibility. In the extended locational pricing, either as the integer relaxation, or as the convex hull story, past decisions are important, and the fixed costs associated with units for the past or units that are not committed or relevant in the pricing model.

Therefore, if you don't have full convexity and you're dealing with this more general case, it turns out you have to make a choice of which principle to apply to the pricing model, because you can't do both. Or, at least so far, we haven't been able to figure out a way to do both. At least, I don't think so.

And under the convex and IR, the pricing dispatch also has the characteristic that it deviates from the physical dispatch. So you get a lot of going back and forth, or should we be constraining the pricing model dispatch by the actual dispatch or should we just have the model constraint? These are topics that we can talk about later.

There is a lot of issues that go beyond just the formulation of the model. We know how to solve the convex hull problem in theory, but it's hard in practice. There's a lot of new work that's been going on, which I've mentioned here, but you'll hear more about that from other speakers, to make this better.

But I still remain to be convinced that we're in a situation, in general, where we can do this full rolling convex hull problem in a computationally tractable way. I hope it turn out to be wrong, but I think that's where we are. And then we get into the question of integer relaxation and other kinds of simplifications.

How close is close enough in approximating convex hull prices? It's an interesting question. And we can talk about that. There are a whole bunch of other issues, which I'll leave up to let you read about, but the most important one probably is the second one on this list. Both the first and second bullets here important. When you get out of the truncated assumption and you do the full rolling model now by construction, the prices and everything is going to change. You can't guarantee price consistency when you have uncertainty.

The same thing is true. If things are changing in the next period, then you have to figure out how you're going to deal with that. My view of this is that you want to impose price consistency in the case where you have no changes in the information. And then that fully determines the pricing model. So now you're done, and you just have to live with the effects of uncertainty as part of uplift calculations which are necessary to support the solution. And there's a lot of other things that we could go into, but I've talked too long. And I'll stop.

*Moderator*: Next speaker.

**Speaker 2**.
All right. Well, thank you for having me here today. I really enjoyed the summary. I wanted to add a little bit more context for the challenges that that we see here and then ones that we think will be emerging fairly shortly.

Just wanted to highlight—the resource mix within the MISO region has been actually rapidly evolving and today the largest portion of capacity in the footprint is natural gas. Just under half of the energy is produced by coal. That's in contrast to where we had a majority of energy produced by coal and only 7% natural gas.

We see that continuing and the expectation of continued portfolio changes is bolstered in part by looking at our queue, not all of which will get installed. But the sizable uptick in solar storage, hybrid plants, natural gas, etc., which is prompting us to rethink about how we offer our services and think about, in particular, how we think about pricing related to that. So our goal ultimately is to manage this change.

We're starting to think about solutions that are holistic across planning, operations, markets and then, of course, the enabling technology. Apart from the general shift in resource types in the footprint, we're also noticing a divergence among sub regions in their resource preferences. For example, some stakeholders are leaning towards sizable shares of renewables, others natural gas and others still are likely to have heavier reliance on coal generators.

As we start looking towards adaptation, we're thinking about ways to change our markets and operations accordingly, to adapt them and make sure that we're providing the same services. So, for instance, with that we're seeing a growing need to look at technology and our computational issues. And I know that was highlighted but I'll talk a little bit about it some more.

We've recently started a market system enhancement, a multi-year project which is helping us to make for a more flexible and upgradeable and secure system. Also with that we're doing research to try to enhance computational capabilities. I'll highlight that a little bit later.

We also have a resource availability and need initiative that's looking at resource adequacy, as well as emergency and scarcity pricing and the possibility of enhanced information prior to the day-ahead. We'll talk a little bit about that as well. But the idea that we can get information out there so that other participants can make decision-making and then the kind of decision-making that we'll have to have along with the clearing and dispatch decisions.

The challenge of non-convexities and timing are significant. I wanted to give two examples of that and also talk about the fact that, though we face them today, we're also expecting that to become more and more of an issue.

Not that long ago, in February of this year, operators had an experience where they were trending towards a shortage or scarcity in the south region and they called on three long-lead units that weren't committed in our day-ahead. But those units couldn't start a few hours ahead, and there were little additional resources available.

So the timing was key also here, because the load peaked shortly after that there was awareness of no-shows, leaving limited time for action. So I wanted to highlight an example where you really get into the issues of timing and sudden changes and how you can make decisions in that timing, along with what resources are actually capable of.

In addition, recently we started to look at how we can leverage resources like demand response better. And some of these timing issues show up, not just in the normal operations, but also in the emergency and alert conditions. We're looking at evaluating the lead times for resources that would show up in emergencies. For instance, if you have a 30-hour lead time for an emergency condition. How useful is that for us if we have a short turnaround?

Another notable item that I think was referenced was the implications that ramping can have both for the need to account for that across time periods, but also to make sure we have the flexibility to respond to the ramping.

This is just some preliminary analysis that we've done around different potential resource portfolios looking forward. With that, we see growing ramp across multiple time frames. This just happens to be four-hour and eight-hour, but we expect sizable growth in some hourly ramp as well. And so, again, highlighting that issue, that pricing issue and dispatch issue around ramping, we think that it's going to become more and more significant.

I just wanted to give those examples that non-convexity is hard, and ramping will likely increase, but that was all under the assumption that there was uncertainty. Once you start adding uncertainty, that makes the problems a lot harder, as was mentioned.

This is an example where we have historical as well as a couple of sample scenarios of different resource portfolios. We see that the load and wind forecast, this is the worst-case scenario because there are additive errors. But we see the load in one forecast error as a percentage of peak load, this is on a monthly average basis, or size of load that we have to deal with today. But going out in the future, we expect those to grow pretty significantly, as well. They're not as predictable by seasons, maybe, as they used to be.

So this idea that we'll have not just the ramping growth, but also growth in the uncertainty and the magnitude of uncertainty. In fact, our wind and load forecast errors in general, on average, have been getting better. But, obviously, when you have more wind or more solar, the total gigawatt impact of that uncertainty is larger.

And of course you get stuck in the conundrum of having to make a decision around resources, but the timing is off. So if you plan too far ahead for uncertainty, you're way off. And if you react too late, you don't have the resources to actually deal with the flexibility that you need to deal with it.

So, we started to think about system risk and how we can manage that and look to this concept of margin, which really is just a supply resources and obligations and how close we are to either emergency or loss of load. Ultimately, we're working to manage multiple elements here and some of these are more controllable than others.

If we look at the uncertainty in the variability around each of the sub items, you can see that the total contribution in terms of gigawatts again of both variability and uncertainty is growing. And so the stability of our margin, we would expect to also become maybe less stable. So this helps us think about that role of uncertainty, that role of variability, how we can think about looking across time horizons, but also know that the further we look out the higher uncertainty we have.

It also helps us think about different areas where we could help. Maybe add in a layer of more controllability or more support. For instance, looking again at the load resources and what they can do for the system and thinking about available generation, the availability, how we can enhance those aspects. For instance, dealing with outages.

Thinking about this changing portfolio, growing uncertainty, growing variability, we started a short while ago to help ourselves through various research efforts and my colleague is on the line here. She's been leading a good portion of these.

Then, as an industry as a whole, we've made really significant progress in enhancing pricing and efficiency and computational capability. We have further work, I would say, underway to address uncertainty. And so if we think about the convex hull, as was laid out, there's been some really exciting enhancements there to figure out how we solve that better, both in terms of the commitment and the dispatch problems.

Some of the work, I just wanted to add a reference here, some work that was recently published with the University of Florida and MISO, and how we can think about alternative ways to formulate the problem and apply that, potentially, both to the rolling window concept and to dispatch, but also to commitment.

We've just started some work with the Department of Energy through their PERFORM program, which we're very excited about. We're continuing work on a stochastic, look-ahead commitment. So, trying to think about ways that we can better quantify and manage that uncertainty. Instead of having a headroom factor that maybe is uninformed, we have more sophisticated ways to try to inform headroom. Maybe even more importantly, a potential reserved product that's targeted towards that uncertainty.

Then, when we look at the computational pieces. Again, the more complexity we add to this the more computational burden we find ourselves in. So we started three years ago now an endeavor with the Department of Energy Pacific Northwest National Labs. Gurobi, Ed Rothberg, was on the team and have started to look at ways to improve the day-ahead clearing engine. And we've got a prototype in place now which we think can get us up to 35 times faster, depending on the case, of course—but really exciting potential about new ways to think about the algorithm and the formulations, as well as even, in some cases, looking at hardware to help with this computational challenge.

So, again, lots of really exciting work going on. And I don't think we've solved it. I think this conversation today is a very good one because we're trying to layer in all the hard pieces. But I do think there's been some really exciting advancements

In terms of what we think needs to come next, we are, as I mentioned during those stochastic trials. It will be interesting to see about how we merge those. I'm skeptical that a stochastic unit commitment will be the first place that we land. I think that'll more likely be an advisory tool that feeds into other products and approaches.

We are looking at how do we reformulate the unit commitment problem and some of the dispatch problems. And so how do we apply those to additional advancements that we've done around a multi-configuration model. So, for instance, combined cycle or storage, so that we can maximize the flexibility of these resources and reflect their costs appropriately.

We started to explore the potential for an uncertainty reserve product, and I'm sure there'll be some fun discussion later. We're just on the beginning of that. I mentioned we're doing computational enhancements and we're continuing to do further, I would say, moving beyond prototype into the next stage while continuing to do further research.

There was a conversation about the rolling window. I think we've got to do more to figure out how. Maybe the answer is here today. But we've got to do more to bring that concept, along with some of the other pricing enhancements and see how we can pull these together as a package.

I mentioned earlier, we're looking outside of just pricing and we know that that also relates very much to the other actions. Outage coordination and pricing are closely coupled. And, similarly, resource adequacy enhancements and decisions. We're trying to look at those in tandem with some of the pricing changes.

I thought I'd throw out there some of the additional considerations and questions that maybe we can chew on, in the framing of this. There is a notion of trade-off around efficiency computation and uncertainty. I would say, from at least one operator perspective, that we're always told efficiency is what we aim for. But if you don't have a feasible solution or your solution is too late, then you're out of luck. So, thinking about how do we get a feasible solution first and then efficiency, if we have a major sudden rapid change, how do we make sure that we account for those and that we can cover those and then ideally improve in our approaches there, so that they're more efficient.

Then, how do we best reflect, related to that, the operator actions that are taking place today to avoid those reliability risks and make those more transparent and again price those? With that, we're also thinking about flexibility. How do we incent it? How do we acquire it? How do we incorporate the cost of both operator actions, but better reflect the cost of supply? There's a lot of good discussion about the role of load. In many ways, it's still very administrative. So how do you think about addressing that?

And, then, with that I wanted to bring in this notion about transmission and long- to medium-term behaviors as other elements of flexibility. So, the timing of outage scheduling and what signals that timing and, in terms of the transmission, we have ways to think about it for capacity. But how do we think about it for flexibility? If we're not pricing flexibility elements, maybe we could be doing better in signaling how transmission could better enhance flexibility.

In addition to that, I had mentioned uncertainty. I know that we could put it aside. But, given the growing nature of it and the importance, I do think it's a good question, how good can we get at forecasting. How does that fit into this time-dimensional problem? And who bears the costs when that forecast is wrong? We've had some good discussions that we're starting with stakeholders about the possibility of more information prior to the day-ahead, so that people can make decisions around must-run units.

That said, the further out you look the more likely your forecast is going to be wrong. Finally, I'll just give the perspective—with MISO, we have a lot of diversity in regulatory models in our region. I wanted to layer in the context, as we have talked about this, how do we think about this, both for competitive retail access states, but also more traditional utility models?

And then, finally, as we think about how we address these, just coming back to the principle of how do we make this effective but also simple. So if we think about, as an example, a stochastic unit commitment with prices that are based on expected value. Will stakeholders even be able to put their heads around that? It took them a while to get their heads around ELMP.

How will we be able to do this in a way that is as simple as possible and understandable as possible? So, again, looking forward to the discussion. Thanks for the invitation to be here.

*Moderator*: Next up is Speaker 3.

**Speaker 3.**

Thank you for inviting me to talk on this very timely topic. I'm going to try to present another approach to multi-period pricing. It was a great introduction by Speaker 1, to look at his table. I'm going to try to place our method somewhere in the second row, last column is general convex, independent multi-period, and also to show that our method could work if you also want to move it down to the last row and column for non-convex situation.

As the previous speakers mentioned, we are entering a new time when the system is changing. We deal with the very different load shape. The load shape caused more frequent ramping capability concerns. We see a growing participation of energy storage and also our problems with fuel delivery system and managing limited fuel supply over multiple days. All of this requires our considering interdependency among different timeframes and system dispatch and commitment.

Intertemporal constraints enforce operational limits between different time periods. We talked about ramping the state of charge constraints from opposite storage and the limited energy constraint, where you could actually exhaust your fuel prematurely when operators need you to provide energy in the later periods of the day or multiple days.

Currently, these constraints are only enforced over the market's time horizon, which is so relatively short**.** In observing all of this, we see that the importance of temporal coupling beyond the market's time horizon becomes more and more important.

If you look at today's existing approaches in different markets, we can see our single-period real-time market, which solves only one time period, and the linkages between different intervals are not considered. This is today implemented, so ISO-New England, MISO, PJM, and SPP. Also, multi-period single settlement, its real-time market clears for multiple time periods, although with somewhat short horizon. But the only first period is settled. Prices for later periods are only advisory. This is what is implemented by New York ISO and California ISO.

Some ISOs are also implementing a flexibility product and to procure additional ramp-up and -down capability by holding a portion of generation in order to meet the future load-following needs. I'm not talking here yet about uncertainty, but just to meet the load shape and provide load-following capabilities for the system.

We can use a flexibility product. That flexibility product is procured by the operator on behalf of the load. MISO and Cal ISO implemented flexibility products.

So what's the issues with existing approaches? First of all, the dispatch might not be economically efficient over a longer time period. Both single-period and flexibility product approaches optimize over comparatively short look-ahead horizon. Also the dispatch by the system toward future infeasibility. Then, as Speaker 2 mentioned, manual actions may be required on the single-period approach and that increase of the payments. Also, dispatch may lack the special incentive, so opportunity cost does not reflect the LMP, what Speaker 1 mentioned when you hold the unit out to prepare it for ramping for the next offer or for several other periods of time, the unit is incurring opportunity costs that are not being reflected in pricing.

That's why these prices are inconsistent with the action under single-period dispatch. Also, that opportunity cost is not compensated in the market and that creates additional uplift. That requires under a multi-period settlement approach.

So what we are proposing, we call it Coordinated Multi-Period Scheduling and Pricing, which consists of three different steps. If you will, the forward steps of the multi-period problem using forecasted system conditions. Then in real time, we saw a single-period problem that is guided by the forward step quantities and prices. That is what we call coordination. I'm going to talk about this in a later slide. Then we do separate pricing and dispatch runs. And then the settlement step, we settled forward step quantities at forward step prices, and an RTM real time step. When there are deviations, it's separate from the forward step. That's what we called a multi-settlement approach.

So if you look at the again at Speaker 1's table, this is a loose evolution of our work together with University of Texas, Austin that Speaker 1 refers to as constrained LMP.

So what's the benefit of this? First of all, it creates a dispatch was persistent serial time. Dispatch matches the forward clearing quantities assuming perfect foresight**.** I repeat this perfect foresight in the same way as Speaker 1 mentioned it, because I will address briefly the uncertainty parts later on.

It also creates price consistencies. Real-time prices match the forward clearing prices, assuming perfect foresight. It creates dispatch-following incentives because prices account for the opportunity cost of intertemporal constraints. In fact, the true marginal cost of resource becomes marginal production cost plus intertemporal opportunity cost. That comes from the optimality conditions for the profit-maximizing solution. It also reduces uplift payments for out-of-market actions.

We also achieve dispatch efficiency and reliability. So we produce visible solutions, again assuming perfect foresight. You can refer to details of this approach to the paper that's showing the bottom of this.

So, the forward step, if we have non-convexity, the forward clearing quantity and price constitute competitive equilibrium. The forward result is the best solution, assuming perfect foresight.

As I said, the true marginal cost of the resource becomes marginal production cost plus intertemporal opportunity cost. That comes from the shadow prices of ramping constraints. This is a stylized formulation of the forward step. I'm not going through the details, but it's a pretty self-explanatory. An important part of that, in the last row, where we show that intertemporal constraints linking dispatch between two intervals, I added to the formulation.

Here, again, is a picture that shows our approach. The real-time uses a single-period horizon. The optimal dispatch from the forward step limits the RTM step dispatch solution which is what we call coordination. This is a blue arrow that shows how we coordinate a single-period dispatch with the results from the forward clearing.

Then, as a result, we have a dispatch consistency. In the one single period clearing we matched the forward clearing, assuming perfect foresight. The real-time pricing incorporates forward intertemporal opportunity costs as offer adjustments. So we add to the production cost and offer adjustment for the intertemporal opportunity cost. As everybody knows. I assume that for a participant it's very difficult to figure out up front what intertemporal opportunity costs would be an embedded in their offers. In this case, we always add intertemporal opportunity cost into the clearing.

In this case, RTM prices match the forward clearing, assuming perfect foresight. So what we are clearing in a single period clearing, we achieved the prices that would be produced by multiple dispatch. So what about non-convexity? If an ISO wants to calculate pricing that reflects commitment costs, the convex hull pricing approach could be used. The convex hull pricing is delivered from the commitment problem that solves non-convex problem. It produces a multi-period price sequence that minimalizes out-of-market payments or uplift.

The good thing is that the coordinated multi-period market design should remain applicable, and the beauty of this would be that it would not only reflect the intertemporal constraints by ramping but also commitment intertemporal constraints in it. Unfortunately, at the moment, it would make computation pretty challenging to run for coordinated design which requires convex hull prices for forward clearing and identification of convex hull prices still remains challenging for realistic multi-period problems. But, as the previous speakers mentioned, several recent papers make progress in new computational methods to solve convex hull pricing. So if we, at some point, achieve a realistic time spent for producing convex hull pricing, that approach could be applied to account for non-convexities.

So what about uncertainty? If an ISO wants to go get quantities and prices to ensure feasibility under load uncertainty, we could use flexibility products that would account for uncertainty in the future, especially the forecast errors as Speaker 2 mentioned.

Conceptually, flexibility products have similar to reserves and the coordinated multi-period design should remain applicable with the flexibility products. On the other hand, you don't really need to get with multi-period pricing. You don't need flexibility to account for the load-following needs. The only thing I also have to mention is, first of all, the time horizon of the flexibility product is important. If it's too short, it wouldn't help much. If it's too long, it's very difficult to figure out the requirements.

Also, I believe that the flexibility project requires a whole continuum of product, depending on your specific system where you may need a 15-minutes product, an hour product, a four-hours product. So it becomes quite complicated, if you need more than one type of flexibility.

To conclude, I'd like to emphasize that intertemporal constraints are becoming more and more important with the future grid we are facing. The existing methods for addressing intertemporal constraints are inefficient. The proposed method allows a single-period market clearing problem to reproduce the multi-period market clearing result. That was the objective. The coordinated multi-period market design could be used with new emerging market concepts like convex hull pricing and flexibility products. As I said, if we achieve certain additional computational progress, we can move that method from the second row to the last row in the truncated rolling dependent multi-period.

Also, the coordinated multi-period market design can reduce the need for out-of-market actions, avoiding uplift for holding units for the future intervals. And that concludes my talk. Thank you very much.

*Moderator*: And, now, Speaker 4. Are you back from lunch?

**Speaker 4.**
No, but I'm ready for the snack.

My current job is at ARPA-E. Before November, I'd spent 30+ years at the Federal Energy Regulatory Commission. My caveat here is a little bit different than it used to be. But the views expressed are not necessarily those of ARPA-E or the Department of Energy.

Here's my obligatory announcement for the current agency that I work for. We are the Advanced Research Projects Agency-Energy, which is essentially designed on the DARPA model. I won't spend a lot of time on it.

As a little background, the Federal Power Act requires that all the prices for wholesale electricity transactions be just and reasonable. Historically, this has been interpreted as efficient market pricing. It's not the lowest price, but it needs to be a sustainable price, that is to say, the price has to be high enough to attract sufficient investment. It's not laissez faire. Until the 1980s, a cost of service regulation was used almost uniformly throughout by FERC to set prices.

In the ‘80s, the commission added on market-based rates, when they could find that the entity was lacking market power, and also added auctions with market power mitigation, which is what we're here to talk about today.

I'm going to take a slightly different tack than Speaker 1 and 3. But I will define the dispatch problem to be non-convex and stochastic. The whole convexity thing was covered by Speaker 1, and the interesting thing about this auction is it's both an auction for dispatch and an auction that produces pricing. The system requires instantaneous balancing and it requires reserves to address contingencies.

The ISOs have created a problem, or essentially solved the problem with virtually no delivery risk. The risk is almost always on price. Now, what is the role of the announced price? The ISOs, every five minutes, refresh a map that tells you exactly what the prices are. They used to be LMPs. I'm not sure that they still are, but they used to be LMPs. But the interesting thing about LMPs in a non-convex market is that LMPs alone have no claim to be market clearing. Yet you'll find the literature replete with the argument that LMPs are market clearing. If you're not going to confiscate offers, you need more pricing than the LMPs. Although the LMP is the low-cost entry price for the last period.

I say low cost because, in non-convex markets, there's very different entry levels for new generation and generation that isn't online at the time. Currently, to my knowledge, there's no look-ahead prices that are available and the models are not very transparent. An important issue that's been mentioned by the previous speakers is that operators are an important part of this decision and their actions have to be included in the pricing mechanism.

I call this non-artificial intelligence. But the idea that you would allow the operators to do this, and then end up not including what they did as part of the dispatch decision—arguably, you would change the reserves. Like in Speaker 2's example, if you called upon a whole bunch of long-start units and they actually started, you would then change the reserve margin to reflect the fact that the operators in essence decided that they needed these things to maintain reliability.

There are many different variations of look-ahead models. Speaker 3 covered them all. So, I'll skip this one.

Now the interesting thing is that everybody seems to think that these models, up to now, are not stochastic. I would argue that they've always been stochastic, although the electrical engineers have been able to hide this in various ways and turn it into a deterministic model. We have always honored what is called N-1 events, that is the ability of the system to survive when any one unit on the system generator or load leaves the system. These are fast-occurring and low-probability events.

They occur very fast. So you have to have units online and transmission capacity available as headroom, in order to deal with these. They consist of generator transmission contingencies. This was a favorite of the old vertically integrated utilities, because the solution to n-1 events was lots of capital spending.

What we've seen more recently is what I would call the slow-developing, evolving probability events. These are due almost entirely to weather: wind and solar, temperature and humidity. But the interesting thing about it is, the closer you get to the actual operation of the model, the better the forecasts get. That, essentially, then starts motivating a look-ahead model, because you have forecasts constantly. And the question is, how do they get better? The N-1 events do not get better with time as a general matter.

Now, you heard Speaker 2 talk about this. I think that you have to talk about the real-time market in context with the other markets that are available. I would include in that a week-ahead advisory scenario-based market, a day-ahead market with price responsive demand, forecasted renewables, ramp rates. By the way, once you put ramp rates into the model, the model automatically spits out the marginal cost of ramping and changes the intertemporal prices due to those ramping constraint. They can be rather dramatic at times.

I would also argue for average incremental cost prices. These average incremental cost prices are settlements without make-whole payments. They essentially indicate an entry at a higher level of cost where you would displace an entire unit that has been committed and has operating fixed operating costs. The LMPs still give you the signal from the marginal entry costs.

Some people argue for only announcing one price. I would continue to announce the LMPs because they are valid entry prices, but they are not the only ones. Then you get to the rolling horizon market and, as I see it, it is the ability to forecast renewables better that motivates this rolling market.

Also, in both the day-ahead and a real-time market, I think we do ourselves a disservice not to include topological reconfiguration. I think the best example that I know of is the SPP example that was developed by SPP and Pablo Ruiz, where, in a significant wind event, Pablo was able to find a reconfiguration of the topology that reduced the curtailments that wind was experiencing.

Interestingly enough, SPP cast this as a reliability issue, because they no longer have transmission overloads. It is also a market efficiency issue. But that's not the way that it's pushed. I think this is something that's going to be absolutely necessary, especially for these evolving events where you either lose a lot of renewables or gain a lot of renewables. My feeling is that topology is going to have to be reconfigured. It's cheap, but it's very computationally difficult.

Price response to demand is something that I think is very important. My feeling is that, in the first 100 years of electricity, generation followed load. I would characterize the next century as load following generation. That is to say, we're going to have this large tranche of renewables, that it's going to be variable depending on the weather. And you have this huge reservoir of both storage—building envelopes, heating and cooling devices, data centers—that can change their consumption, that can move it over time, with virtually no effect on the service that the electricity is providing.

As an example, I would say, the data center could manage itself much better by bidding into the market. What is absolutely essential, that would be high valued usage, and what can be moved to another time. And the example I would use is updating Google Scholar. Now there may be some people out there that need updates every day or every minute. But, as a general matter, most people could probably wait a week to see their new publication listed in Google Scholar.

Now, one of the big issues with the price-responsive demand is aggregation and communication. That allows it to directly participate. It can indirectly participate by essentially creating a program for it to respond to frequency changes and voltage changes, in which case it does not have to communicate directly with the ISO. Both of those are still problems to be worked out.

The key here, I think, for everybody is we, first of all, want an efficient dispatch for energy and reserves. That brings up the question, what is the role of selfies? And when I say selfies, I don't mean the picture taking kind. I mean the self-commits, the self-schedules and the self-dispatches. None of these are efficiency enhancing, or they are only efficiency enhancing by chance.

So you have to ask yourself, should we put the selfies on the same pricing regime that we put entities who bid and offer into the market of the non-convex configurations of their generators and get enhanced pricing? Should they be on the same par?

Another question we need to answer—and I didn't hear a lot of discussion about it—is prices, in the economics textbook, should be signals for entry and exit. As I said before, LMP is a marginal entry signal. But it's not an incremental entry signal, where a new generator would literally completely displace another generator that's more expensive. Of course, prices are for website math and entertainment**.** I’ve found myself sometimes in the afternoon just watching the prices on MISO and PJM to see how they change, especially in in extreme weather events. They're very boring most of the time.

So the models are stochastic but there are all kinds of problems that go into choosing the stochasticity and how you represent it. As I said before, some ISOs already do different forms of stochastic modeling and decision making, except that they don't follow the normal textbooks. Some operators are offered multiple different scenarios and the operator chooses which one it's going to implement in the dispatch model.

There are two-stage stochastic models and all kinds of other things. Also in the model, you have to decide what the horizon is, what the interval size is, what's de-committable, what’s committable, how to include minimum run times, minimum down times, then again on your interval sizes. And how to introduce topology optimization and soft constraints and how to represent dynamic constraints. This is true, actually. For the day-ahead model, also.

Computation and communication—that's a difficult problem hasn't been solved yet. Probability distributions come to us with multiple events and multiple probabilities. They all can't be digested, especially by a look-ahead model. You have to reduce the number of events to a manageable size. Although I have not done it myself, I've seen other people do it and it's not an easy problem.

At the same time, we're adding more detail to make the market models more efficient, that is, new combined cycle modeling, new pump storage model, topology optimization. There's got to be this trade-off. And if we're really looking for the efficient dispatch, you want to include more and more realism or get closer and closer to the actual operation of the model.

Then, for price-responsive demand it’s aggregation and communication. There is hope, as Speaker 2 pointed out. Their research projects have found a 10X improvement in solution times and sometimes up to 35X, which is quite impressive. That research will continue.

Finally, the prices. Question is, what are the prices telling market participants? Are they advisory for entry/exit bids and offers in the future? Again, the low-cost entry signal is LMPs. I'm not sure that that anybody still publishes LMPs. Maybe they do.

But the average incremental cost, which actually in the latest formulation looks a lot like something close to the convex hull with two exceptions, which I'll talk about. But the interesting thing is that today's ELMPs are neither fish nor fowl—they’re not LMPs and they're not full incremental entry prices. So the question then becomes, what are they? And what functions are they performing? They're not revenue adequate and they produce uplift payments.

My closing question is, what would the convex hull be if we penalize self-dispatch, as most ISOs do today? Every auction model that I am aware of doesn't pay people to stay on the dispatch that they were given or whatever they won in the auction.

And the other one is to not let non-dispatched unit—and that means units that aren't on reserve—set the price. It would be interesting to see what the result of those two changes would be to the convex hull model. Like I said, the latest iteration of the average incremental cost price looks like it has a lot of the properties that the Hung-Po method has. It's certainly a relaxation. It doesn't stray very far from the optimal solution, which I think is good.

With that, I'm done.

*Moderator*: The agenda calls for a 10-minute break. We'll be back at 2:40…

If we're ready to start, we'll go to the first questioner I saw.

***Question 1*****:** Yeah, really fascinating presentations. Thank you to all the presenters.

I want to pick as a point of departure Speaker 4's comments about demand response and price-responsive demand. Because I 110% agree with what he said on that. But I also think that that's where so much of this starts to become extremely tangible.

I'd be interested in all the presenters' reactions to this, but it's what also makes me start to get very nervous when I hear talk of buying a flexibility product or buying flexibility products as opposed to paying for or properly compensating flexibility.

I think that two problems arise. One is definition, and Speaker 3 referred to this when he talked about the fact that flexibility is not one thing. It's a continuum and what kind of flexibility you need is going to change from moment to moment, from system to system, and it's going to evolve over time.

But it's also a question of access. And when I hear talk of buying flexibility products, what I really here is a slippery slope toward all the problems that have been created for capacity markets. Such that they drain compensation away from the one market that the vast majority of flexible demand or price-responsive demand is likely to have access to, which is the energy market.

In so doing, and in buying things years in advance by definition, they have the effect of foreclosing on the opportunity to leverage and exploit those opportunities. I wonder if I'm the only person that starts to get nervous when I hear that kind of talk. While I know that the incredible challenges that we all face, that have been raised here in getting multiple pricing and multiple dispatch right, nonetheless, it's just hard to me. It's hard for me to underestimate or understate the importance of focusing on that, as opposed to just defaulting to buy years in advance something that is maybe not denominated in capacity, but it's nonetheless going to be as exclusive and as poorly defined as what we've been doing for capacity markets.

*Moderator*: Who on the panel wants to take first crack?

*Respondent 1*: Brilliant observation. I agree with you completely. I tried to mention this in the talk but let me try to jump on the bandwagon. When you set aside the uncertainty part of the story, and you're looking at the load following, the point that I should have emphasized more is, when you're looking at what Speaker 3 referred to as load following, then the prices that come out of the intertemporal optimization—no matter how you derive them—through his method that he talked about where he edited the prices of constraints in our temporal constraints or you just solve the full optimization problem, the prices support the solution.

Therefore, profit maximizing responders would do everything that we think about with the prices that support solution. In particular, this provides incentives for making sure your generation is flexible so that you can ramp up quickly enough and take advantage of the opportunities that are going to be out there.

When you set aside the uncertainty part of the story, I think there's no need for that additional products. And the prices would be seen by the loads and everything would be efficient. I think that's a good solution. When you add the uncertainty back in, this is what I referred to as operating reserve problem. But that's just a generic term, where you're saying, "OK, now, it's not just following that expected profile that we looked at, but we might deviate from it significantly in a very short period of time when we've not scheduled things for it and all the other stuff." And so we need to have some capacity available that we can respond to quickly and that's what is the scarcity pricing for operating—

*Moderator*: We lost you.

*Respondent 1*: Somebody muted me.

So, what I was saying is, operating reserves are a different kettle of fish. The load following and the load-following story would be taken care of by the dynamic pricing that we're talking about. And you don't need a separate product to deal with the duck curve sort of problem. That's taken care of automatically.

The operating-reserves story, now you get into this continuum that Speaker 3 talked about where you have multiple kinds and how far are you looking ahead, and capacity and how fast can you respond and so on. We're not going to get that perfect, I don't think, soon. But I think the way it's done in ERCOT is representative, and the procedures that are being worked on in PJM, are representative of how to do that and do that better in the future.

Those prices, incidentally, those prices go through to demand, so demand response sees all of those kinds of things, even if they haven't bid into the dispatch, they can take advantage of it. And then if they can bid in, that's fine, also. So it's all internally consistent

*Moderator*: Any other panelists?

*Respondent 2*: I think the exploration of a reserve of some type is just that, exploration. Because I think it is problematic, just as Speaker 3 said, that you have to deal with the timing. What's the right timing for flexibility? Then, we're struggling here with the idea that, whether we like it or not, operators are creating headroom to deal with this.

So the trick is, how do we get this in a way that is more explicit? I agree, we sort of said here's an approach, set aside uncertainty. Well, I want to push back and note that we can't set aside uncertainty. It's growing and it's real and it's sizable. I don't know that we have an answer. I'm hesitant to leap into a reserve product or a flexibility product, too, but it's something that we're going to have to deal with.

*Respondent 3*: If you don't have any other means to create flexibility, we need to do it as an operator, to deal with some abrupt events that we don't foresee. But, also, we all know that market is not a true market if you don't have a true demand participation in it, as Speaker 1 said. Unless we expose demand to high prices and let them actually sell what they buy, we don't have a good solution.

*Respondent 4*: I just would add one thing. Most of these enhanced pricing regimes increase the price in the market, which ends up lowering the demand curve in the capacity market—which hopefully in some kind of equilibrium drives the price in the capacity market very low, so it becomes either unimportant or unneeded. Unlike ERCOT, who just doesn't have a capacity market.

*Questioner*: Your lips to God's ears.

*Moderator*: Onto the next person.

***Question #2***: Well, thank you, that was really interesting.

I have two interrelated questions that I claim are interrelated. Anyway, both rather non-technical. Listening to all of the panelists, it seems like look-ahead pricing or multi-day, multi-interval pricing would make sense given the changing resource mix in the various markets. I'm curious as we look forward, I guess, starting with Speakers 2 and 3, what are the biggest barriers to implementing this? Is it a design issue, with all the complex design choices you have to make? Is it software, and all the money and time it's going to take to program it? Or is it acceptability, with the market participants and the stakeholders and the regulators? Those are three different things.

Then I guess a second question for all the panelists, or any of the panelists, is this a kind of thing where you think some market will figure it out, and that will become the standard solution like LMP? Or do you think we'll see all kinds of different experimentation and then we'll go into a Harvard Electricity Policy Group in five years and have to spend like 45 minutes hearing all the different flavors in the different markets?

I guess I have a preference for symmetry, but you're all building on top of markets that are already not exactly alike. So I'm curious. What are the biggest barriers to actually acting on this? And how do you think it will unfold, if you had a crystal ball?

*Moderator*: Who wants to handle that first?

*Respondent 1*: I'll chime in. I think one of the questions is the intervals and the settlements and how many times are you settling. So you're adding a lot of weight on that settlement process, possibly, depending on how you do it.

The other aspect that I think I would want to look at further is the timing. What's the appropriate timing? Because if we have ramps that we're trying to deal with on the duck curves, but you go further out, I'd really want to understand that uncertainty profile in the trade-off between those elements. I think it's very helpful because you don't want to veer off target and that look ahead really helps you with that.

But I'd also want to want to understand how much uncertainty do we expect in those time horizons, so that we can we can think about that, as well.

*Questioner*: That's a design issue. But you introduced an element that I didn't cover, which is uncertainty about the problem we're solving before we can even put in the intellectual capital to solve it. The problem is evolving.

*Respondent #1*: Yeah, and I don't want to imply that we couldn't move forward with something like a look-ahead now. It's just that I do think we're going to see both ramping and uncertainty, and I'd want to look at the timing issue to that.

*Respondent #2*: Here's my opinion. So, again, I think how fast you move with that approach is footprint dependent. So what I will be waiting as ISO New England, for example, is one, it depends how much penetration of renewables you have and how bad your curve is. Number two is, if we have a significant amount of storage coming in, when you need a lot more, you have a lot more coupling among different intervals.

Another thing is, as some of you may know, we are approaching our energy security implementation in the near future and that may require a longer period of time look-ahead with the additional products that those ISO New England proposes. It may actually trigger us to implement multi-period pricing. At the moment we don't feel we need this urgently, because we don't really see a lot of inefficiencies with today's ISO New England state. That would be my answer. In terms of computational, it's not that bad.

*Comment*: One of the things we're seeing in SPP—and for folks that don't follow SPP closely, we're at about 30% renewal penetration today. So, this is a real problem now. SPP operations has what's called an uncertainty response team and their job is to evaluate both the mid-term by the next few days, as well as the intraday needs of uncertainty. And what they do is they do their analysis and they'll pass it on to operators to either pre-commit resources, long-start resources, pre-day-ahead, to see if they need resources there. The long lead resources.

Or what they'll do intraday is, they're acting to evaluate what near-term would be a couple hours out. Do they have enough resources available online to meet a range of uncertainties? And so I think this gets to Speaker 2's point. They're taking actions to ensure the reliability and so they're doing that. I think that was Speaker 4's point earlier is that they're going to get it. And they do it.

The problem we're seeing is these actions are all out of market and they're obviously affecting the price. When you do commit these typically quick start resources, they're just going to sit around waiting and sometimes the uncertainty is there. And sometimes it's not. From our perspective, we're more fans of the products.

The ramping product should hopefully pass FERC in the coming weeks here. And then the next up is SPP is working actively on an uncertainty product they do have. They've evaluated different time periods—one hour, two hours, four hours. I believe the current timeframe they're looking at is about an hour to get what they think is necessary. So these are real problems. I think the problem we see with putting it in the LMP price, and we see this today, is that people don't know what that price means. Sometimes people will not take action as a result of that. When you have a reserve product or a ramp product or uncertainty, the thought is that will be very clear what they're doing versus the LMP, which can capture rent constraints, as well as other things. That isn't clear. So that's what we're seeing. So we appreciate the discussion today and we're happy to provide more insights. Thank you.

*Moderator*: We have another question.

***Question #3***: Yes, thank you. I have appreciated the discussion. I just want to make this point that's not in my wheelhouse, which is I think a lot of what can and should be done in the different ISOs to address the different intertemporal types of problems and improvements to pricing and dispatch and unit commitment that we've been talking about is very dependent on advances in the ability to speed up solution time.

I know that people who are much smarter than me about these things--Speaker 2 talked about a little bit, Speaker 3 and Speaker 4 talked a little bit about the research that's being done on how to solve these problems more quickly. Now, how do you initialize them to solve more quickly? We're seeing that, for example, in Ontario, where they're proposing a pre-dispatch engine that runs hourly, with up to a 17-hour look-ahead prior to real time. They want to run that every hour, including market power mitigation**.** There just are computation time limitations on their ability to do that. I feel like I'm hearing about these problems and I'm thinking now there will hopefully be some breakthroughs on how to solve some of these problems more quickly.

Once there are, then I think that there'll be questions in the different ISOs about which problems should that additional computing power be applied to, because of the potential for cost savings, which may differ by region. So that's just what I wanted to add.

*Moderator*: Thank you.

*Respondent 1*: I think that the work that's been done at MISO and also by Gurobi demonstrates that we can get speed-ups in these markets. Although, inevitably, the speed-ups come with better models for modeling things like combined-cycle plants and pumped storage, that then slows the model down again. So I think to address the earlier question—I didn't say this when I was at FERC, but I'm a big fan of some standardization and some consistency and some symmetry across the ISOs.

But what you may see happen is that in MISO and PJM, for example, I think each has over 100 combined-cycle plants. And getting combined-cycle plants to efficiently dispatch is an important problem for them. I'm not sure how that exists in other ISOs. So the implementation of whether or not you introduce certain aspects into your model is probably based on the gains that it gives your market. You're going to have to essentially capture the ones with the most gains, so that the models may look different. Certainly, in the west, storage is a very important thing to model properly, but in PJM and MISO storage might not be a big thing to model.

One of the things is wind variability—SPP, as he said, has got it already and they have to take care of that problem, probably that's one of their most important. PJM and MISO are looking for it coming to them. So I think that that the implementation essentially takes place, depending on what is the higher-valued thing to do with your model. But I think there should be some speed-ups coming.

Probably the most important thing is to speed up the worst-case analysis. Some of Speaker 2's slides said some of the improvements are like 35X, but then some of them are not anywhere near 35X. But you want your day-ahead market to solve and your look-ahead, real-time market to solve within a certain period of time. Even then that's not guaranteed an optimal solution. So there's a whole bunch of interesting numerical problems.

*Respondent 2*: I think there's maybe a couple of things to add to what you're saying. I think two really important points—one is that a lot of these timing issues are associated with the mixture of resources that show up at a given moment right. Then, the solutions that you do are also dependent on the resource type. So, partly why we've been interested in combined-cycle units and even pumped hydro—some of the work that my co-author at MISO is leading there is because the resources are available and adding that incentive for flexibility is important for those resources.

So, I agree. I think the solution and the problem are very much dependent on a mixture of resources at a given moment in time. Then, in terms of the computational components, again, that work, I think, really is exciting for a couple of reasons. One is that it is enhancing the performance through speed and, I agree, benchmarking the hard cases is really the important piece there, and I think my co-author has put out a paper recently on some methodologies for benchmarking, because that's a hard thing to do. But the benchmarking on the hard cases is important, but apart from the performance improvements, what's exciting is the overall methodology of that approach allows you to compete different algorithms and different techniques against one another.

So this linear sense of how we solve isn't how we have to operate. And we can start to incorporate additional data analytics and other elements. Now, you've got to be careful with that because it's harder to show that you got the absolute answer, but they can really help speed things up. And I think we're just opening the door to what we can start to do there. But, again, the more we open it up, the more we add to it and we take it away.

So we've started to add more complexity through our resource modeling, and you can see the bandwidth decline. So, it's an important question about how we balance it. And I agree, it is likely to be regional based on the nature of the problem and the nature of the answer.

*Respondent 3*: May I comment? I think, as everything in the world, we are trading off between computational capability and complexity. The more physics you add in your model, maybe the closer you are to the physical capability of your fleet. But, on the other hand, you may screw up. You have so much non-convexity, you screw up your prices big time.

You always have to make a good choice or tradeoff between how complex your model is and how much you want to disregard for the reason of creating a better pricing system. One example is in other traditional markets a lot of things are internalized instead of centrally decided.

For example, also, instead of having three-part bids, you can offer one-part bidding, which would remove some of the non-convexities that we are dealing with. And the same thing with some other physical properties. Also, I would say that if we expect, one way or another, adding additional flexibility in the system, certain deviations from the physics could be compensated by that additional flexibility. Again, it's my personal opinion.

*Respondent 2*: I know my co-author is on the line here. Did you want to add anything to that?

*Commenter*: Yeah, so, on from the computation side, we have done a lot with this project. So, one thing we did is, like we just mentioned, we try to leverage it. For example, historical commitment because we're solving commitment every day. And so you get a lot of historical commitment and, really, we're trying to figure out how to leverage that.

And then, just adjust a small subset of that. But the tricky part is how to do it right and not stuck with the sub-optimal. Then, for current market model, we've made really good progress. But, then, we look at the future, it has common cycle. We're actually in the process of preparing the filing for the configuration-based, common-cycle model. But on top of that, some of you already mentioned, and they wanted to 15 minutes interval that had to better prepare for the variation on flexibility. That makes the problem much harder. Because with 15-minute interval you have a lot more ramp constraints, like binding ramp constraints. So the problem for a hard case could be 10 times or, even more, 50 times harder. You need that much more time to solve. And so that's basically the thing we're trying to tackle for this next the phase.

But, on the pricing side, it's similar. The commitment and pricing problem, they are related and some of the investment on the console pricing was actually beneficial from the commitment formulation improvements. I could derive the combined-cycle formulation for the generator. But just when we feel pretty happy, we're almost there, we are able to derive the full combined-cycle formulation for current generator and be able to solve a day ahead. Then we'll be ready to implement derive the combined-cycle and configurating the combined-cycle. That will require us to derive a much more complicated combined-cycle formulation for the upcoming results modeling. Then the storage hybrid resources will all make things much more complicated.

*Respondent 2*: I think that's a great example of how you layer these on to each other. You get the combined cycle, you get the look ahead, you get the convex hull and you put them all together and now they are enormously computationally challenging.

So the question is, how do we choose which aspects to eat up that bandwidth sooner, while we're advancing the capability? That's a good point.

*Moderator*: Any other comments from the panelists?

*Respondent 4*: I was thinking about one of the questions earlier, and what do we need to do to make this transition. The computational feasibility is an obvious challenge and making reasonable judgments about how to simplify the problem versus make it more complex and do all these things is a real hard part of the story.

But I worry about the other part of the problem, which I mentioned in my talk, but I didn't emphasize probably enough, which is that there are certain conditions we all will impose on the models that we adopt. I had a list of things like feasibility, which is related to this computational question. So we should be able to actually do what we say we're going to do. That would be a good thing. And economic efficiency for the actual dispatch and then making the prices consistent as we can with the actual dispatch. So this is the kind of thing we talk about, what the operators do. We should price it. If you don't price it, you're going to get yourself in trouble.

But other ideas are also extremely important, like that the prices and compensation methods support the dispatch. You want to make sure that when people are faced with these prices and payment rules that they then have an incentive to do what we think is the economic dispatch. In other words, that they have an incentive to comply with what the operator has been calculating.

A lot of these things worry me because people forget about those kinds of constraints. And when you adopt all those constraints, you get down to not a single method, because it depends on the nature of the problem and all the things you're dealing with. But you eliminate a lot of things that you can't do otherwise.

So I think this is going to be extremely important, that you have to be able to support the solution with the pricing and compensation method. Uplift is partly the answer to this problem always, because it’s strictly a logical matter. If you randomly choose the prices and then you pay uplift to get everybody back to where you want, then that supports the solution.

That's why trying to find prices that don't require very much uplift is one of the most important elements that you want. In particular, if you could minimize the uplift that would be good. And that gets you back to the convex hull story. But in some of the proposals we’re talking about, which people are worried about, we have things which are out of market. So they're being paid things so that people aren't seeing the right signals. Then, you get all the perverse effects that we’re trying to avoid. Then, sometimes we're talking about things where we don't pay people any uplift because we think they shouldn't get it for some reason. Then, they have an incentive to do something different. And they do something different with their own schedules to take advantage of that opportunity.

Most of the situations that I'm familiar with are things that have unraveled seriously. It's because we forgot some of those basic economic principles about making sure the prices are consistent with the dispatch and support the solution and so on.

And this seems to me to be a place where the Federal Energy Regulatory Commission has a unique role, or in Texas, the PUC has an important role, because they’re overseeing that market. Because it's easy to forget these ideas, and if somebody's not constantly reminding them that they have to have systems which adhere to these principles, we're going to get ourselves in trouble. I hope we don't create more problems by going to all of these other products that we're trying to create, and we don't price everything right and then we miss lots of opportunities.

*Moderator*: We have another hand up next.

***Question #4***: I appreciate the presentations and all these ideas, having been working with some of you on a lot of these issues going back many years. But I think that the computation issue came up. Speaker 2 brought it up. But there's also the issue of transferring data between databases. And I know that that that's been an issue, at least was an issue at PJM, I would say, in the past. So is it the computational issues which are very challenging, or do we also have to solve the database issues that go along with it so that we can access quickly and not have to move databases around, so that we can speed up the computation times? They're related, but just getting a sense of the panelists, what their thoughts would be on that.

*Respondent 1*: I agree. I think it's a combination of software data transfers and hardware and the whole thing. And the iteration is actually what's an interesting component of that I know my co-author will have thoughts on this. I will also pass it to her.

*Commenter*: Actually, historically, when we look at the total solving time. For example, at MISO, the integer programming solving time is about 20 minutes. It needs a few iterations. The time for passing data, passing with some other applications, it's actually much longer than that. And for example, historically, we exchange with the security analysis is through large CSV file. That's very slow. Then, even the network application itself, it's not very efficient. And so, through our HIPPO work, we actually were able to improve all these packages and can directly talk between the software and the security powerful analysis package. It only takes like 10 seconds to check the security once solving continues these 36 intervals for any of the solutions. That we're about to just call it directly from the solver, so that you can solve everything though one pass, instead of like today in production, you have to do multiple iterations.

I think there's great opportunity to improve on these processes—data transfer, everything's greatly improved, you can use more time for the hardest part, solving the mix integer programming problem.

*Respondent 2*: Let me add to that. The way the data is presented to the algorithm, it's been known for years can make a huge difference in the way the problem is solved.

In moving in the first grade optimization challenge at ARPA-E, one of the things that the entrants had to figure out—first of all, the computer that was given to the entrants had many nodes and many cores, but, in transferring data between them, there was essentially a constraint that some of the people who weren't familiar with a high performance computing didn't understand. Once they understood—

So, yeah, that simple data handling problems can be really important. And, for example, how much information can you pack into the cache memory can mean a factor of 10 to the two in terms of computing time.

*Respondent 1*: I think if we're going to embrace more data analytics, I think it'll also become more important. So, even under the model that we have today, the iteration and the configuration for the hardware you have is important. But if we're going to try to leverage additional techniques, I think it will be hugely important.

*Respondent 3*: Yes, there are two things. One thing is computational efficiency of your algorithms and another one is exchanging data. Everybody knows in high-performance computing there are certain overhead that after a certain number of nodes, overhead is prohibitive, so you can't really add any more nodes to your company HPC, because it just would not give you any benefit.

You're familiar, probably, with the previous generation of the software. The new generation of the software coming from vendors now does in-memory transfer of the data. Even between EMS and the market side, the transfers become much more efficient. Also, if you're solving security constraint problems where you need to exchange constraints between two different components of the software. It used to be done through the files and it would have to travel through the network. And now, it could be done in memory. The memory is not that expensive anymore.

On a computational side, MISO and PJM, as being very large systems. were hit first. Because you can't really produce a real suboptimal solution. Your reality gap is large. You have to have more and more time in order to be able to reach an acceptable gap. And that's why MISO at the moment is struggling with it, because their system is very large in size. That's what HIPPO is and that's what the ARPA-E competition is that's trying to resolve these kind of things, where you apply new computational approaches. So we're hopeful that, at some point, there will be a breakthrough and we are observing some analysis. Computational capabilities are also increasing every year. As R&D people, we have to be optimistic.

*Respondent 4*: This data transfer problem is a very serious problem. It's an even bigger problem when we go down to the distribution system and try to do real-time pricing on distribution systems. Just because of the scale, number of locations devices and all that kind of thing. A lot of work is going on in that area as well. But my current take and understanding, which may be incorrect, but I'll share it anyhow. This is that in theory, it's easy. We just don't know how to do it.

*Questioner*: I can follow up with that. I'm working on a proceeding in Alberta right now on some of those things in the comments. I would think that the distribution system, even though there's more pricing points, might be easier because we don't have any congested constraints as a general rule, given the way the system is designed. Usually, it's a radial network designed to fit peak.

So, really, all we need to do is worry about marginal losses, not that that’s trivial, but it's a little bit easier than a mesh network like the high-voltage transmission system. I'm just curious, you took me by surprise with that comment.

*Respondent 4*: This was a factual question, but my understanding is that you have to do with reactive power. You have voltage constraints everywhere on the distribution system, that's what's driving how they're running the system. And you're going to be compensating people for doing things in order to provide reactive power voltage support. We know how to do that in theory but in practice. That's a very large data-handling problem.

*Questioner*: OK.

*Respondent 2*: You can add to that unbalanced power flows. The Three-phase power flow is not balanced at the distribution level.

*Respondent 4*: I don't really think about that. That’s even harder.

*Questioner*: Is that because you're switching at lower voltage?

*Respondent 2*: You just, basically, you split the lines. The lines go off in different directions, the phases go off in different directions.

*Questioner*: You basically split everything off into single phase.

*Respondent 2*: Of course, add to that the fact that most people don't even know what their distribution system is, except they have a picture of it.

*Commenter*: I think with modeling on a computer, you have a lot of opportunity for the multi-threading and parallel computing. So, like my own example under security analysis, historically, you don’t mind an iteration to 5-10 minutes for the MISO model. But when we leverage all this powerful computing, it's actually not that hard to do. But we're able to just solve it in 10 seconds. That's just a huge difference. So, you have to work with the vendor and then to really push for the for the improvement of the efficiency.

*Respondent 1*: I think the architecture of the solving of the problem is huge. And if you can get stuff in parallel, it's huge.

The other thing that I think was interesting about the DER, maybe less from a distribution system and maybe more from a wholesale market system is, and I don't think we have the answer to it yet, as to what extent do DER aggregations or load actually help with some of the non-convexity problem.

So, on the one hand, you've got volume and scale that adds problems. On the other hand, if they're more continuous, what does that do to our computational problem? So we started to play with that a little bit. And I don't think we have the answer yet.

*Questioner*: I just saw something on the chat room. I'm going to channel that for a moment. Have you thought about price responsive demand which is a little bit more continuous not as lumpy, as opposed to demand response?

*Respondent 1*: Sure, whatever you want to call it. The controllable load. Let's call it that. How's that?

*Commenter*: The problem eventually is to get everything to be like a price-sensitive demand, then that would be great. But if you have a mix between that and the non-convexity, that becomes very hard.

*Respondent 1*: Yeah, so it might get harder before it gets easier.

*Moderator*: Are there any perspectives from any of the representatives of the other ISOs, who are here? Like Cal ISO or PJM.

*Commenter*: If you don't know me, I work at New York ISO. We are facing many of the same challenges that ISO New England and MISO mentioned. We are very much looking into optimization techniques and how to decrease run times, but we're also thinking hard about the latency issues.

Data latency issues are a big concern of ours, when we start thinking about the problems that California is facing. We think hard about, how old is the forecast data that we're actually pumping through these models before we actually feed it off to the dispatch? And, therefore, how much uncertainty does the five-minute dispatch have to deal with?

That's a little bit of a new focus for us, naturally, because the state is very ambitious on clean energy and how we're going to get there. A lot of worrying about out-of-market actions and how to treat thermal resources when you get to a resource mix, where many, many megawatts of reserves are being carried on thermal while the energy is being provided by intermittent and storage. So those are some of the things we're thinking about.

I do think that demand-side activities and participation is going to be really, really important, especially with price formation, but I don't have a silver bullet for anybody.

*Moderator*: Next question.

***Question #5***: I was encouraged to come back to this product versus price issue, which was a conversation going on in the chat room.

We talk, especially just this this immediately preceding conversation about computational problems, it reminds me of the webinar, the ESIG webinar that I was on. I was one of the panelists and Speaker 4 was one of the commenters, about how much optimization is too much.

Someone introduced what I'll refer to maybe somewhat pejoratively as the operator problem. Speaker 4 referred to that, as well. You can't really have a meaningful conversation about this topic, without factoring in what the operator does, in fact, on the ground, while acknowledging that operators do things based on all sorts of different incentives, a lot of it having to do with just making sure that they don't get called on the carpet at the end of the day.

It worries me, again, we've got capacity markets writ large, where the operator, the ISO/RTO, is coming into a situation where you've tried to design a market to drive for efficiency and optimize cost, and then the operator, out of a desire for confidence and comfort and the ability to sleep well at night just kind of overrides it. So, instead of operating as ERCOT does with 11, 12, 13% reserve margin, you've got ISOs with a 25, 30, 35% reserve margin and no good reason why there should be any difference, much less that much of a difference between the two.

So you get this product versus price issue on flexibility products for flexibility compensation. I just see the same thing happen. Maybe it's a governance issue. Maybe it's an operator compensation issue. I don't know. There are regulators on the call. It'd be interesting to hear their perspective.

Someone chipped in with the observation, which is fair, that there are some ways to address this which control back into the operators' hands, whether it's PJM's price responsive demand product or various other forms of dispatchable or controllable flexible demand. But, again, I think that leaves maybe most of the potential sitting on the sidelines. I'm interested in perspectives on this, again, what I'll call somewhat pejoratively the operator problem, and how it might actually just render kind of irrelevant a lot of this very, very important and very complex price optimization work that's being done.

*Respondent 1*: The comment I'd like to make on the operator problem is that, right now, if the operator dispatches a whole bunch of units that have high minimum operating levels, the LMP price goes down.

If, in fact, you take those units and you essentially say, "All right, you scheduled all those units. We're going to put them into the reserves acquire." That, to a great extent, prevents the price from going down because you have to have those in your reserve margin, and that stabilizes the price. It's really important that we incorporate whatever the operator does into the final pricing system.

Which is what technically the model, if you look at it in a broad context, was asking for. The operator is saying, "There's not enough reserves I have to put more units on the system, and we have to then reflect that in the pricing out." By the way, that does have a feedback loop that says the operator who creates too many high prices may feel some pressure.

*Respondent 2*: I want to maybe push against the notion that the operators are making bad decisions. I think, in many cases, they're dealing with decisions that have to be made and they're dealing with some of the same problems of the non-convexity. Things change. We put things in the market, and we have series of actions to plan for that. But whether we like it or not, things change. So, I think the question is, how do we give enough? And I think one of the notions around this sort of uncertainty product was, how do we, given as acknowledgement to that, and have it explicit and price it?

I do think that, in many ways, there are decisions that are made prior to real time. That's why we have a day-ahead market, for instance, where we can try to incorporate some of the uncertainty and price it through things like ELMP or convex hull pricing.

The only challenge to that is when you put out a product, and I agree with Speaker 3 there, you have a time horizon and, as the portfolio levels, the important time horizon is also going to evolve.

I think the question is how do we get flexibility. In general, the operators are making decisions because, short of an explicit way to price and deal with uncertainty, they have to deal with it anyway. So, they're not doing a bad thing. It's just how do we get that more reflected in prices.

*Questioner*: Again, I didn't mean it to be pejorative, I'm not saying operators are bad things. Some of them might. But someone specifically mentioned that he's concerned about "putting it in the price" because operators may not be comfortable waiting to see the fruits of the signal, I think. Maybe Speaker 4 is right. Maybe there's a way to accommodate that and still have a feedback loop, such that it does end up in the price, such that resources or options that don't necessarily have access to operator dispatched actions would nonetheless be able to participate and affect the price.

But, at the end of the day, all of this does or at least all of the great majority of the demand-side potential depends on either operators being able to get comfortable waiting to see the fruits of the signal or having some way to make sure that the system is dynamic enough, that opportunities that wouldn't necessarily be dispatched by the operator can nonetheless participate and lower the cost of integrating all these intermittent resources.

*Respondent 2*: Well, that's where I think the stochastic thinking is really appealing because it gives you a better, more explicit way to manage and think about uncertainty as a dynamic thing. Then, I think the convex hull pricing is interesting because then you're able to incorporate actions that are taken to startup a unit, for instance.

So I think there are ways that we can work our way towards better pricing, but, also to your point, to the extent that you're able to incorporate those pieces, you have probably broader participation.

*Moderator*: Let's go to the next question.

***Question #6***: Thanks a lot. I'll end with a question. But I actually wanted to follow up on some of the earlier comments, since so many people on this conversation have been echoing my normal questions about pricing and demand.

I want to just make a couple of points, some of which pick up on Speaker 2's comment and, I think, the other person from my MISO's comment that you impart what bringing demand into this does is it begins to resolve the non-linearity, the non-convex problems that you have in the current system because demand can respond much more flexibly.

Also, with respect to some of Speaker 1's comments, part of the issue here, when we get down into the distribution level, is being able to develop parallel solutions in different parts of the distribution system and manage the seams both across distribution and with transmission. That's something that I think we need to learn how exactly we're going to do, and we don't yet know.

The other point that I that I wanted to make here is that I think there is another missing element, and that is that we really are going to need to be solving many of these problems over multiple time frames.

On the demand side, we know from some of the work that has been done, particularly some of the work that I've seen, for example, coming out of Georgia Tech looking at power electronics, is you can actually get distributed intelligent devices that are responding on a sub-cycle basis to give you responses in terms of energy or reactive power that can begin to make some of these problems diminish. The issue is going to be, I think, one of how do we begin to integrate multiple tools together.

That in turn will require coordination, both at an engineering level but also at a policy and economics level, which I think we haven't fully figured that out. I'm curious if any of the panelists have particular thoughts about that. In particular, I noticed in one of Speaker 2's slides, you had an example of a four-hour ramp rate that was I think over 50 gigawatts in MISO. That's larger than what I've seen in prior analyses and suggests that we have some real challenges that I think are going to be very difficult to solve if we can't figure out a way of integrating demand in a much more flexible and active way then is done today in MISO and is done in many other ISOs, where demand response remains largely an emergency-only product that we can't really flexibly dispatch, let alone have something that's price responsive.

So, I'd be curious about what the panelists think about how we move forward in getting some of these issues resolved in time to be able to deal with events like a 50-gigawatt ramp.

*Respondent 1*: I don't know the status of the power electronics development goal, though I know there's a lot going on in that domain, but this has been an issue for 20 years. As a matter of fact, I was talking the other day to Frank Wallach about some papers that were out way back when. And I think Ross Baldick was on the call, he could tell us, but people arguing that the reactive power was cheap or free if you could just get enough engineering solutions, you wouldn't have to worry about.

I'm all in favor of that. And I think that if we can do that, we should, because a lot of these problems would go away at the distribution level, I think, and elsewhere as well. A lot of constraints would be removed. I don't think that's going to actually happen soon. It's hard to implement that. In the meantime, we're got to deal with it. The pricing part of the story, I think, is absolutely critical.

*Respondent 2*: Can I add to that? I mean, the way we do reacted power today, since it doesn't appear explicitly in the model that we use, is that the operators see a need for reactive power. They often put in what they call cut sets, or PJM has a word for closed loop interfaces or things of that nature, which force very, very inefficient local generators to start up, run at their minimum operating level to produce reactive power that has essentially a zero marginal cost.

And everybody says, "Oh, the marginal cost of reactive power is zero." But when you look at how much it costs to get that zero marginal cost reactive power, it costs a startup cost for an old, inefficient generator at minimum operating level for an old, inefficient generator

So, if you were to actually look at what it really costs to provide that reactive power, you would be running very quickly to alternative options. But it never shows up in pricing.

*Respondent 1*: Well, I agree with Speaker 2. We should price what they do.

*Respondent 2*: Right, yeah. By the way, does the convex hull ever have a reactive power in it?

*Respondent 1*: Well, in theory, yes.

*Respondent 2*: It would probably produce much higher prices.

*Respondent 1*: I don't know anybody who's actually done any empirical investigations of that. The theoretical model is quite general.

*Respondent 3*: I think there was something that that was said which may be worth pointing out, which is the management of seams with load-side aggregations. I think there's another interesting problem to deal with there, which is making sure that the information about the responses available to operators, and an understanding of how it impacts the flows across the T&D interface is really important. One of the questions we need to figure out, along with the pricing, is how do we get the right information exchange through the T&D interface.

I know there's loads of people working on this. But I think it matters because the size of your aggregation affects computation as well as the impact it could have on the T&D. That's just something with throw out there.

*Moderator*: So, from what I'm hearing from the panelists is, if I may use my prerogative as moderator, if an ISO had sufficient either storage and/or a material amount of storage and/or load that would respond to prices or could be dispatched as an ancillary service by the ISO—how would that affect your view on development of a forward or look-ahead sched or look-ahead mechanism?

*Respondent 3*: My understanding of Speaker 3's point—he can correct me if I'm wrong—but just restate what he said was the solutions to dealing with these intertemporal problems which are going to include demand side and storage and all the other kind of things, inherently create intertemporal interactions. There's constraints across periods so I think it's like the usual situation, which is the arrival of these technologies is going to depend on better intertemporal pricing. The integration of those technologies is going to depend on better intertemporal pricing, and they will intend by their arrival to moderate the effects of the intertemporal pricing.

Because there's going to be a balancing that's going to take place, and you'll get an equilibrium kind of situation. So, I think the theory is independent of this. It doesn't matter what the technology is. But I think the reality is that the trends are both going in the same direction, this look-ahead and rolling settlements story and then make up for any uplift caused by uncertainty problems is going to have to be more prominent in the future, rather than less.

Storage is a good example. It's all about intertemporal pricing. That's the only thing that matters in storage when you get in the end of the short run. You've got to address that.

*Respondent 2*: And a lot of the price-responsive demand is the equivalent of storage. You're simply going to defer your consumption to a later period. And the important thing, I think, we focus on high price periods, because they're apparently a big reliability problem. But, from an economic point of view, you want the demand to be consuming in the troughs. The very fact that we have negative prices or had negative prices indicates that there's not enough demand participation, because the demand should be sitting there waiting. As the example I used is to update Google Scholar. Not a high value product, but something that Google provides to everybody.

But the bottom line is, it doesn't need to be done at noon or at five o'clock in the evening. It needs to be done when the prices are low. That's really important for the future—that you basically consume when the prices are low and avoid when the prices are high. The only way you could do that is to have price-responsive demand.

*Moderator*: We have another question.

***Question #7***: I'm from California ISO. So we fully agree about the importance of look-ahead in the market. We have been doing that last 11 years. Initially, the driving reason for that was to capture top-of-the-hour scheduling in our environment, with the renewals and ramping especially when solar goes down, it's almost impossible to operate without look-ahead. Now, the main challenge in doing that is, in order to do that properly, you have to model ramps, which are not constant for the range of resources. We have to do what's called dynamic ramping.

And while doing the dynamic ramping, you have all kinds of different timeframes. So you may have energy products, you might have flex products, you might have a reserve product. All those products have different timeframes and modeling dynamic ramps on all those products, sharing those ramps, is more challenging than actually doing combined-cycle units. And, for the information, we have 420 combined-cycle units in our real-time market right now.

So we are thinking about introducing new 15-minute flex products, and that 15-minute flex product is going to introduce flex down and flex up**.** We're going to introduce additional dynamic ramping problems. But the bigger problem is that, once we get this these flex products, we cannot procure them like continuously on a regional basis, they had to be procured locationally and be transmission feasible, which will dramatically increase the problem. Another challenge we see in this role in renewables is that many of these resources have what we call very similar prices. They have almost identical prices, large number of those, relatively small resources, with identical prices is a big problem for all the computational algorithms out there that we need to use to solve the market.

And the challenge that you're facing is that, as this deep ramping story goes down, we have to make sure that state-estimated solution is provided to the market as soon as possible. If you do a look-ahead market and you calculate 10 minutes ahead, if your state estimator and [UNINTELLIGIBLE] solution is another five minutes, you're already behind the curve, it will be always late ramping, if you cannot quickly solve state estimator and provide input to market to have good starting point to capture that ramp.

So those are challenges that we're seeing in our system. I agree with what Speaker 4 said earlier, we hope that you'll stay away from distribution. Because in distribution, as he said, it's going to be three phases. So you can think about not just a large number of points, but also the whole system has to be tripled. So all the modeling and everything has to go three times up.

*Moderator*: Do any of the panelists have any response or thoughts?

*Respondent 1*: Well, I think maybe this is a topic for the future. This has come up several times today, and it is actually maybe more worrisome, is the sort of heterogeneity of the response capabilities of all these different resources. So when we think about dividing it up into 10 minutes and then half-hour and then one hour, or something like that, that maybe awfully crude.

Is that a problem, particularly with some of these resources that are very difficult to schedule? Obviously, we're going to do some approximation there. We're not going to get a perfect pricing mechanism and a perfect dispatch mechanism. It may not be as easy as I would hope it would be.

Maybe somebody can explain it to me later on. I don't fully understand exactly how to solve this problem unless we have a different representation for every resource.

*Moderator*: Are there any other comments or questions from the panel, from the attendees?

*Respondent 2*: But I think the time-delay issue that CAISO and NYISO have brought up is interesting. Because that adds another complexity that I hadn't thought about. So if you're trying to do smaller intervals and further look-ahead, your data transfers, your ability to get information and bring it back, it sounds like it's an interesting problem. I'm curious, maybe how folks are planning to address that. Is it a big problem or just something you can address quickly?

*Respondent 1*: The term I've heard used to apply to this is latency. I think it's a pretty serious problem. The places that I've talked to, in raising this, have been places dealing with renewables arriving, and it becomes much more important. I think it is a serious problem.

*Questioner*: Well, there are two parts to that. First of all, [UNINTELLIGIBLE] are hard to cycle very frequently in a large system.

So we are currently cycling every 30 seconds and real-time market cycling every 5 minutes. That's good. So that's not a problem. We plan to cycle every 20 seconds, so have three solutions every minute, and we will capture the latest one, when real-time market starts. Now, then, it comes down to answer to status with a solution to real-time market to get a starting point for real-time market. And that's the one that we also use what was mentioned earlier, memory transfer. Actually, we're not transferring memory cache we’re [UNINTELLIGIBLE] from the same place.

*Moderator*: Any other questions, comments, observations? Going once. I think we've exhausted the audience, at least for purposes of comments. Thank you, everybody.