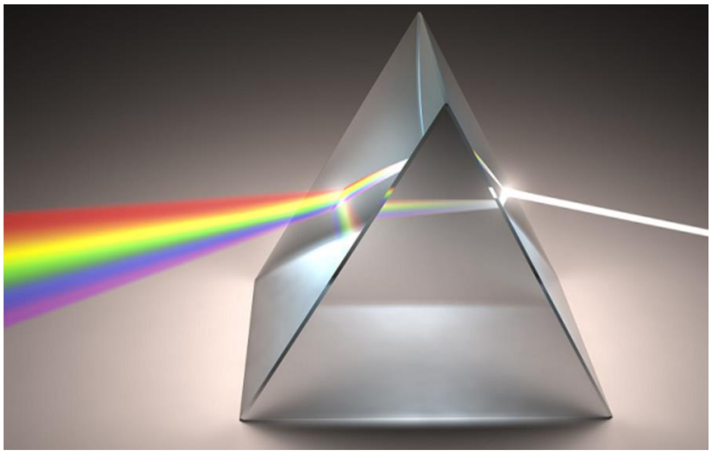

A PRISM-BASED CONFIGURATION MARKET FOR RAPID, LOW COST AND RELIABLE ELECTRIC SECTOR DECARBONIZATION

A competitive market path to rapid, low cost and reliable decarbonization of the electric power sector

ABSTRACT

A growing number of rigorous studies show that deep decarbonization of the power sector can be achieved with little or no additional cost, while preserving electric system reliability, provided an efficient mix of clean energy resources is deployed. This paper proposes a competitive market innovation, using the same type of advanced computer models used in these studies, to evaluate bids and select efficient resource mixes through a regularly scheduled competitive procurement auction. Resources will be selected for their aggregate ability to balance electricity production and use, in all hours -- including extended periods of low wind and sunlight -- and to keep electric sector emissions within a rapidly declining carbon budget consistent with IPCC guidelines, all at the lowest cost. This new configuration market will work together with today's electricity spot markets to replace, within several decades, inefficient, high-emitting fossil fuel plants with a reliable and affordable mix of wind, solar, storage, flexible load and existing and emerging clean dispatchable technologies.

Steven Corneli

Steven Corneli is an independent consultant on clean electricity business and regulatory issues associated with the deep decarbonization of the power sector. From 2001 to 2016, he worked for NRG Energy in various executive roles related to wholesale market development and advocacy, government and regulatory affairs, market and climate policy, and clean energy development. In 2012, he became NRG's senior vice president of policy, strategy and sustainability. In that role, he was responsible for coordinating business, policy and public affairs strategies across NRG's heritage and emerging clean energy business units to support the company's successful transition to a decarbonized future. Prior to joining NRG, he worked in the Minnesota Attorney General's office as a utility consumer advocate for eight years, during which time he served as the small consumer representative on NERC's Operating Committee. Mr. Corneli has a master's degree in public policy from the University of Minnesota, and a bachelor's degree from St. John's College in New Mexico. He spent a decade between college and graduate school managing a 700-acre family farm in Wisconsin.

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Executive Summary

The need to rapidly convert the global power system to zero carbon resources, while keeping electric service affordable and reliable, is increasingly accepted by power companies, customers, and the regulators who oversee power markets. Dramatically falling costs for wind, solar power and battery storage increase the prospects for low cost decarbonization, but raise significant concerns about how to ensure both reliability and low costs, especially during prolonged periods of low or no sunlight and calm winds. Insufficient electricity production during such periods would fail to meet the fundamental requirement for power system reliability, that electricity production must continually and closely match electricity consumption across entire regional electrical interconnections.

Due to this balancing requirement, power sector rules and standards have long placed a premium on technologies that can increase or decrease their output on demand and at all times. Fossil fuel generation technologies, in particular, have evolved to typically be able to increase production when needed. This inherently "firm" capability of fossil resources allows each fossil resource to act in combination with, or as a substitute for, other generating resources. As a result, it is remarkably easy to identify and build fossil generation portfolios that meet the fundamental balancing requirement. The same "firmness" of fossil technologies also makes it easy for electricity markets, if properly designed, to produce price signals that, over time, drive investment in efficient mixes of fossil technology types.

Variably intermittent and time-limited (VITL) resources such as wind, solar energy, energy storage and flexible load, however, do not have the same ability to maintain or increase their production at any time. It is, however, possible to identify certain combinations of such resources that can make the best contribution to meeting the balancing requirement. This requires comparing the hourly wind and solar insolation patterns in many potential locations and identifying the most complementary combinations of VITL technologies and locations, that will best work together to match electricity consumption profiles, over a wide range of weather and demand patterns. A similar, additional layer of analysis can identify a smaller and less costly set of VITL technologies that would be sufficient, assuming the continued use of existing nuclear plants and, potentially, a small amount of natural gas-fired generation, both of which can result in dramatically less costly decarbonization. The data and computational power needed for such analyses are, however, many times more complex and costly than the current approaches to finding efficient mixes of fossil fuels.

That complexity creates much higher levels of risk, uncertainty and other transaction costs for converting the power system to clean energy resources than those of just continuing to use primarily fossil generating resources. The higher transaction costs for efficient clean energy investment may even be a significant, but largely unrecognized, barrier to the effective decarbonization. Further, there is scant evidence that even efficient electricity market prices could overcome the barrier created by the massive complexity of finding efficient combinations of highly complementary clean energy resources. By contrast, there is ample empirical evidence that various kinds of central optimization processes are needed, and widely used, to identify and procure efficient mixes of complementary inputs in fully competitive industries.

Accordingly, this paper proposes a new competitive, algorithmically optimized, long-term power market to regularly identify and procure new tranches of clean energy resources, to ensure the deep decarbonization of the power sector, while ensuring continued electric system reliability, at the lowest possible cost. The market's optimization process will be used to evaluate bids from a wide variety of clean energy projects, and will identify and select combinations of projects that minimize the cost of meeting both the power grid's balancing requirement and a science-based declining carbon budget. This optimization-based evaluation of the bids will be carried out by a specially developed version of a new, emerging type of power system simulation models, which due to its use of data with very small granularity, both spatially and temporally, on wind and solar irradiance, are referred to here as a *precise, renewable integrating system model* (PRISM). Such models are undergoing rapid development and use in the power sector for a wide variety of planning, policy analysis, and resource allocation decisions.[1]

This *configuration market* would run every three years, throughout the next several decades of rapid power sector decarbonization, and procure in each market round an incremental tranche of new clean energy projects that will, in aggregate with existing resources that remain in operation, ensure that both the balancing requirement and the declining carbon budget can be met at the lowest cost, under a wide variety of likely weather and demand conditions. The configuration market will offer each cleared project a long-term hedging contract, structured as a swap with load, in which the project receives a performance adjusted stream of fixed revenue, based on its as-bid levelized cost, and load receives the floating revenue stream of the project's spot electricity market revenues.[2] The resulting revenue certainty, at the project level, will support the ability of all winning projects to secure low-cost debt financing, even at large and continuously growing volume of clean energy projects required for successful decarbonization.

The paper also explains a number of configuration market design features, including the timing of market rounds, the entity or entities that would host or conduct the market, its settlements and money flows, bidding and price setting rules, retirement and retention of existing resources, resource adequacy, the role of distributed energy resources (DERs) in the market, transmission dependent bids, self-supply options, and market power and its mitigation. Further, consistent with the innovative and evolving nature of the PRISM technologies and the configuration market itself, the paper proposes a number of early implementation modes that would provide learning-by-doing and product refinement opportunities to help the configuration market itself to evolve quickly and efficiently.

1. The need to decarbonize faster and better.

Two trends are converging to dominate the debate on climate change. In the first, climate science increasingly points to greater risks of climate crisis at current greenhouse gas emission (GHG) rates. Averting the worst risks therefore requires more rapid decarbonization of energy use, and hence of the power sector. Decarbonizing electricity production is also critical to decarbonizing overall energy use, since electricity – if it is cheap enough – can be readily substituted for fossil fuels in many transportation, heating and manufacturing uses. In the second trend, dramatic reductions in the cost of wind and solar power, and a potentially similar trajectory in battery costs, make it increasingly viable to achieve significant levels of power decarbonization quickly, without dramatic increases in the overall cost of producing electricity. The convergence of these two trends has resulted in a popular view that the world can cheaply switch entirely from fossil fuel to renewable electricity generation, and should do so quickly, in light of the little time left before cumulative GHG emissions reach levels that will make catastrophic warming unavoidable.

But despite their low costs, the variable intermittency of wind and sunshine makes them ill-suited to provide all the electricity used in the economy. A wide variety of recent decarbonization studies, using newly available data and algorithms for modeling power systems that include high levels of wind and solar resources, show that wind and solar, augmented with battery storage, can indeed provide the majority of the electricity consumed in many modern economies. But to be economical and reliable, while eliminating power-sector GHG emissions, these electric systems also need a suitable mix of other clean energy resources, including electricity storage, existing nuclear plants, and new dispatchable thermal power technologies powered by zero carbon fuels or carbon capture and sequestration (CCS).

These new studies typically use extensive, geographically and temporally precise data on wind speed and solar irradiance levels, collected over multiple years and across entire continents, to estimate how much wind and solar electricity would be produced in each hour of the year by new wind and solar resources built in any suitable location. The studies then use sophisticated models of the electric system to identify the mix of new wind and solar resources which, in combination with various existing and new clean resources, can meet load in every hour of the year while also keeping the entire system's GHG emissions within a specified limit and at the lowest cost. Due to their innovative use of very precise data on renewable energy production capabilities over time and locations, and their suites of complex algorithms that can integrate these resources into combinations able to meet the core reliability requirements of the electric grid, this paper refers to any such model as a *precise, renewable integrating system model* or "PRISM" for short.[3] Such models are rapidly evolving, and are increasingly used to explore clean energy mixes that would best support rapid decarbonization under a variety of assumptions. Such tools are being used to evaluate bids in some integrated competitive planning and procurement processes, which offers an initial proof of concept for the configuration market itself.[4]

As explored more below, these models show that only relatively specific mixes of VITL and other clean energy resources can meet these reliability requirements and a given carbon budget at lowest cost. The optimal mix typically will vary substantially with the relative costs of the various resources, but also varies dynamically with the amount of each resource type included. For example, more wind and solar will require more storage, while more dispatchable resources using zero carbon fuels will require less storage, and likely less wind and solar as well. This means that, for any set of available resources with different relative costs, there is a related specific mix of resources that will work together the best to support a reliable electric system that emits no more than a specified amount of GHGs per year, at the lowest cost. In this sense, the resources are dynamically complementary, in terms of the technology types, locations, amounts and costs.

Given the need to find and use the best mix of these dynamically complementary resources for decarbonization to work well, this paper proposes a new, competitive market for the identification, selection and financing of critical elements of clean electricity systems.[5] This *configuration market* would be structured as a periodically held competitive procurement process, which in each market round or period will use PRISM optimization to evaluate competitive bids to develop a wide variety of proposed grid-connected clean energy resources and to select the most efficient mix of such projects.[6] Efficiency will result from the selection of the combination of competitively bid new projects and existing resources which meet the specific optimization constraints of the PRISM, most notably those of (a) balancing aggregate generation and consumption in every hour under a wide variety of weather and demand conditions, and (b) emitting no more than a pre-specified and continually declining carbon emission constraint, all while meeting the objective of minimizing both fixed and operating costs.

The configuration market will exist alongside, and be closely linked to, an evolving version of today's centrally operated spot electricity markets, which use a security-constrained economic dispatch (SCED) linear programming mechanism to select the most efficient mix of power plants to dispatch in each five-minute interval. The SCED-based dispatch ensures that the aggregate output of all power plants continually matches consumption, at the lowest cost, while meeting most of the transmission systems critical operational constraints. At the same time, it simultaneously generates the locational marginal prices paid by the spot electricity market to generating resources at each location in each dispatch interval, and charged to each load serving entity based on its retail customers' aggregated energy consumption in each interval.

These SCED revenue streams will play a central role in the configuration market, as well. Specifically, new projects that are selected or cleared by the configuration market will be offered long-term hedging contracts, contingent on their completion and satisfactory performance, sufficient to cover any costs they do not recover in short-term energy markets. The hedging contracts will be broadly structured as financial swaps, with a fixed leg held by the resource, based on the project's levelized as-bid cost, in dollars per megawatt-month of nameplate capacity, and a floating leg allocated to load serving entities, based on the resource's actual energy revenues in the SCED market. The allocation to load of these SCED market revenues would be done in a way broadly similar to the way transmission costs and capacity market costs are allocated to load today. To assure efficient operating incentives, the fixed leg revenues to the project will be subject to adjustment based on the actual performance of the resource in terms of following dispatch directions and avoiding forced outages, i.e., outages due to factors other than the unavailability of the project's underlying prime mover. Participation in the configuration market will be voluntary, in that new resources that do not want or need such hedges can choose to simply participate in the SCED market as they do today.

Existing resources will generally not participate in the configuration market, except in the case of resources that expect SCED market revenues to be insufficient to support their continued operation. These resources are allowed to bid their going-forward costs into the configuration market, and if its PRISM-based optimization finds their continued operation will reduce the costs of complying with the balancing and carbon constraints, they will be offered revenue hedges based on their going-forward costs to support their continued operation until the next configuration market round.

This procurement and hedging process will ensure three critical outcomes needed for rapid power sector decarbonization. The outcomes are: (1) the identification and selection of an efficient mix of complementary resources drawn from a pool of bids from projects that all have a high probability of being successfully developed; (2) sufficient revenue stability for the winning projects, despite uncertain and volatile SCED price paths, to support the low-cost financing needed for efficient development of a very large volume of such projects over several decades;[7] and (3) the efficient retirement of existing resources that would otherwise interfere with or prevent the entry of sufficient clean energy resources needed to avoid the worst risks of climate change.

All these features and related details of the configuration market are explored in Part 3 and the Appendix, below. Those details and features will be clearer, however, after a careful exploration of why a PRISM-based analysis and resource selection process is needed, in addition to today's SCED-based spot market prices, to assure the success of rapid and deep power sector decarbonization.

2. Why a PRISM-optimized mix of clean energy resources?

The need for such a complex evaluation process, that can explore all the potential combinations of potentially thousands of complementary resources, derives from two key factors. The first is the complexity of the electric power system and its fundamental reliability requirements needed to avoid blackouts that can cascade across entire regions, such as occurred in the northeast US in 1965 and 2003. One of the most foundational of these requirements is that in each moment the aggregate amount of electricity generated must closely match the amount of electricity consumed across an entire electrical interconnection.

The second factor is the task of finding the mix of resources capable of achieving this balancing of load and generation at all times, which is vastly more complex with high levels of VITL and other complementary clean energy resources than it has been with typical fossil fuel technologies. Because these two factors are central to reliability and investment in the power sector, a brief overview of each helps shed light on the need for the proposed configuration market and its key features.

a. The fundamental balancing requirement.

Electric systems must constantly balance generation and consumption, because an excess of generation relative to load increases the frequency of the grid's alternating current above its design standard of sixty cycles per second (Herz), while a shortfall of generation relative load slows the frequency down.[8] Generators can only operate in perfect synchronization with the grid. That is, their own velocity of rotation must exactly match the grid's frequency, and in fact is dictated by it, since the grid's frequency acts to accelerate or pull slightly slow generators, and to brake or drag slightly fast generators, into synchronization. Even relatively minor frequency deviations can have catastrophic consequences, since, as they pull generators to speed up or drag them to slow down, they can cause excessive currents, heat and vibrations in the rotating generating equipment, which can quickly damage or destroy major mechanical and electrical components. To prevent this damage and the long-term loss of operability, rotating generators are equipped with automatic protective devices that disconnect them from the grid if the frequency gets outside of a narrow acceptable range around 60 Hz.[9]

This disconnection prevents damage to individual generators, but it doesn't avoid broader negative impacts across the grid. Instead, even broader harm becomes more likely with each disconnecting generator, since its loss causes aggregate generation to fall even further below current load, leading to even lower frequencies and additional disconnections. The likely result, without further intervention, is a rapid spiral of falling frequency and increasing generator disconnections. Transmission elements, in turn, can become overloaded due to the changing locations of generation relative to load, leading to protective transmission disconnections -- which can themselves spiral out of control, leading to an exponentially cascading blackout across large regions.

To prevent such runaway system collapse, North American reliability authorities require that, in the event of dangerously low levels of frequency, distribution utilities in regions affected by low frequency disconnect entire low-voltage feeder lines from the grid, and with them all of the homes and businesses they supply. Enough load must be disconnected in such "rolling blackouts" so that available generators can match it and maintain the grid's frequency at its safe, design standard level.[10]

Rolling blackouts are costly and unpopular, and are only used because the consequences of an unmitigated mismatch of generation and load are potentially much worse. And since prevention is far better than either the cure (local rolling blackouts) or the unmitigated disease (cascading regional blackouts), power system reliability requirements and practices are primarily focused on assuring the existing fleet of generating resources can and does continually adjust its aggregate output up and down, as needed, to instantaneously match demand and avoid overloading transmission elements. The resulting synchronized, continually adjusting, coordinated operation of hundreds of independently owned generators, across state and national boundaries, has led to electric interconnections being called the world's largest machines.[11] As such, it is appropriate to think of generators and other controllable resources, in both the short-run sense of how they are operated, and in the long-run sense of how they are selected, as inputs to an interconnection's key production problem, which is to continually balance aggregate electricity and consumption.

b. The dramatic complexity of meeting the balancing requirement with VITL resources.

The need to maintain a constant frequency by continually matching electricity consumption and generation will not go away in a grid with high levels of wind, solar and battery storage, even though most of these resources use inverters and other power electronics, rather than rotating electromagnets, to synchronize with the grid.[12] But the challenge of identifying and developing mixes of generating resources that are capable of operating in a continually balanced manner will be radically different in a grid with high levels of VITL and the other existing and new clean energy resources that will be needed to decarbonize the power system in a timely manner.

The challenge becomes clearer by decomposing this selection process into two steps: first, identifying from among all feasible proposed projects, just those which, in aggregate, would be capable of providing the controlled and constantly varying flow of energy needed to meet the balancing requirement; and then further refining these projects to find the mix of proposed resources that can do so at least cost.[13] Just the first step, for systems with high levels of VITL technologies, will require astronomically more data and computation than have been historically required to find equivalently controllable combinations of fossil fueled resources. The second step, of finding the lowest cost of all these feasible combinations of clean energy resources is also a massively more complex information and computation challenge for clean energy resources than it is for fossil resources.

i. The simplicity of selecting fossil fuel technologies to meet the balancing requirement. Historically, finding the feasible and lowest cost combinations of fossil generating technologies has been relatively easy, due to the fact that all fossil fuel generating technologies are "firm" – that is, if they have dependable fuel supplies and, when operating within their design parameters, can typically achieve anywhere between their minimum operating level and their maximum rated level of power production relatively quickly, whenever needed.[14] This ability to start or increase their output on demand, at virtually any time, means one fossil resource's output can be added to that of other resources already in operation to constantly balance increases in electricity consumption. Their firm nature also means a fossil unit's incremental output can be used to replace the output of another resource that suddenly stops operating, due to mechanical failure or fuel unavailability.

The firmness of fossil technologies, at any time, means that one can largely ignore the questions of whether the aggregate amount of fossil resources can balance consumption in each particular hour or group of hours, and of which types of resources are needed to do so. Instead, electric systems have been able to simply rely on having enough megawatts of nameplate fossil resources of any type to meet projected load plus reserve requirements in just one hour – the hour of annual peak demand – due to the implication that the same set of firm resources could always match its aggregate output to lower levels of consumption, whenever they occur. Similarly, finding the lowest cost combination of types of resources, among all these feasible technologies was, with fossil technologies, a relatively straightforward, low-dimension problem.[15]

ii. The astronomically greater complexity of selecting high levels of VITL and other clean technologies to meet the balancing requirement.

Finding combinations of resources that are capable of meeting the balancing requirement, and selecting from among them those that have the lowest total cost is astronomically more complicated for systems deploying large amounts of wind and solar power, which are currently the lowest cost and most readily deployed types of clean energy resource. The primary reason is that the amount of power that wind and solar can generate at any moment depends on the concurrent solar irradiance and wind velocity at the locations of each and every existing and potential wind or solar project. Since these individual availabilities are highly stochastic, it is extremely difficult to accurately evaluate their joint ability, across multiple potential sites, to contribute to system-wide balancing.

The odds of their joint availability can be improved, sometimes dramatically, by deploying a mix of wind and solar and by locating these projects in regions with different weather patterns. For example, a system with high levels of solar power could increase the ability of renewable energy to match load simply be adding some wind power, which is often available at night. By contrast, adding more and more solar power would eventually result in diminishing ability to match peak load (which, with high levels of solar deployment, typically shifts to just after sundown), and in the increasingly uneconomic curtailment of daytime solar energy production.[16] These simple examples illustrate how variably intermittent resources are dynamically complementary – that is, they can be highly complementary when deployed in certain quantities and combinations, but can create problems, rather than benefits, in other combinations.

Going beyond the low-hanging fruit of the most obvious complementary combinations, while avoiding the unintended negative interactions among resource types, such as curtailments and related incompatibilities, is not a simple matter. To actually identify the specific combinations of these dynamically interactive resource types and locations that contribute the most to the balancing requirement, and thus displace the most fossil fuel-based emissions, requires a sophisticated analysis of wind speeds and solar irradiance, in hourly or smaller increments of time, at each potential project location, over enough years to capture each project's expected variability at different times, seasons and weather conditions. The resulting joint probabilities of energy output in each hour must then be compared to probable levels of aggregate load in each hour, to accurately estimate how much firm fossil capacity, and its associated emissions, can be expected to be displaced or avoided by each combination. And this analysis needs to extend beyond the hour-by-hour analysis appropriate for firm fossil resources, since the availability of wind and solar power in clusters of adjacent hours matter acutely in terms of how a power system with high levels of such resources can balance generation and load. For example, the amount of available power needed to balance load at sundown or sudden drops in wind speed increases dramatically in systems with large shares of energy provided by wind and solar power.

Adding battery, thermal or gravity-based storage and flexible demand to the mix can significantly improve the balancing capabilities of a clean energy mix, but finding the right amount and types of storage and flexible demand requires additional complex, availability-based data and analytics, and due to even more dynamic interactions among VITL technologies, may also change the amount of solar and wind needed to achieve a given contribution to the balancing requirement. Finding the best balancing solution becomes even harder if the objective includes the continued operation of existing nuclear plants, and the introduction of promising new "clean firm" technologies as part of the mix, since the inclusion of these resources will result in dynamic changes, depending on their cost and availability, to the optimal mix of the other clean energy resources. For example, adding wind to solar could improve a "renewable-only" portfolio's ability to help balance the system and lower its cost, but at the same time decrease the ability of a "renewables plus nuclear" portfolio to help balance the system, while also increasing its costs.[17]

As the last example shows, the interaction of dynamically complementary resources can produce results that are counter-intuitive and unpredictable using common heuristics. For example, above a certain level of wind and solar deployment, it can reduce overall costs substantially to deploy or sustain a zero-emitting, firm resource (such as nuclear) with a far higher cost per nameplate megawatt and per megawatt-hour, instead of deploying additional wind and solar, despite their much lower cost per typical megawatt and megawatt-hour.[18] The lower costs that can result from adding nuclear along with wind, solar and batteries results from the nuclear resource producing substantial amounts of electricity at all times, including during extended periods of low or no solar irradiance and wind speeds. The nuclear resource thus reduces the need for expensive storage and high levels of curtailment that would otherwise be needed to balance generation and load in these extended periods. Further, the nuclear resource avoids the need for duplicative wind and solar capacity during the sunny and windy hours when it is also running, further reducing overall system outlays, provided the nuclear fixed costs are not so large as to eat up all of these other system cost savings.

Identifying any such efficient combinations requires the comparison of thousands of projects in potentially astronomical numbers of combinations, and can't be done via the simple rules of thumb, industry expertise, screening curves, or simple linear programming routines that worked for fossil fuel technologies. The massive data needs to characterize potential projects, the vast number of potential combinations that could fully meet the balancing requirement, and the complex process of evaluating which of these combinations offer the lowest cost, make the process of identifying the lowest cost set of clean energy resources that can meet the balancing requirement much more difficult, complex and challenging than the analogous process used to identify and select fossil fuel portfolios.[19]

It is worthwhile to consider the root cause of the greater simplicity of the fossil case. A key factor, at least, is the firmness of fossil fired generating capacity, which means it is generally fungible and substitutable, under typical historical operating conditions, with other fossil generation across all of the 8760 hours of the year, and this substitutability is largely independent of location. By contrast, the various VITL technologies are not fungible and substitutable across hours without sufficient availability of each technology's prime mover in the same hours. This availability varies by hour and by location, in patterns that have varying levels of predictability and correlation. Accordingly, the aggregate probability of how much electricity they can deliver in any hour depends on which resources are deployed in which locations, and on the unique probability distribution functions of wind and solar irradiance in each location, in each hour. As a result, finding the lowest cost combination of these resources requires the evaluation of a wide variety of likely wind and insolation patterns and weather conditions over each hour in multiple years at literally thousands of potential sites, together with site-specific data on costs and project feasibility.

The evaluation of all these resources requires both vast amounts of highly granular time and geographic data and the ability to optimize across vast numbers of potential combinations. These many combinations, in particular, pose an analytical task many orders of magnitude more complex than the analogous analysis for fossil fuels. This task could only be done by large and fast linear or mixed integer programming tools designed to coordinate their optimization across a number of objective functions, while accurately representing the core dynamics of the electric power system. In short, it would require PRISM tools like those which are only now are becoming available.

c. Complementary inputs are used in specific combinations or "recipes".

The differences between fossil and VITL inputs explored above can be summarized using the economic concepts of substitute and complementary inputs to production. Fossil resources are highly substitutable among each other as inputs to the synchronized, balancing machine of an electric interconnection, while the clean energy resources are dynamically complementary inputs to the same machine. In production, substitute inputs can be combined satisfactorily in any number of ways. By contrast, complementary inputs reflect the existence of specific technology characteristics that result in the need for more or less specific combinations of inputs to produce a particular good or service. Unlike unobservable consumer preferences, these characteristics are directly observable or predictable based on engineering information, trial and error, or production efficiency analysis. Such specific combinations are sometimes thought of as specific recipes that may be known to one, some, or all manufacturers.[20]

For example, natural rubber and synthetic rubber are substitute inputs in producing automobile tires, and the resulting automobile, as a machine, will perform just as well with either or with any mix of the two. But certain other inputs are needed in specific combinations. A reciprocating automobile engine needs exactly the same number of pistons as there are cylinder bores in the engine block, along with a matching, balanced crankshaft and flywheel specifically designed to connect, synchronize and balance the pistons in each specific engine model. Incorporating these complementary inputs in any combination other than the required mix will result in a machine which does not work at all.

d. Decentralized markets are often inefficient ways to identify and select complementary inputs.

Because of these critical differences between substitute and complementary inputs, businesses that need both types will typically use different approaches in procuring them. For substitutes, it is typically most efficient to observe market prices and procure whichever combination of the substitutes meets production needs at the least cost. If the price of one substitute increases, the optimal mix will include proportionately less of it, and more of the others. But this same approach typically does not work for complementary inputs. In the automobile example, for example, it would clearly fail in cases when the price of engine blocks falls relative to the prices of the pistons, camshaft and flywheel each block requires. Accordingly, a producer who needs complementary inputs will typically first identify the various combinations of inputs it can best use, elicit bids from their various suppliers, and on the basis of those bids identify the least-cost combination of inputs it can actually use, and buy those. Since producers typically purchase inputs from multiple, competing suppliers, they need to be able to evaluate different combinations of different components offered at different prices.

Due to the inability of decentralized market prices to convey the information needed to identify efficient mixes of complementary inputs, competitive economies have evolved other processes, outside of markets, for doing so. For example, Coase (1937) pointed out that competitive firms exist, in large part, to support efficient internal managerial selection and control over these combinations, typically through contractual purchase or use agreements, rather than basing them on marginal changes in market prices. In the ninety-three years since Coase's paper, the development of linear programming (LP) and the related discipline of operations research have been increasingly employed by competitive firms to better optimize the complex and complementary aspects of production and logistics. Such competitive use of non-market optimization has extended even beyond individual firms. In cases with substantial inter-firm economies of coordination, business practices and institutions have evolved to support such managerial optimization among multiple competing firms. This multi-firm optimization of production and logistics happens in many fields, which can be as diverse as vegetable processing, regional electricity markets and highway shipping.[21]

The common element in all of these examples of competitive intra- and inter-firm optimization is that each has evolved because of a need for more efficient approaches to production than simply minimizing the cost of input bundles in response to changing market prices. Further, they are unambiguously examples of competition, and not of command-and-control socialism or central planning.[22] In many cases, the competitive market processes deployed by competitive firms are advised, facilitated or even carried out with the aid of centrally processed linear or other mathematical programming tools.

For example, in the case of highway shipping, some shipping firms use *combinatorial auctions* to simultaneously identify and procure optimal combinations of shipping routes that reflect different complementarities available to various trucking firms.[23] Some combinatorial auctions and other related competitive procurement processes use computers running complex algorithms to evaluate the compatibility and interactions of various input combinations at various prices as part of the bid clearing or winner selection process. This is particularly useful when the complementary combinations are dynamic, i.e., the optimal mix depends on the availability, cost, and positive or negative synergies between each potential input and the other inputs. In these cases, the speed with which LP or related tools can solve massive combinatorial problems is essential to finding the optimal competitive solution. Today's SCED spot markets for electricity, for example, centrally solve extremely complex dispatch problems every five minutes, while creating what can be large arrays of efficient locational prices in each such interval. In this way, SCED markets avoid the need for costly redispatch and uplift common in electricity spot markets that rely on decentralized generation schedules, developed by many buyers and sellers, which must then be inefficiently reshuffled and redefined at the last minute by market operators to comply with transmission system constraints.

The configuration market proposed in this paper would build on this history of centrally optimized competitive processes for the efficient provision of complementary inputs. Specifically, it would use a competitive, combinatorial auction approach to procure the lowest cost mix of competitively available, dynamically complementary clean energy inputs capable of meeting system balancing requirements. The configuration market would repeat this process at regular three-year intervals, throughout a decarbonization process lasting several decades.[24] In this regard, the configuration market has structural similarities with other, algorithmically cleared or algorithmically assisted auctions, such as the SCED market itself, as well as combinatorial procurement auctions and some recent spectrum auctions used to reallocate frequencies from television broadcasters to wireless providers of telephony and a variety of other digitally delivered services.[25] All of these applications go well beyond simple English or Dutch auctions, and have characteristics generally associated with mechanism design, which focuses on developing game-theoretic procedures to improve economic efficiency when decentralized market prices alone are unable to support efficient outcomes.[26]

e. High transaction costs -- a major barrier to deploying complementary clean energy resources?

In addition to finding the lowest cost mix of currently available projects and technologies needed to balance the system reliability in each step of the decarbonization process, the proposed configuration market will serve two related purposes, namely reducing information costs and other key transaction costs that disproportionately affect clean energy resources, both of which may prove critically important for successful decarbonization.[27] The configuration market will eliminate the substantial information cost disadvantages that clean energy resources currently face, relative to fossil resources, associated with finding the best resource mix to meet the balancing requirement. Eliminating this disadvantage will not only significantly reduce clean energy costs, but will remove what may be a significant but unrecognized cost barrier to decarbonization.

The existence of such a barrier may help explain the findings of Alova (2020), that regulated utilities, who generally bear some or all responsibility for meeting the balancing requirement, are investing in renewables to a far lesser extent, and in fossil energy supplies to a far greater extent, than independent power producers (IPPs), who bear no such responsibilities. Alova reports that only 20% of renewable capacity globally is owned by regulated utilities while 75% of it is owned by IPPs. Further, those utilities that are investing in renewables typically also add new fossil generation at the same time.[28] It is popular to attribute limited utility investment in clean energy on the lack of a carbon price, or on the high opportunity cost of replacing profitable fossil equipment. Yet another, simpler explanation for the observed behavior may be the much higher information, risk and other transaction costs associated with meeting critical balancing requirements with high levels of VITL technologies, which are the most affordable and available clean energy resources, rather than with fossil resources.

To the extent this is the case, relying entirely on policies that make fossil fuel investment more expensive (e.g., a carbon price) or renewable energy less expensive (e.g., renewable portfolio standards, tax incentives, etc.) may be a relatively inefficient way to change the observed behavior, since – as the direct costs of renewable electric energy fall below those of fossil-based electric energy -- the cost problem is increasingly not one of relative technology costs, but rather the information costs and uncertainties associated with not knowing how to solve the balancing problem efficiently with high levels of VITL technologies.

The configuration market will also directly solve a major set of transaction costs that clean energy investments are burdened by and that existing fossil resources simply do not face at all. This is the cost of achieving debt financing at rates offered to capital investments in sectors that do not face the highly uncertain and volatile revenue streams associated with today's competitive wholesale markets. The risk premium associated with such market price risk can be substantial, especially for newer technologies that are highly capital intensive and that are expected to increase the volatility and uncertainty of wholesale market prices. Reicher et al., (2017) show that successful decarbonization will require the near continuous deployment of extremely large amounts of clean energy technologies over multiple decades, which would require substantial de-risking of market price risk in order to provide the requisite volume of debt financing at costs low enough to compete with the alternative of incremental and existing fossil resource investments. The configuration market, by offering cost-based swaps around SCED prices to all resources that are found to economically support both the PRISM clearing mechanism's balancing and the carbon constraint, will help ensure that low-cost debt financing is available in the volume needed for decarbonization to succeed – an outcome that SCED markets, alone, are unlikely to support.[29]

3. Integrating efficient clean energy combinations through a PRISM.

This paper proposes to harness the emerging power of PRISM tools to achieve the goals articulated above. This section describes the most comprehensive such approach envisioned, namely the full-fledged configuration market; more incremental approaches are described in Section 4, below.

The configuration market would be a long-run procurement analog to, and operate alongside of, the short-run, operational SCED market in each region.[30] Both markets share a common structure that uses mathematical programming to select, from among competitively bid resources, the combinations that can best perform complex tasks at the lowest cost. The SCED market optimizes the short-run use of existing resources, to ensure the most efficient dispatch of the bidding resources to securely meet load in each five-minute interval. The configuration market addresses the long-run development of resource types, to ensure the most efficient mix of complementary clean energy resources is actually deployed in the region. By analogy with the data-driven revolution in how to build a low cost, winning sports team, the configuration market analyzes massive amounts of data to identify the various player skills most necessary for winning, and then recruits players with the right combination of skills to join the team.[31] Once they're on the team, the SCED market's job is to make sure they run the best pattern at each play.

To recruit the right players with the right skills, the configuration market's mathematical programming and sophisticated system models would compare the incremental contributions to cost, carbon emissions and system balancing of thousands of potential combinations of the clean energy projects that bid in each round. It will identify, from among all those potential combinations, the specific combination of projects which, together with the existing resources that remain in operation, will best be able to meet expected loads across all dispatch intervals under all likely weather and demand conditions, while also meeting a continuously declining carbon constraint, at the lowest total cost.

Then, to ensure those resources actually join the team, it will offer each project a long-term contract, that serves to hedge the project's volatile and potentially insufficient SCED market revenues, pay each project the amount its competitive bid shows is needed to build and operate the resource. The resulting revenue stability will allow each new project to readily secure low-cost debt financing. A new tranche, which will allow the entire electric system to balance generation with consumption in all hours, while its emissions to stay within that round's new, lower carbon constraint, will be procured in this manner every three years. With each new tranche of resources in place, the electric system will be as reliable and robust as it was before, but will have taken another step in reducing its total carbon emissions, in line with the configuration market's declining carbon budget, throughout the several decades of power sector decarbonization.

Meanwhile, the system's real-time operations will continue to be optimized by the SCED spot energy market, which will continue to efficiently dispatch the team in the various patterns needed to securely balance generation and load in each five-minute interval, and to send each resource price signals that ensure it will find it profit-maximizing to follow dispatch signals. These prices will, at a minimum, allow each resource to recover its variable operating costs, and may, subject to suitable design parameters, also provide significant opportunities to recover fixed costs and incentives for investment in new resources and divestment of existing resources.

In this way, the configuration market would integrate with and augment, rather than replace, SCED spot markets. But the configuration market will add three capabilities that SCED markets, alone or in combination with today's capacity markets, are likely to prove inadequate to deliver: (i) identification of the most efficient mixes of the complementary clean energy technologies needed for reliable, lowest cost decarbonization, (ii) a stable revenue stream sufficient for all those resources to achieve low-cost debt financing at the project level; and (iii) a means to identify and accelerate the selective retirement of resources that are impediments to efficient, reliable decarbonization.

These capabilities may be particularly important to the success of decarbonization, due to a particular form of path dependency that is prevalent in the power sector, and which can result in the long-term lock-in of existing investments, even when newer, less costly resources are available.[32] This lock-in happens primarily because many power-sector resources have much lower going-forward costs than total costs.[33] The decision to bring a new resource into operation is only rational when expected future revenues are equal to or greater than total cost, while the decision to retire an existing resource is only rational if expected revenues are less than the much-lower going-forward costs. Accordingly, existing generating resources can remain in operation for long periods during which power market prices are at or above going-forward costs, but below the higher total cost level required for investment in new resources.

Experience shows these conditions can persist for many years in over-supplied power markets, which the power sector has also been prone to, such as the more than 200 gigawatts of new gas technology built between 1999 and 2006.[34] Twenty years later, the lock-in of this oversupply continues to hamper clean energy investment. The long-term influence of this short burst of exuberant overinvestment in gas technology at the end of the last century illustrates, more generally, how susceptible the power sector is to path dependency. It underscores the fact that, during the period of rapid decarbonization, purely decentralized aggregate investment decisions could result in a substantial and long-lasting overbuild of specific clean energy technologies, and have the perverse effect of impeding further innovation and decarbonization for decades.

To avoid this, the configuration market is designed to support only efficient combinations and amounts of complementary clean energy resources during the decarbonization process, and to avoid excessive quantities of any resource type or combination of resources. Avoiding overinvestment in an imbalanced mix may be of critical importance, since such overinvestment could persistently block subsequent entry to technologies that may be essential to low cost, reliable decarbonization. The configuration market is also designed to identify and accelerate the retirement of existing resources that are inefficient in their ability to support the objective of minimizing total cost while meeting the critical constraints of hourly balancing and an increasingly stringent carbon emission budget.

The configuration market's ability to support efficient and timely retirement may be essential to successful decarbonization, given the vast current supply of operating fossil fueled resources and their natural economic tenacity, when facing current prices at or above their going forward costs, and future expected prices that many market analysts, and most predictive linear programming system dispatch models, tell them will soon return to their long-run marginal cost-based equilibrium. Along with being able to identify optimal retirement candidates, the configuration market will be able to identify and help retain nuclear and other existing resources that contribute to meeting the carbon and balancing constraints at least cost, but whose continued operation is threatened by increasingly volatile and uncertain prices in SCED markets facing ongoing waves of clean energy investment for the foreseeable future. See Section 3 (b) (iv) below.

a. Basic process framework.

i. Periodic market rounds.

To regularly procure incremental tranches of an efficient mix of complementary clean energy resources, the configuration market would hold a new procurement auction round at regular intervals. The interval should be long enough to allow for deployment of most wining projects, but short enough so that the clean energy manufacturing and development businesses can expect steady work flows over time. Such steady and growing workflows are important to assure business continuity for the supply side of the clean energy technology sector, which in turn is helpful for achieving economies of scale in production and continuous innovation and learning-by-doing benefits, such as falling costs, better performance and rapid maturation of emerging technologies.

The three-year period for the configuration market cycle proposed here is intended to strike an appropriate balance between longer and shorter cycles, with the proviso that the three-year cycle may need to recognize and support certain technologies with a longer development cycle, as may be the case for new nuclear, electricity-to-fuels and CCS-based resources. Such projects could be cleared in the configuration market for both the current and the next market round, if needed to accommodate their longer development time. More innovative, emerging technologies could also bid under a separate, innovation carve-out process specifically intended to support development, demonstration and early deployment of new clean energy technologies. See Appendix III (ii)

ii. Market hosting.

To realize the cost and reliability benefits of a geographically and technologically diverse set of renewable energy resources, the configuration market procurement process would need to be conducted on a region-wide, and therefore typically on a multi-state basis. Under the federalist approach of the Federal Power Act (FPA), the procurement process could be conducted by a variety of existing or special purpose entities.

For example, the portfolio optimization aspect of the procurement auction could be hosted by a regional transmission operator (RTO), giving suitable deference to state clean energy and GHG emission reduction goals. Or it could be hosted by a multi-state board such as those authorized under Federal Power Act Section 209(b) which would perhaps most feasibly result from multiple states agreeing to form such a board and petitioning FERC to appoint them to it, pursuant to a charter mutually developed by the states.[35] Alternatively, such a multi-state board could assign the hosting of the procurement auction to an ISO or RTO in the region comprised of the participating states. Another potential host is an ad-hoc voluntary coalition of regional balancing authorities and their associated transmission and generation owners and developers, which would resemble the de-facto structure of the Energy Imbalance Market (EIM) has gained participants in the western US.

Paying for the long-term hedges and administering the development contracts associated with them could be carried out in a variety of manners best suited to these different hosting arrangements and authorities. An RTO that files a tariff implementing the configuration market with FERC under Section 205 of the FPA could establish the payment and settlement terms associated with these hedges as part of that tariff, under existing legal authorities and precedents which allow RTOs today to conduct and settle capacity markets and to include jurisdictional transmission costs in their settlement process. This approach would be particularly well-suited to a configuration market approach that is explicitly designed to ensure resource adequacy, either by augmenting an energy-only SCED spot market or by replacing an existing capacity market. As discussed below, PRISM analysis may be particularly well-suited in a power system with large amounts of VITL resources. See section 3(b)(iii) below.

A multi-state board could apply the same authorities to any hosting organization and tariff it approves under the authority FERC delegates to it, including a regional RTO or ISO covering the participating states. Alternatively, such a state-board could design and approve the tariff of a new regional entity that would be designed to carry out the configuration market, comparable to the development and tariff approval of the EIM.

In a less fully-fledged approach, a coalition of states could, without forming a Section 209(b) state board, agree to use the clearing results of the configuration market's procurement auction as prima-facie evidence of prudence, need and reasonableness in each state's own cost-recovery proceedings for regulated utility assets, and as qualification criteria for receiving state clean energy incentives for competitive assets, without creating a centralized settlement and hedging process at all.

iii. Procurement auction optimization basics.

In each periodic procurement auction, the market host would issue a standard request for proposal (RFP) and a pro-forma contract for new clean energy projects. These projects would be evaluated through PRISM-based tools using the as-bid costs and performance parameters of each project instead of engineering economics cost assumptions or historical cost data from comparable projects, as are typically currently used in prospective PRISM studies. The configuration market's PRISM optimization process will solve for a mix of new and existing resources that can, at least cost, meet the modeled system's balancing requirement in each five-minute interval, and whose annual emissions from all those dispatch intervals are within the carbon constraint for the period in question, under a suitable variety of historical wind and solar availability conditions.[36]

The carbon constraint will ideally be based on the most current IPCC analysis of global GHG emission reductions needed to fall within an acceptably conservative risk of economic and ecological damage due to climate change.[37] There is growing evidence that the need for such carbon emission reductions is well understood and accepted by power sector resource owners, as more and more power companies and large customers set science-based emission reduction goals.[38] Procedurally, the budget could be developed and agreed to by resource owners and load participants in the configuration market, and potentially established through a tariff filing under Section 205 of the Federal Power Act.[39] Alternatively, it could be derived from aggregated state carbon emission goals and established through a multi-state accord.

In addition to the data from new resource bids, the PRISM data base would also be populated with publicly available data on existing resources' fuel types, heat-rates, energy production levels and profiles, and on historical and projected load levels and load variability. Existing transmission would also be modeled, as would proposed transmission additions approved through the regional transmission planning process.[40] Finally, existing resources that face the risk of retirement under expected SCED-based short term prices would be encourage to bid into the procurement auction at a level they deem is necessary to prevent their retirement, subject to market power mitigation. Resources, whether new or existing, that are selected through the procurement auction will be deemed to have cleared the configuration market, and will be eligible for fixed cost recovery risk management instruments, as discussed next.

iv. Fixed cost recovery risk management.

As discussed above, there are numerous reasons why a SCED-based market may fail to provide either sufficient price levels, or the volume of credit-worthy counterparties, needed to support the capitalization of the massive amount of clean energy resources required for rapid and efficient power sector decarbonization. To avoid and resolve both problems, new projects that clear the configuration market will be eligible to receive a fixed-for-variable swap at their as-bid cost for an extended period, e.g. ten years, or as appropriate for various resource types.

To be more specific, each new project will bid its levelized cost per year, expressed in terms of its expected energy production, rather than in terms of nameplate capacity, installed capacity (ICAP), unforced capacity (UCAP), or expected load carrying capability (ELCC). The bid and the pro-forma contract will be structured as a swap, in which the configuration market pays the project its as-bid levelized cost as a monthly fixed payment, and in return the configuration market transfers the project's energy market and ancillary service revenues from the SCED market to load. The pro-forma contract would also specify performance requirements, such as bidding in the SCED markets and following all their dispatch signals, as well as acceptable levels of forced outages, i.e., failure to operate when called on and when the project's underlying prime mover is available. The pro-forma and final contracts would include specific penalties, consisting of reductions in fixed payments to the project for failure to meet these performance standards.[41] These penalties would include foregone cost recovery in the event of energy or ancillary services revenues expected but not earned due to specific types of non-performance, such as abnormal levels of forced outages or failure to utilize good engineering and utility practices.[42]

The fixed cost recovery payment of these contracts will resolve both the market price volatility challenge and any missing money challenge created by future SCED-based markets, and thus support efficient financing of large volumes of clean energy resources. The performance standards in the contract will be designed to provide marginal incentives to operate and perform efficiently similar to those offered by the SCED-based spot market, but in the context of a hedge against the SCED market's risks of limiting or distorting the signals for efficient clean energy investment needed for rapid decarbonization. The configuration market would identify and provide similar hedges for existing resources that support low cost and reliable decarbonization, but face insufficient revenue certainty in the SCED markets to avoid retiring, as discussed in part 3(b)(iv) below.

v. Settlements and money flows.

Under the full-fledged configuration market, net payments to resources would be settled against load in a way similar to how capacity and transmission costs are settled in today's RTO markets, in which they are typically allocated on the basis of peak load by customer class. The key difference is that, while capacity and transmission costs settled on load are never negative, the fixed-for-variable swaps of the configuration market may settle net zero or even net negative costs on load. This is particularly likely to be the case with continued dramatic reductions in the cost of clean energy resources, and especially if the associated SCED market, along with the configuration market's resource adequacy contribution, are structured to provide significant scarcity pricing in the energy market. The combination of low clean energy fixed costs and substantial but uncertain scarcity prices would result in load serving entities receiving a substantial amount of variable market revenues through the variable leg of the swap, at precisely the time they would be exposed to prolonged, high SCED prices. Under such conditions, the total revenues received by load through the swaps could equal or exceed the amount they pay to clean energy resources through the fixed side of the swap.[43]

b. Core design details.

The cliché about the devil in the details applies more critically to market design than to many other organized activities, and good design details in some circumstances (e.g., a wholesale market serving multiple states with competitive, unbundled generation and retail electricity supply) may be bad in others (e.g., a region with vertically integrated utilities that continue to use the point-to-point and network service of Order 888's open access transmission tariff (OATT). Further, good design in any circumstance requires significant, interactive input from a variety of disciplines, experts and stakeholders, along with highly competent evaluation and implementation.

This is especially true for algorithmically assisted markets, such as today's SCED markets and the proposed configuration market, which incorporate complex digital optimization and matching in their procedures for clearing or selecting winners. The design of such markets must go beyond theoretical and empirical research in economics and auctions, to also integrate relevant computer and data-science expertise, as well as theoretical and real-world expertise in auctions, mechanism design and game theory. Additional industry-specific expertise must also be a central part of any market design, to avoid proposals that comply well with economic theory but don't work in the actual industries that use them.

In the case of the power sector, this expertise must include electrical engineering related to bulk power system design and operation; operating parameters and costs of existing and a wide variety of emerging clean generation and load management technologies, including those based on inverter technologies and other power electronics; and control systems suited for sharing the data and control signals needed by such technologies. Without applying such expertise in the technologies of tomorrow, there is a significant risk of tomorrow's markets only working well for the technologies of yesterday.

Mindful of the extensive scope of the needed expertise, and of the maxim that a little knowledge is a dangerous thing, the author offers, with some trepidation, the following sketch of details in several core areas of the configuration market. It is hoped that those with more expertise in the above areas will winnow, revise and further develop these sketches in subsequent efforts to improve and deploy early versions of the configuration market.

i. Configuration market bidding and pricing formats.

The auction literature tends to categorize auction formats by whether its bidding is open (bids are observable by other bidders) or closed, whether the price paid to winners is uniform (a single price paid to all winners) or discriminatory (a different price specific to each winner), whether those prices are based on the winning bid or the second highest bid (or second lowest in an auction to sell), whether the auction is for a single item or for multiple items, and whether the auction is to sell items or procure them. As envisioned here, the configuration market will be a sealed bid (closed), discriminatory (pay-as-bid), first-price, multiple-unit procurement auction.

To spell out some of the implications and reasoning for these choices, we consider what they mean in the configuration market process. First, the revenue hedging contracts awarded to new projects that clear in the configuration market will be priced based on the sealed bid of each cleared project, rather than on a uniform price as is provided for in current capacity and SCED-based energy markets. Sealed bids are preferred because the cost of each project is fundamentally a private value, that is, it is known by the bidder, and that cost is not determined or even determined by the costs of other projects. Open bids are generally thought to be efficiency-enhancing when each bidder's value is not private, and hence is not independent of that of other bidders. In such cases, open bidding helps bidders develop a better sense of the true value, and hence to bid at it. With private values, there is no additional information needed for each bidder to know and bid at the value. And, at least in simple auctions with private values, open and closed bids have equivalent equilibrium bidding strategies, so they can be considered equivalent.[44] Further, open bids in practice tend to increase the potential for collusion and bid rigging, which in the configuration auction would result in excess profits for winning bidders and excess costs for the buyer. Finally, sealed bids are widely used in procurement auctions in the power sector and elsewhere, and are thus familiar and acceptable to power sector project developers. For all these reasons, the configuration market, as proposed here, will use sealed bids.

Discriminatory prices are proposed instead of the uniform-price auctions used in current capacity markets and SCED energy markets. This is because the configuration market will procure substantially different types of resources, in combinations in which those resources are complementary inputs to producing reliable electricity, rather than procuring combinations of perfect or near perfect substitutes. Uniform price auctions are feasible for multiple products that are close substitutes, but are not typically used for procuring multiple complementary inputs to a production process. In practice, complements in production are usually procured either separately in amounts dictated by a production recipe, or in some sort of a combinatorial or "package" auction that can identify the lowest cost combinations that provide, or add up to, an efficient mix of needed inputs. Either of these approaches result in different prices for different resources or combinations of resources, rather than a single price for all resources. Since the configuration market is a type of combinatorial procurement auction that will identify the overall package of efficient complementary inputs, and since those inputs are expected to vary widely in their cost and performance characteristics, discriminatory pricing is the preferred, and potentially the only, option.[45]

Discriminatory prices in an auction could result from a variety of pricing rules, but pay-as-bid is recommended here due primarily to its widespread use in procurement processes throughout the business and public sectors. The widespread practice of using pay-as-bid prices in procurement auctions is sometimes criticized as inefficient, under the not uncommon view that second-price auctions are generally more efficient than first-price auctions. However, in a multiple-item auction, neither second-price nor first-price auctions have clearly superior theoretical efficiency benefits -- and, with large numbers of bidders, optimal bid prices in a sealed bid, first-price auctions approach those of the second-price auction.[46] These considerations, coupled with the practical merits of the widespread use in procurement of pay-as-bid pricing, and the additional challenges of uniform pricing across strongly complementary combinations of inputs suggest pay-as-bid pricing will be the best approach in the configuration market.[47]

ii. Carbon constraints in the configuration market and implications for carbon pricing policies.

In each period, the configuration market's PRISM-based bid evaluation process would identify the set of all resources that minimize the total cost of the system while meeting two specific constraints. First, the winning resource set must be selected to be capable of balancing aggregate energy production with projected aggregate energy consumption in each dispatch interval while maintaining adequate reserves, considering a wide variety of weather-related variations in solar irradiance and wind-speed at each existing and newly bid wind and solar site. Second, the winning resource set must be selected so that, in their operation to achieve this continual balancing, their aggregate CO_2 emissions do not exceed more than a pre-specified amount each year. The winning resource set is also selected to be the cost-minimizing set from among all the other sets that might meet these two key constraints.

Under conditions of demand growth and the spontaneous retirement of existing plants, the PRISM process would deploy additional new resources capable of meeting both constraints at least cost. If demand is projected to be flat or fall, or if no existing plants spontaneously plan to retire, the carbon constraint would be expected to identify retirement or reduced operation at specific existing plants, potentially accompanied by the deployment of new clean resources, as needed to meet the carbon constraint and the balancing constraint at least cost. New resources from among those bidding into the configuration market, that are identified as part of the total resource mix best suited to meeting these constraints at least cost, would be deemed the winners of the configuration market, and would be offered the hedging contracts discussed above. The inclusion of this binding carbon constraint in the PRISM clearing mechanism raises the question of whether such a constraint would be sufficient, in the absence of a carbon price being included in the spot market's SCED optimization process, to achieve the targeted emission reduction pathway. The author's view is that a suitable carbon price applied in the SCED market would enhance the efficiency of the configuration market, but is not absolutely essential for it to achieve the intended GHG reductions over time. The reasoning is as follows.

PRISM analysis doesn't typically assume a price on carbon as an extra fuel cost in order to keep GHG emissions within the constraint. Instead it solves for resources whose efficient operation meets the carbon constraint along with the hourly balancing constraint, which simulates the SCED market's dispatch. While this set of resources may (or may not) have higher total costs than a fossil-heavy mix of resources, any such higher costs result in the model from paying for clean resources which are then constrained to balance efficiently in each dispatch interval, not from increasing the marginal cost of generation from fossil resources as a price on carbon would. The PRISM analysis' accelerated clean energy deployment and its increased simulated dispatch of clean resources to meet the carbon and balancing constraints are what drive the modeled carbon reductions, with no assumption of or (in the model, need for) a price on the carbon content of fossil fuel. Meeting the carbon constraint in the model, however, does produce a shadow price on the carbon constraint. This shadow price can be interpreted as an efficient price on carbon, but it results from changing the resource mix to produce an efficient dispatch within the carbon budget, rather than from finding the price on fossil fuels' carbon content that would eventually produce a similarly low carbon resource mix and dispatch.

Accordingly, we should expect the configuration market's carbon constraint to tend, for the same reason, to reduce an electric system's emissions in the real world. These real-world reductions would result from the deployment of more clean energy resources with zero marginal costs, which will shift the dispatch supply curve to the right, resulting in less generation from higher emitting resources, which have higher marginal costs, and in more generation from clean resources, resulting in reduced GHG emissions. Further, such deployment should cause the overall supply to increase, relative to demand, due to the deployment of additional clean resources, causing – all else equal -- prices in the SCED market to fall. The combination of reduced dispatch and falling SCED prices should, at least directionally, lead to additional retirements of some existing fossil resources, further reducing emissions.

Over time, this reduction should at least trend toward the same reduction path as the configuration market's carbon budget, assuming the PRISM tools and data are continually improved to more accurately simulate the electric system and its operation. Still, the actual realized emission path may not be entirely consistent with the reductions anticipated to result from each round of the configuration market. For example, the dispatch simulated by the balancing constraint in the PRISM projection could be biased relative to the real world dispatch, which reflects many system dispatch variables, such as electric system topology and its constraints, varying fuel prices and demand levels, weather, and resource availability, that are simplified in the model or restricted to less variability than may occur in the real world. Further, the incentives to retire during periods of oversupply depend critically on the expectations of future market fundamentals held by the owners of existing resources, as discussed in section 3(b)(iv) below.

Given the uncertainty regarding how well the configuration market's carbon constraint would translate into real world emission reductions, an appropriate price on carbon applied in the actual SCED market dispatch would certainly help actual GHG emissions to better align with the market's carbon constraint. For starters, a carbon price affecting the SCED market would also provide increased energy revenues to existing clean energy resources, which could reduce their vulnerability to retirement during periods of suppressed or uncertain SCED market revenues. Similarly, a carbon price affecting SCED participants would increase the SCED market's own incentives for new clean firm and clean flexible technologies to compete with fossil resources (including clean fuels competing with natural gas for use in combustion technologies), resulting in faster displacement of GHG emissions in operations than would result from the configuration market alone. These price driven incentives could be particularly effective in supporting the efficient deployment of distributed clean energy resources, which may not find it economically or operationally viable to participate in the configuration market.

A dispatch-level price on carbon would also help solve the asymmetric entry and retirement signals provided by the SCED market discussed above, and facilitate the efficient retirement of plants that do not contribute to meeting the PRISM market's carbon constraint. A price on carbon in the dispatch market would push the less efficient, higher marginal cost fossil plants even further out of the money, leading to their more rapid retirement or conversion (in the case of suitable gas turbine technologies) to a special category of reserves that would primarily be needed for longer lulls in the availability of wind and solar irradiance.[48] An upstream price on the carbon in fuels, including that used in stand-by generators on customer premises, would help avoid the leakage to the customer side of the market that would result from a carbon price that only applies in the SCED market. Incentives to develop clean alternatives to such increased fossil fuel use could be particularly important, on both the grid side and the customer side of the market, during extended periods of low wind and solar output and exhausted storage capacity.

All such SCED-based carbon prices, however, if applied only in part of an electric interconnection, will be subject to leakage, in that emissions displaced by raising the dispatch costs of those fossil fueled power plants that are subject to the price on carbon will tend to be replaced by the dispatch of comparable fossil resources that are not. Similarly, leakage will be most significant within a single RTO's SCED market than among different RTOs in the same interconnection, due to the integrated marginal cost-based dispatch within each SCED market.

Leakage, however, should be much less of a problem for configuration market-based emission reductions, which are caused not by raising the dispatch cost of emitting power plants, but by deploying more non-emitting power plants with both lower marginal costs and lower emissions than the emitting plants. Configuration market-based clean energy resources will further avoid leakage due to being deployed in combinations that meet the overall carbon constraint by displacing fossil resource generation most efficiently. Unlike a price on carbon in sub-jurisdictions, this will avoid leakage, since the cleaner plants will have a dispatch advantage over all fossil fuel plants that can run to serve the same load. Indeed, the regional configuration market should have the effect of actively reducing leakage due to sub-jurisdictional carbon prices, by deploying clean energy resources in the optimal combinations to meet both the balancing and the carbon constraint.

In sum, the configuration market should be able to help support and achieve rapid decarbonization without a carbon price in the SCED markets that operate in the same territory. But there is little doubt that decarbonization would work better and more efficiently if such a carbon price were imposed on all fossil fuels, and reflected uniformly across each SCED market's dispatch, to reinforce and help true up the configuration market's emission reductions. Without such market-wide uniformity, significant leakage of emissions from power plants subject to the carbon price, to those not subject to it, would dilute a carbon price's benefit. Even in such a suboptimal situation, however, a regional configuration market should reduce the amount of such leakage, by deploying clean energy resources in combinations that displace fossil generation anywhere in the region in a highly cost-effective manner.

iii. Resource adequacy and the configuration market.

In the US power sector, the term "resource adequacy" means having enough aggregate generating capacity installed and available in a broad, interconnected region, to provide an acceptable probability of being able to meet above average peak load levels, and thus to avoid the alternative of needing to deploy controlled load shedding.[49] Insufficient resources at the time of peak loads will depress the power grid's frequency, with the same potential for cascading failures, as would significant generation shortages at any other time. Hence resource adequacy is governed by reliability requirements and standards similar to those governing underfrequency events, including the requirement for distribution utilities to shed load in rolling blackouts if reserves fall below required levels.

Smaller geographical or political areas within such an interconnection may each have their own standards and rules for ensuring resource adequacy, but avoiding a cascading failure is dependent on each such sub-area ensuring their share of the amount of generation needed across the entire interconnection. Resource adequacy is currently defined and maintained in North America through a hierarchical system of such requirements and a variety of standards and incentive systems at the interconnection, regional, state and sometimes sub-state levels.[50]

The emergence of VITL resources as significant or even predominant sources of energy production and balancing control is likely to require fundamental changes to the definition and the management of resource adequacy. The reason is that, as discussed above, the historical resources relied on during the development of current approaches to resource adequacy were generally capable of being dispatched, at any time, at or up from their economic minimum output level, to their maximum output. As a result, aggregate output could always be adjusted upwards to the total installed capacity in megawatts of all resources that are mechanically sound. Accordingly, as long as there are enough megawatts of installed fossil and similarly dispatchable capacity to meet peak loads and concurrent outages at significantly higher than their expected levels, there will a very high probability that load shedding will not be needed at peak time and at all times of lower aggregate energy consumption. Historically, joint probabilities of generator outages and higher than normal levels of load have been used to determine how many megawatts of generation are needed to meet a pre-determined probability of load shedding. The conservative probability of one load shedding event per ten years is currently used as the standard for resource adequacy across much of North America.[51] This standard typically produces a resource adequacy requirement of very roughly fifteen percent more generation than peak load. Using the same analytical approach, it would be perfectly possible to identify a much less conservative resource adequacy standard, such as one load shedding event per six years, or per year, which would then produce a lower resource adequacy requirement.

As we have seen, VITL technologies, due to their stochastic availability, lack the additive and highly substitutable operating characteristics of fossil fuels. This makes it more challenging to figure out how much the installed capacity of various combinations of VITL resources actually contributes to resource adequacy. It also raises the possibility that resources may be inadequate to match load not just at times of extremely high load, but also at times of extremely low availability of wind, solar, and charged storage devices. Both problems call for a new approach to measuring resource adequacy and identifying suitable amounts and types of resources able to assure it at higher levels of deployment of VITL technologies. As with the current analytical approach, a new approach could be used to determine a variety of more or less conservative resource adequacy standards, with corresponding different system configurations meeting those standards. However, such compliant configurations would not necessarily be measurable in megawatts. For example, a high VITL configuration in a given electric system could require many more installed megawatts to meet a one event per six years standard than the megawatts needed by a high "clean firm" configuration in the same system to meet a one event per ten years standard.

PRISM analysis of efficient technology combinations could simplify and standardize approaches to determining the resource mixes needed to meet various levels of resource adequacy, in a world where the resource requirements to meet a given standard vary with the type of resources deployed. Just as different mixes of resources that can meet the balancing constraint can vary dramatically in their cost and their carbon emissions, we should expect different mixes of resources that can meet a given resource adequacy standard to vary dramatically in their cost and carbon emissions. Accordingly, it could be highly efficient to use the same optimization tools to co-optimize, or to help co-optimize, the resource mix that meets resource adequacy standards, along with the balancing and carbon constraint, at least cost.

PRISM optimization seems well poised to serve such a function, since its balancing constraint already identifies an aggregate mix of resources complementary in matching their combined output to aggregate load at all times, including at times of the highest likely peak load and during prolonged periods of little or no wind and solar energy production. PRISM tools could help identify the combinations of clean energy resources, and if necessary, limited amounts of fossil fuel use, needed to meet a given level of resource adequacy.[52] And, consistent with the observation of Schlag et al. (2020) that the capacity value of various VITL technologies decreases at higher deployment levels, PRISM analysis would be particularly useful in helping to identify the evolving combinations of clean energy resources that will be support specific resource adequacy standards as VITL deployment increases.

Further, the greater accuracy and precision of PRISM analysis should allow better evaluation of the impact of high levels of renewable resources on the frequency, expected value and revenue incidence of scarcity prices of procuring various amounts and combinations of clean energy resources through the configuration market. This could potentially allow the configuration market to be designed to achieve a minimum or “floor” level of adequacy, such as, for example, a one-in-five instead of a one-in-ten LOLE. This would provide a base-line protection against an extreme frequency of involuntary load-shedding events, while still allowing the SCED market to produce frequent enough scarcity prices to incentivize additional investments, on both the supply and the demand side of the market, to provide any higher levels of reliability desired by customers.

For example, the analysis of ERCOT reserve margins in Brattle (2018) suggests that a reserve margin of about 8% will result from that market’s SCED-based scarcity pricing mechanism. If a configuration market in a comparable region were designed to provide the high VITL equivalent of a 6% reserve margin, it stands to reason that there would still be relatively frequent and robust scarcity pricing in the SCED market. The resulting price risk could then spur additional, fully decentralized, investment in technologies that would manage customer price and disconnection risk, driving the effective reserve margin to the same level as ERCOT’s current market design.

Under such an approach, the configuration market could serve primarily as a low-cost, widely available hedge for those resources that find suitable levels of voluntary hedging in the secondary market unobtainable or prohibitively expensive. At the same time, scarcity prices due to periodic reserve shortages in the SCED market would continue to drive those facing price risk to enter into both physical and financial hedges of the price and reliability risks that would result from the otherwise slightly undersupplied market. These hedges would support additional investment, outside the configuration market, in the types of supply side and demand side resources needed to help balance the system during periods of supply shortfalls, and thus achieve a market-based level of resource adequacy, above the floor level designed into the configuration market.

One might anticipate that more capital intensive, large scale clean energy resources would choose to participate in the configuration market, due to the low cost longer term debt financing it would support, while smaller scale, less capital intensive clean energy resources, including those most frequently needed to manage localized distribution system power outages, would skip the configuration market due to their ability to capitalize without large amounts of long term debt, and the unlimited upside they would face in the SCED market's potentially very high, but irregular, scarcity events.

There is, however, a risk that the most popular decentralized response to such scarcity would be large amounts of fossil stand-by generation, which may be among the only economic, locally available resource that can be relied on during extended periods of low wind, solar and battery availability. Indeed, in the absence of a comprehensive, upstream price on the carbon content of all fuels, distributed fossil generation could become a convenient and popular way of bypassing, and thereby defeating, the configuration market's carbon constraint. If such bypass can be prevented, such a hybrid "configuration plus SCED" market approach to resource adequacy could potentially provide the best of both worlds – the strong, decentralized incentives for efficient operation and scarcity management of SCED markets, along with the efficient combinations of highly complementary, long-lived and capital-intensive investments in clean energy resources needed to maintain interconnection frequency while achieving rapid decarbonization.

iv. Retirement bids in the configuration market.

Current LP models used to predict prices and the most efficient expansion path in the electric sector are designed to both add and retire resources in response to the prices and revenues created by the interaction, within the model, of supply and demand. In the author's experience, these models deal with the asymmetry of market price signals for entry and exit (i.e., expected prices at long-run marginal cost and going-forward costs, respectively) as follows. If the prices and dispatch generated in the model are not sufficient to meet some predetermined level of revenue sufficiency for a particular resource in the model, the resource is "flagged" for retirement, and excluded from subsequent runs of the model. Initial oversupply conditions in the model can generate such revenue shortfalls and retirement flags, but resources can also be flagged based on their age, their need for new pollution control equipment, or other features that serve as proxies for major capital expenditure needs. When enough resources have been flagged and removed, prices reach a level that supports entry, and at that point, the model deploys just enough of the most efficient resource type or types to maintain that equilibrium in the lowest cost manner. Typically, that equilibrium is reached fairly quickly, since most of the LP models used for projecting prices and other market fundamentals assume perfect foresight – unlike the configuration market, as discussed in Appendix III(i) below.

The configuration market's PRISM clearing mechanism will use a protocol similar that discussed above for identifying and flagging resources for retirement. Such flagging, on its own, would merely predict the retirement of the flagged resources, without actually causing it. Indeed, such predicted retirements may very well not happen, since the flagged resource owners may face significant incentives not to retire assets that are not easy to include in an optimization model.

Such incentives, in the author's experience, stem from resource owners' expectations of price recovery due to either other units retiring first, or to a more broad-based return to market equilibrium. The first set of expectations often create a game of "chicken", in which a resource owner believes the winning strategy is to not retire its own ailing assets as long as there are other owners of assets who might retire theirs first. The second set of expectations points to a similar strategy, under which resource owners believe it is profit maximizing to continue to operate at a temporary loss so as to reap the higher value of the affected assets as power prices return to equilibrium, which many believe categorically will happen.

This “equilibrium is coming soon” view on the part of resource owners is shared, and reinforced, by many investment fund managers, sell-side and buy-side analysts, investment bankers that promote and support power sector M&A activity, and many of the individuals who sit on power sector boards of directors. It is even more fully entrenched by LP models used across the power sector to project power prices and market fundamentals, since these models are hard-wired to produce an equilibrium expeditiously, and can’t readily be used to predict an extended disequilibrium. The “equilibrium is coming soon” view is often further reinforced by some market designers who view it as irrational to not expect a market, and especially SCED spot markets, to return to equilibrium quickly. Given the pervasiveness of this view, and the confirmation bias it supports among the owners of existing resources, countering it is likely to be a major challenge during an extended period of rapid decarbonization.[53]

Even without a special retirement mechanism, the configuration market would tend to counter both the game of “chicken” and the “equilibrium is coming soon” incentives that can interfere with rational retirement decisions. First, simply by flagging resources for retirement in the PRISM clearing mechanism, the configuration market would assume the resources do actually retire, and find the least cost mix of additional new resources that, together with the remaining existing resources, meet the market’s balancing and carbon constraints at the lowest cost. These hedging contracts offered to these new resources would induce their development, so they would be physically added to the system, increasing overall supply relative to demand. This relative increase in supply will reduce the incidence and intensity of scarcity prices in the SCED market, and over time, without retirements of existing resources, lead to continually lower SCED prices. The persistent ratcheting down of the carbon constraint in the configuration market over time will repeatedly drive additional such rounds of clean energy deployment, making it clear that equilibrium is not really coming until the decarbonization goal is actually achieved, regardless of whether a few or many existing plants retire in any given year.

SCED spot market prices may recover periodically as a result of significant retirements, but in between there will be longer periods with prices depressed by the addition in each market round of the new clean energy resources needed to meet the configuration market’s declining carbon constraint. Further, due to the combined effect of oversupply during periods of low levels of retirement, continually growing displacement of fossil energy production by the clean resources introduced in each market round, and a minimum floor on resource adequacy levels supported by the configuration market, existing resources should expect continually falling SCED spot market revenues.[54]

As a result, it will no longer be rational to expect either to win the short-term game of chicken or the longer-term game of waiting for equilibrium. Accordingly, owners of resources that earn insufficient revenues in the SCED spot market to cover their going forward costs will cut their losses by retiring those resources and investing their incremental capital instead in new clean energy projects that are likely to clear the configuration market and produce earnings at least through the tenor of the hedging contracts.

v. Retirement bidding to retain key existing clean energy resources. Unfortunately, this same ongoing cycle of SCED spot market prices below the levels that would sustain all existing resources could result in the retirement of zero- and low-carbon existing resources, even if they are not flagged for retirement by the PRISM clearing mechanism. For example, otherwise viable existing nuclear plants and post-PPA, merchant wind and solar resources could be forced into retirement, despite their potentially valuable contributions to the balancing and carbon constraint. Similarly, efficient existing natural gas capacity that could be essential to maintain for use during extended periods of low wind and solar insolation, would be dependent on SCED spot market prices, and hence may also face incentives to retire under the ongoing addition of clean energy resources by the configuration market. While a carbon price affecting the SCED dispatch, consistent with the shadow price of carbon in the configuration market's PRISM clearing mechanism, could help avoid this result, it would not necessarily prevent it.[55]

To prevent the inefficient retirement of resources that the configuration market finds would contribute to meeting the balancing, carbon and cost constraints, existing resources that anticipate recovering too little money in the SCED markets to be able to remain in operation would be able to bid their going forward costs, inclusive of planned major capital expenditures and the required return on incremental invested capital, into the configuration market. Any such resources not flagged for retirement in the configuration market's PRISM bid evaluation would be cleared, and offered a hedge at the level of their going-forward costs, which would be available until the next configuration market round, and which could be rebid at that time. Market power concerns and mitigation regarding retirement bids are discussed in part III of the Appendix.

To be clear, existing resources that are flagged for retirement will not be offered a going-forward cost hedge, regardless of whether they submit retirement bids. If the owners of such resources want to keep operating them in the hopes of recovering sufficient costs in the SCED market, despite their flagged status (which should, as material information, be disclosed in the owner's filings with the Securities and Exchange Commission), they will be free to do so. The broad knowledge of the mechanics and trends of the configuration market among investors and asset owners, however, would tend to undermine both the "game of chicken" and the "equilibrium is coming soon" reasons for delaying plant retirements, leading to their timely retirement. Accordingly, this paper does not propose or further develop the concept put forward in earlier versions of the configuration market, of paying retirement incentives to such plants.

v. Transmission-contingent resources and projects.

Efficient transmission development, including getting the right balance between regulated transmission and competitive generation, has always been a challenge for the power sector.[56] The combination of significantly different functions, regulatory and cost-recovery regimes, and development time-frames, as well as the fact that transmission can function as both a complement to and a substitute for generation in specific locations, have all contributed to this challenge. This could be a major challenge for rapid, deep decarbonization, which may depend to a significant degree on new wind and solar projects in regions with rich wind and insolation regimes, but also with limited existing transmission links to major load centers.

Such transmission dependence also poses a particular challenge for the configuration market, since many clean energy resources that could be competitive in regions with excellent wind and insolation regimes will be unable to bid in the configuration market due to a lack of pre-existing transmission.

Earlier versions of the configuration market concept suggested that new transmission lines would themselves bid into the configuration market, in which they would clear if they supported, and were a part of, the least-cost combination of resources that would meet the PRISM constraints of robust system balancing and a binding carbon budget. Reviewers raised a number of valid concerns about the feasibility of this approach. Accordingly, the proposal has evolved to use prospective scenario analysis, as described in part III(i) of the Appendix, to enhance both transmission planning and to elicit bids from projects that would not be feasible, and therefore not bid at all, in the absence of major transmission enhancements.

Under this new approach, in each market round, the configuration market host, using the market's data and PRISM tools, would generate several different scenarios with optimized amounts of wind and solar development, as part of the overall efficient resource mix identified in the scenarios. Specifically, one set of scenarios would assume no new transmission, and another set of scenarios would allow and co-optimize new transmission development with deployment of new wind and solar. Within each set of scenarios, sub-scenarios would consider alternative reasonable assumptions for the future costs and availability of clean technologies which, in appropriate combinations, can serve as substantial substitutes for optimized portfolios of new transmission-dependent wind and solar, e.g., as clean firm technologies and VITL technologies are substitutes in Sepulveda et al. (2018). The end result of the scenario analysis would be an estimate of the cost-effectiveness, in terms of reductions in overall system costs, due to specific new transmission expansion to support specific amounts of new solar and wind in the most promising locations.

Where specific new transmission assets to support additional solar and wind development were found to meet an appropriate threshold of cost-effectiveness, compared to non-transmission alternatives, two parallel steps would result.[57] In the first step, the optimal new transmission development would be included in the regional transmission plan, where it could be met by either merchant or regulated transmission developers, with its costs allocated according to the relevant formulas and protocols for the region. In the second step, the next round of the configuration market would include a specific request for proposal (RFP) for bids to develop wind and solar resources in the region or regions to be served by the planned transmission line, with the awarding of contracts for winning bids contingent on the completion of the line. The RFP would also identify the expected interconnection costs to be borne by new projects, based on the projected costs used in the scenario analysis and the existing cost-allocation methodologies approved by FERC. Such transmission-contingent bids would then be cleared like other bids, but the conditions precedent for initiating the revenue-hedging agreement for such projects would include the permitting and completion of the transmission line according to a reasonable schedule.

vi. Distributed energy resources.

This proposal considers distributed energy resources (DERs), such as distributed storage, distributed generation, and smart devices that optimize the time of use of electricity, as likely primarily to be deployed by consumers or their agents in order to reduce the cost, price risk and delivery risk of their energy purchases in the SCED-based markets. As such, these resources would contribute indirectly to the configuration market through the modifications to aggregate demand profiles that each market round of the configuration market considers in selecting optimal supply side portfolios and in allocating costs to load through the settlement process. The interaction of DERs with the configuration market's financial settlement process will need to be carefully considered, due to the potential for settlement based on factors such as a load-entity's four highest annual coincident peaks, to create incentives to deploy distributed resources to simply reduce the entity's allocation of costs, rather than to reduce the overall system's costs or contribute in an efficient manner to its resource adequacy.[58]

Demand side resources are likely to participate in SCED-based markets either passively, by simply modifying the time-of-use of grid energy, or actively, by bidding into energy and ancillary services market. Active participation is generally envisioned for either aggregated demand-side resources, or larger individual distributed resources, such as commercial and industrial customer standby-generation, storage or load modification. Demand-side resources that participate actively in SCED-based markets could also participate in the configuration market. This is certainly analytically feasible, since some of today's PRISM tools are designed to be able to include demand-side resources, including VITL technologies, in their optimization process.[59]

For such bids to be evaluated in the configuration market's PRISM clearing process, their expected operating parameters, dispatch, and payments from the SCED market would need to be knowable, since the PRISM process solves for their efficient utilization in each dispatch interval it calculates. These performance characteristics and utilization rates will depend, not only on customer-facing aspects of each DERs value proposition and the financial arrangements between the aggregator and the customer, but also on the SCED market's DER participation and dispatch rules, and potentially on the way any distribution system constraints affecting DER operation are resolved and co-optimized with the SCED market's participation rules. All of this suggests that aggregated DER participation in the configuration market will need to be evaluated and, if feasible and valuable, designed and implemented after their integration into SCED markets and the development of efficient distribution system tools for supporting such integration while maintaining safety and reliability at the distribution level.

Meanwhile, during this period of DER integration into SCED markets, which may actually now be underway due to the recent issuance of Order 2222 by the FERC, PRISM scenario analysis can play a significant role in helping explore and parameterize the role various amounts and types of DERs could play in low cost, reliable electric system decarbonization. Questions such as how cost-effective DERs can be at balancing growing levels of wind and solar power, what amounts and types of DERS can best perform this role, and the role of such controllable DERs in the electrification of transportation and the built environment are currently the subject of much speculation and conflicting beliefs, but not enough PRISM-style analysis. Answering these questions can, in turn, help rationalize the ongoing wave of "grid modernization", "non-wires alternatives" and distribution system planning proceedings and initiatives underway in many states, while also helping identify the minimum-efficient scale and most beneficial approach to distributed energy resources management systems (DERMS), which often seem to be treated today as categorically good, in a monotonically increasing way. PRISM analysis of their potential contributions of value to the bulk power system can help parameterize and rationalize these discussions, and so help ensure the most value-enhancing deployment of DERS, DERMs and related distribution system control and management systems.

vii. Self-supply options.

Some RTO capacity markets have provisions for load serving entities to opt-out of the capacity market settlement process, and instead to self-supply a comparable level of capacity in order to meet their share of the region's resource adequacy requirement.[60] The configuration market as proposed here would also have two self-supply options, to recognize that for a variety of reasons an LSE, large customer, or group of such load interests may prefer to identify and select its own set of clean energy resources, rather than defer or delegate that decision to the configuration market.

The first option for self-supply is a buy-all, sell-all (BASA) approach. In this approach, the self-supply entity would bid all the projects it intends to use to meet its own clean energy objectives into the configuration market, and would simply net the revenues it receives from all cleared projects against the configuration market's load charges in the settlement process.

The second option is a virtually optimized (VO) approach. Here, the self-supply entity would develop its supply portfolio independent of the configuration market. However, to ensure that self-supply entities are paying a fair share of the costs of meeting the balancing and carbon constraints of the entire system they are part of, self-supply entities would be required to submit independently verified cost and operating characteristics of their resources to the configuration market.

Based on these costs and characteristics, the self-supply resources of each self-supply entity would be evaluated through two PRISM scenarios based on the pending market round data. One scenario would require the clearing of the self-supply resources, and the other would exclude them. If the total costs are no higher in the scenario with the self-supply resources, the self-supply option would be approved with no settlement required. If the total costs due to the self-supply resources are higher in the scenario that includes the self-supplied resources, the self-supply entity would be able to choose to (a) either proceed with developing the self-supply resources, while paying an additional fee through the settlement process based on the incremental costs its self-supply portfolio would impose on all other customers, or (b) convert to a BASA approach. To facilitate the development of effective self-supply bids, the configuration market host would facilitate use of its data and comparable PRISM tools by self-supply entities, between rounds of the configuration market, to explore resource mixes and bid levels that would be likely to clear.

viii. The path from design vision to viable product. The details provided above in section 3 and in the Appendix go into a number of the topics that must be considered in even a modestly complete market design proposal. Such detail is particularly useful to help review how well a market design proposal hangs together, and if any critical elements are missing or incompatible. While this level of detail is important, it also runs the risk of making the configuration market concept seem more final and ready for implementation than it really is. Like any new product, a market design needs a well-thought out initial design vision, but it also needs careful and flexible product development to ensure the ultimate design actually works well, meets customer, user and society's needs, and can be produced and delivered at an attractive cost. Accordingly, this paper turns now to a number of early, incremental modes for deploying and using PRISM analysis in ways that would allow testing and learning-by-doing opportunities to help the configuration market succeed.

4. Incremental implementation modes and paths.

In many examples of successful innovation, products are developed incrementally, through an iterative process of testing both product design and effectiveness against the needs of specific target customers. Though this approach, product design and function evolve with the entrepreneur's growing awareness of customer needs and value, and as a result, innovative products can be tailored to best meet the needs of a growing market at a cost that enhances the products adoption.[61] Such an entrepreneurial strategy for developing and deploying new market designs could avoid a number of the cost over-run and integration challenges that plagued the roll-out of nodal market SCED systems in a number of US markets, while producing a final market design that is tailored to the unique but still emergent features of electric systems with high levels of VITL technologies.

Such an entrepreneurial approach could start PRISM data and tools being used in several early deployment modes, which would support continued refinement of the tools and the additional of incremental design characteristics that would end up, if all goes well, in a full-fledged configuration market.

i. Clean energy planning and policy development.

PRISM tools are increasingly being used today in this mode, which is a natural outgrowth of traditional utility resource planning and competitive power company strategic analysis.[62] Growing levels of VITL technology deployment are helping drive this use, since traditional linear programming tools used in the power sector, which base estimates of renewable energy availability simply on average capacity factors, do a poor job of identifying the contribution to real-time balancing that such resources can actually make. More widespread use of PRISM analysis with standardized, accurate data sets and recent, market-based cost data would provide participating organizations, policy-makers, and power sector companies with much better insights into efficient combinations of VITL technologies to support, accommodate and actually develop.

Such use could materially improve investment and operating efficiencies among companies, states and provinces in a common RTO or interconnection footprint, such as among the PJM states and the EIM participants. One can imagine, for example, the use of such tools by EIM participants creating the same kind of savings, in terms of the efficiency of their long-run investment plans, that the EIM currently brings them with respect to their short-run interchange scheduling plans. Potential users of PRISM tools for clean energy policy and planning include:

- Utilities, clean energy developers and state regulators in multiple states in a single interconnection seeking converging policies and strategies to achieve at least the early stages of deep decarbonization in an efficient manner;
- RTOs and regional balancing authorities developing regional transmission expansion plans that incorporate and facilitate state energy policy goals;
- Corporate buyers seeking to go beyond REC-based and other non-time-stamped approaches to achieving their clean energy and decarbonization goals.
- Cooperative and municipal utility organizations seeking to coordinate their decarbonization efforts across the G&T and distribution roles on a sub-regional or regional basis.

ii. Identification of preferred resource mixes. A number of states, utilities and private companies have identified various types of clean energy resources as "preferred resources". Such resources may be weighted more highly in resource plans, utility cost recovery proceedings, or competitive procurement proceedings. Generally, such preferences are developed without consideration of the actual effects of the preferred resources on system cost, balancing, or GHG emissions. PRISM analysis could improve the efficiency and accuracy of such investment priorities, by focusing them on resource types and amounts which, if deployed, would actually contribute to lower costs, continued or enhanced reliability, and the most cost-effective reductions in power sector GHG emissions.

iii. Incentive eligibility. PRISM analysis could also be used to determine the eligibility of specific resources and projects for state, federal or voluntary market clean energy incentives, such as tax credits, renewable energy credits, clean electricity standard credits, or a variety of voluntary environmental credits or seals of approval. For example, a clean electricity standard could provide full eligibility for clean energy credits to the quantity of megawatts of various resource types identified in a suitable PRISM analysis, with lower or no credit levels awarded to resources that exceed the optimal levels.

iv. Competitive Procurement. Several jurisdictions and utilities use competitive procurement as ways to meet clean energy goals, and often use existing LP tools to help develop the resource plans that dictate the quantities and types of resources to procure. In some recent cases, the competitive procurement and resource planning processes have begun to merge into a competitive planning process.[63] In such a process, bids from the competitive procurement process are used as inputs into system expansion plan phase of the planning process, rather than using the typical engineering cost assumptions, e.g., as described in Wilson et al. (2020). The results of the planning process then can include the issuance of power purchase agreements to the developers selected by the system expansion plan model. This saves the administrative costs and time associated conducting a separate procurement process after the planning process is done, and assures the plan is based on the real costs of projects that are actually available, rather than on engineering assumptions.

In cases, such as HECO's, where the planner already uses PRISM tools to find the optimal mix of clean energy resources, such a competitive procurement process will have a basic structure somewhat like that of the proposed configuration market. As such, this kind of hybrid planning and procurement process may be the best early deployment and development opportunity for the configuration market itself. For example, a PRISM based procurement mechanism could be used by states that require a mix of IRP and competitive procurement by their LSEs, or by individual utilities or regional groups of utilities seeking to achieve high levels of efficient decarbonization. IPP projects could be procured through power purchase agreements offered directly by the utilities, while cost-regulated projects would be able to offer their winning status and as-bid costs as prima-facie evidence in state jurisdictional rate cases and other cost-recovery proceedings, and jurisdictional regulators could choose the probative value to assign to such evidence. Indeed, this same regulated cost recovery approach could be used in the configuration market itself, in regions where there are both IPP and regulated utility resources are developed.

Increased use of PRISM tools in all of these early deployment opportunities would support the rapid development and enhancement of the models, data sets, and related system analysis tools to better support the market clearing function envisioned in the configuration market over time. At the same time, sequential development along such a pathway would support learning-by-doing across the evolving configuration market value network. In particular, each of these phases or modes of deployment would identify strengths and weaknesses in the PRISM approach which would need to be enhanced or solved in future iterations for the configuration market itself to work efficiently and create real value for its users and their end customers, including the support of efficient, reliable and rapid decarbonization.

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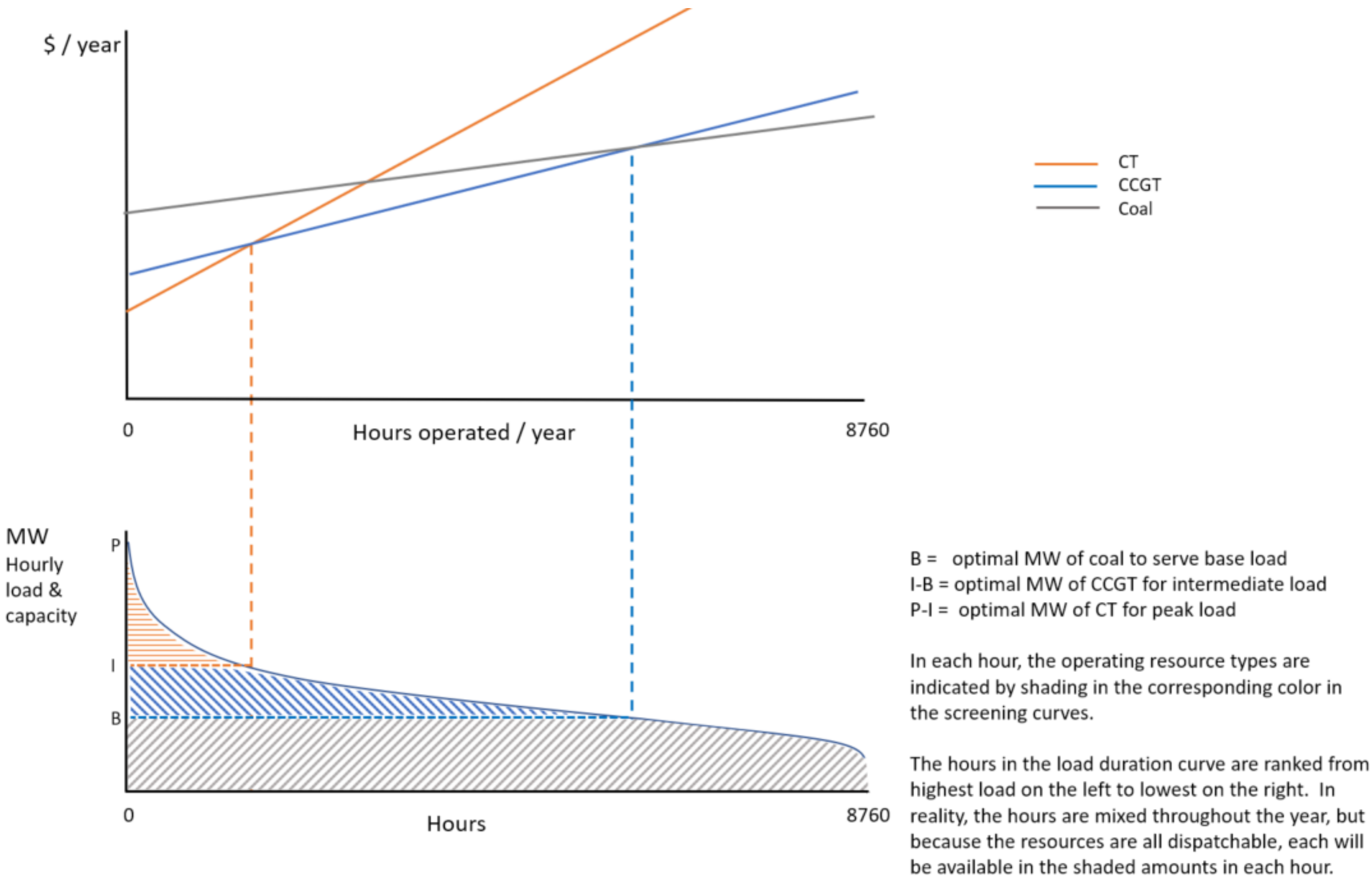
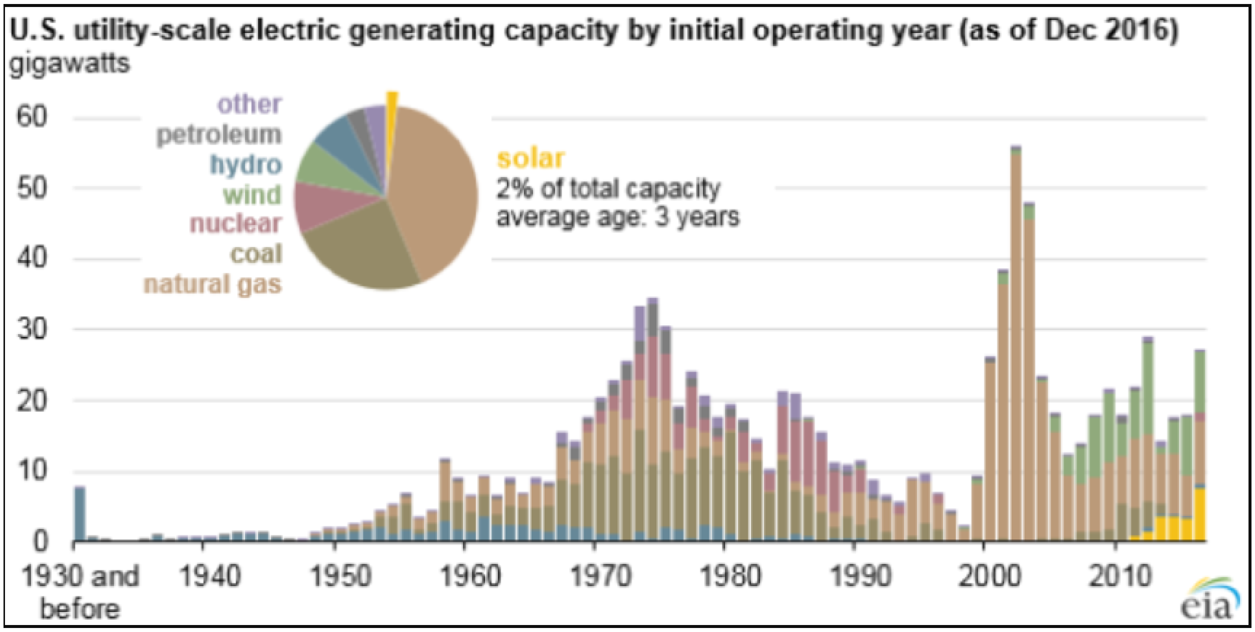
Appendix

I. Simple resource planning using screening curves and a load duration curve.



Screening curves (top) plot each resource type's annual cost as a function of its annualized fixed cost (the y-intercept of its screening curve) and its variable fuel and operating costs (as the slope co-efficient of its screening curve) over the 8760 hours of the year (on the x-axis). The intersections of the line segments in the lowest cost envelope of the screening curves show the number of hours each resource type would run in a least-cost configuration. Mapping these numbers of hours onto the corresponding points of a load-duration curve (bottom) shows the number of megawatts of each type of resource needed to efficiently serve its corresponding number of hours. The data requirements are simple – 8760 hours of load, the annualized fixed cost of each resource type, and each resource type's variable costs -- and the computationally most challenging part is sorting load from highest hour to lowest hour. This can be done in an instant with a spreadsheet, and the solution of the simple linear cost minimization problem can be done with elementary algebra or even with graph paper and a ruler.

II. Historic US power sector annual capacity additions by resource type



III. Additional Configuration Market Design Details.

i. Intertemporal optimization in the configuration process.

Mathematical programming-based analyses of clean energy technology deployment pathways can treat the development of resources over time in different ways. Some optimize the continuous pattern of investment over an extended period of time, such as between the present year and 2050, while others optimize all investment in just one single period to identify the mix of resources needed to achieve a given level of decarbonization at a given time. The multi-year path optimization approach typically sets up the model to have what is often characterized as "perfect foresight," while the single period optimization approach is typically characterized as "myopic."

Perfect foresight means that the model optimizes intertemporally, so as to avoid too much of investments in early years that would be rendered uneconomic in later years. Perfect foresight requires the model's inputs to include assumed costs and technology availability for each future year. Myopic approaches, by contrast, consider technology costs and operating characteristics for a given year, on the basis of assumed technology costs, demand and generator availability for that year.

The myopic approach can also be used in a stepwise fashion over multiple years, with the results of each previous period's optimization being the baseline for the optimization of the next period. Some think that this approach can better represent how decisions will be made in the real world, where future technology costs and availability are unknown. In prospective studies, this stepwise-myopic approach also involves assumptions about future technology costs, availability, and other parameters. These assumptions are often varied, across different scenarios to simulate the real-world implications of such unforeseen changes in cost and availability of various technologies. The configuration market as proposed here would use a step-wise myopic approach, but would not need to use assumptions for the cost and availability of technologies in each step, since the procurement auction in each step will elicit real time information about those critical variables.

This may not result in as efficient a set of investments as perfect foresight would, if it were really available. But perfect foresight does not exist, so there have been many examples of stranded costs and technologies nipped in the bud since the start of the industrial revolution. These “gales of creative destruction” have often been viewed as inherent in, and essential to innovation and technological progress.[64] Path dependence, as discussed earlier in this paper, can be thought of as the polar opposite of creative destruction, since path-dependency can lock-in inefficient technologies and inhibit innovation and technological progress.

In the context of rapid decarbonization of the power sector, the optimal path of technology innovation and deployment will likely require a middle path between excessively large waves of creative destruction, on one side, and too much path dependent lock-in, on the other, both of which could make decarbonization difficult, infeasible or prohibitively expensive. The configuration market would favor such a middle path by persistently but incrementally replacing and augmenting existing technologies with the combinations of clean technologies that can collectively provide the same levels of reliability, safety and affordability, at the lowest cost.

To avoid creating excessive path dependence associated with these new technologies, while also avoiding exposing its them to excessive risk of premature creative destruction, the configuration market’s early waves of clean energy resources should themselves be reasonably compatible with the subsequent deployment of a wide variety of emerging technologies, under a wide range of future cost and performance characteristics.

To achieve these goals, the configuration market, as proposed, would rely primarily on its iterative, step-wise myopic incremental procurement of optimized, incrementally decarbonized, supply additions and retirements in each market round. This incremental procurement of the cost minimizing combination of resources currently available will allow the configuration market portfolio to evolve gradually in line with unforeseen changes in technology costs, availability and performance, while continuing to invest in mixes of technologies that work together to balance the system and meet carbon constraints in the most cost-effective manner, as discussed more below.

However, there are a number of inter-temporal dependencies that this stepwise-myopic approach cannot efficiently resolve, such as new renewable generation that cannot bid without new transmission first being available. The proposed configuration market would address many such inter-temporal problems through the use of forward-looking scenario analysis. Insights into how inter-temporal optimal investment challenges could be managed through such a combination of iterative, step-wise myopic, incremental procurement rounds and forward-looking scenario analysis can be inferred from a number of recently published PRISM-based decarbonization analyses.

For example, Sepulveda et al. (2018) examined the trade-offs in the optimal mix of clean energy resources under a variety of scenarios, including several that assumed different future costs for the clean firm and VITL classes of technologies.[65] Each scenario consists of a cost-minimizing pathway of incremental deployment of clean resources over time that meets the GenX model’s declining carbon and system balancing constraints.[66]

These scenarios can help show how the configuration market's iterative procurement process would support inter-temporal optimization. Two specific scenarios compared the impact of higher and lower costs for renewables and storage technologies (i.e., VITL technologies), assuming the same conservatively high cost assumptions for clean firm technologies in both scenarios. The difference in relative costs made little difference in the optimal resource mix, up to the time when fifty percent decarbonization is attained. After that, however, the scenario with moderate cost VITL technologies deploys mostly clean firm resources and few additional VITL technologies, while the scenario with low cost VITL technologies deploys substantially more VITL technologies, and fewer additional clean firm technologies.

These results are not qualitatively surprising, since a portfolio of VITL technologies that is optimized to provide, in aggregate, a high level of balancing capability, should be relatively substitutable for dispatchable and firm clean technologies. What is more interesting, however, is the insight that the two paths of resource deployment do not diverge immediately. The optimal deployment mix is the same in each scenario until 50 percent decarbonization is reached, regardless of the subsequent relative costs of clean firm and VITL technologies in either scenario.

A configuration market using incremental stepwise optimization, if presented with a similar path of relative technology costs over time, should produce a similar pattern of technology deployment. Like a prospective PRISM analysis made with stepwise myopia, the configuration market will base each market round's resource selection on the currently available resource mix that meets the balancing and carbon constraints at the lowest cost.[67] Accordingly, even with complete uncertainty about whether VITL technologies will, in the future, have low or moderate costs, relative to clean firm technologies, the optimal mix selected by the configuration market in each current year would be the same, up to the time when actual realized technology costs diverge. After that, whichever technology type turns out to be less costly will start to gain a larger share of deployment.

For such cases, where the differentiating factor is the marginal benefit of any particular technology or group of technologies in meeting the carbon and balancing constraints at least cost, the configuration market's iterative incremental optimization process should, to a significant degree, avoid the need to base current investment decisions on projected future technology costs. This would avoid significant risks that could otherwise result from attempting to decide today which resources should be developed in the future, and in what amounts, to achieve deep decarbonization.

At the same time, it avoids the risks, potentially equally severe, of simply trusting decentralized investments in response to scarcity prices to produce the most efficient and reliable mix of highly clean energy resources – a process, that continuing the earlier analogy of an automobile engine, could produce an oversupply of an undersupply of pistons relative to cylinder bores, and fail completely to provide the all-important balancing and synchronizing camshaft and flywheel.   In the power sector, it is easy to think of decentralized market price-based investment decisions in low cost, easy to deploy wind, solar, natural gas and batteries crowding out both existing nuclear and new clean firm resources, resulting in a higher cost, less reliable power system with unacceptably high carbon emissions – especially with a repeat of the overbuilds and lock-ins that have, so far, been common to the power sector.

The iterative optimization approach of the configuration market would not, however, solve all inter-temporal aspects of the clean energy and decarbonization challenges. For example, it would not in itself fully insulate early investment against being stranded due to unforeseen technology breakthroughs that would render the early investment uneconomic or superfluous. To the extent that specific risk jeopardizes the needed quantity of investment in certain clean energy technology types, the risk could be defrayed through a long enough fixed tenor for the hedging agreements awarded to cleared new resources.[68]

Iterative optimization will be unlikely to provide the prior investments in technology, systems, infrastructure and institutions that need to be in place for a variety of clean energy investments to be able to bid into the configuration market at prices that will result in their selection through the clearing process, or in many cases, to be able to bid at all. Many clean energy resources depend on such enabling ecosystem elements, that are currently incomplete, immature, or unavailable. For example, potentially optimal levels of wind and solar development at sites with the best economics and irradiance or wind availability profiles is unlikely in the absence of sufficient transmission connecting those sites with load centers.

Similarly, the widespread use of controllable distributed energy resources (DERs) to help balance renewable energy production and ensure reliability is unlikely to achieve scale and be able to participate effectively in wholesale market balancing regimes without a well-established, commercially attractive, and competitively neutral approach to adapting and managing distribution systems to support their widespread deployment. The widespread deployment of new nuclear facilities is unlikely in the absence of sufficient assurance that future levels of VITL technology deployment will not exceed those that would erode the headroom, in terms of sufficient annual hours of sufficient levels of unmet demand, that such plants would need to operate cost-effectively. More broadly, many new and emerging technologies are unlikely to achieve the maturity or scale needed to compete head-to-head with existing technologies on the basis of cost and performance, without adequate early demonstration, deployment and learning-by-doing opportunities.

While the full solution of these challenges lies beyond the scope of a wholesale electricity market, PRISM tools could help solve many of them, and some of those solutions could be incorporated into the configuration market. For example, as discussed in Section 3(b)(v) above, prospective scenario analysis using PRISM tools and configuration market data could identify the most efficient new transmission expansions needed to deliver energy from the most beneficial portfolios of new wind and solar projects, and the inclusion of these transmission projects in the regional transmission plan could then support the participation of those new solar and wind projects in the configuration market.

In a similar approach, scenario analysis using the configuration market's PRISM tools and data could illuminate the trade-offs between various DER deployment scenarios and the types and costs of resources deployed through the configuration market. The resulting insights into the most cost-effective DER technology types and quantities could then inform the distribution planning, operation and DER incentives considered by state regulators, distribution utilities and DER providers, helping them create an efficient DER deployment and management environment.

ii. Innovation carve-out.

Prospective scenario analysis using the configuration market's data sets and PRISM capabilities could also help incubate promising early commercial clean energy technologies through the critical gap between first-of-a-kind projects and commercial competitiveness. In such a process, PRISM scenarios would screen for, and identify, specific technologies with cost and operating characteristics which, if deployable at achievable costs and large enough scale, would result in lower cost and more rapid decarbonization. In each market round, the configuration market could conserve a modest amount of capacity – e.g., several thousand megawatts -- below its target resource-adequacy target, as a set-aside for projects comprised of technologies that meet these. Technologies that meet the screening criteria would be eligible to bid for long-term resource hedges. Winning bids would be selected, up to the full level of the innovation set-aside, by an independent evaluation by innovation and technology experts, based on objective characteristics of project viability, potential scalability, and project cost net of out-of-market cost sharing, state and federal incentives, and philanthropic support. Winning projects would receive long-term revenue hedges sufficient to support their development and operation, contingent on their completion and continued successful operation.

A wide variety of technologies that a variety of decarbonization studies already indicate could be critical to the success of decarbonization, could benefit from the learning-by-doing, scale and moderate but real competitive pressure offered by such an early deployment opportunity. For example, new nuclear, carbon capture and utilization and related electricity-to-fuels (ETF) technologies, and specific DER deployments could be jump-started through such deployment opportunities. Further, more than just the technologies themselves would get a jump-start. Early, quasi-commercial development would also help galvanize and forge the complex value networks or "ecosystems" that are required for a technology to achieve commercial maturity. For power technologies, key elements of such networks are their pathways to participate in the wholesale SCED market, while market-spanning technologies, such as ETF and DERs, need to also be able to integrate into their other product and service markets and their networks at the same time. Early development of such technologies in the context of a configuration market could nurture, accelerate and help rationalize this inter-network integration.[69]

iii. Market power mitigation in the configuration market.

Market power can lead to substantial inefficiencies in existing SCED and capacity markets, so its identification and mitigation are major concerns in power market design, and need to be considered in the configuration market context. In both SCED and capacity markets, market power can be exercised by either new or existing resources. Existing resources can exercise market power when the supply of power plants in a particular market area is concentrated enough so that an individual generating facility, or a group of facilities under common ownership or control, can both cause and benefit from economically or physically withholding its output from the capacity or energy markets. Only existing plants can exercise such withholding, which suggests that in the configuration market, the analogous concerns should focus primarily on retirement bids and the characterization of existing resources used in the PRISM-based market clearing process.

a. Market power mitigation for new, bidding resources. New resources with market power typically exercise it by bidding above the levels that would result from robust competition. Such bids are more likely if there are few bidders and if bidders can easily collude to limit bids or increase bid prices.

However, actually identifying competitive bid levels is much more difficult with proposed projects, since the project does not actually exist and its costs cannot be observed. For this reason, market power mitigation for new projects generally is addressed through bidding rules, which are designed to induce bids at project developer's expected costs, and to limit or prevent collusion.

As discussed above, the author proposes that the configuration market accept sealed bids for new projects, and pay winning bids on an as-bid or discriminatory basis. Accordingly, the configuration auction as proposed is a first-price, discriminatory auction. Auction theory generally indicates that, in a first-price procurement auction for identical objects, bidders know that the lowest bid will win. They therefor have an incentive not to bid below their own cost. They would like to bid above their cost, to earn extra returns, but know that the higher they bid above their cost, the more likely they are to lose to another bidder. Accordingly, auction theory suggests that, in a private-value auction with symmetric bidding information, each bidder will find it optimal to submit a bid somewhat above their own cost, but no higher than the level they expect the cost of the next highest bid above theirs to be.[70] Further, as the number of bidders increases, this amount by which the optimal bid exceeds the project's expected cost will decrease, and in the limit of infinite bidders, the excess above each bidder's cost will approach zero.[71]

To the extent this specific theoretical result implies a more general applied rule -- namely, that, the more bidders in a first-price auction, the closer their optimal bid levels will be to their actual cost -- the configuration market seems likely to impose additional competitive pressure on bidders to bid at levels that closely mirror their project's costs. In the configuration market context, each project that bids will be competing against not only other bids from projects proposing the same technology, but against all combinations of various technologies that could meet the carbon and balancing constraints of the PRISM optimization at a lower cost. This will make it difficult, if not impossible, for a bidder to know either the number of effective competitive alternatives a resource faces, or the cost at which their own bid would be rejected from inclusion in the efficient combination of resources to be cleared by the PRISM evaluation. At the same time, the existence of the PRISM cost minimization objective means that bidders do know that, all else equal, the higher their bid is above their cost, the more likely they are not to win. Further, they have the same incentive any bidder has not to bid below their cost, which would saddle them with ongoing economic losses if they win. So, one can suspect, they would bid at or just above their costs, since they will not be able to form expectations of what the next highest bid might be.

This reasoning, combined with the widespread real-world use of discriminatory, pay-as-bid procurement auctions, including the multi-unit or "package" auctions that most resemble the configuration market, seems like a sufficient reason to consider the sealed bid, pay-as-bid approach as the primary mitigant against the exercise of market power by new resources bidding into the configuration market.

b. market power mitigation in retirement bids from existing resources. Retirement bids from existing resources, in the configuration market, would resemble bids of existing resources in today's capacity or SCED markets. Accordingly, it is important to understand how such resources can exercise market power in today's capacity markets, and how such market power is mitigated, to see if similar measures will be needed in the configuration market.

In capacity markets, existing resources that face a high level of competitive pressure from other resources with comparable going-forward costs will find it profit-maximizing to bid their own going-forward costs, net of expected energy and ancillary service revenues. However, resources with little competitive pressure may be able to bid well above their going-forward costs and potentially to cause capacity prices to clear at levels substantially above those that would result from competitive, going-forward cost bids. Current capacity markets typically use a two-stage test for this sort of market power abuse. The first stage tests for the conduct of a resource bidding above its going-forward costs, while the second stage tests for the impact of that higher bid actually causing a higher price to clear the capacity market. Bids that fail both tests are typically mitigated by having their non-competitive bids replaced, in the capacity market clearing process, by administratively-determined going-forward costs. High levels of concentrated ownership and the existence of a large number of pivotal suppliers can create structural conditions that facilitate widespread bidding above going forward costs in extensive regions served by today's capacity markets.[72]

In the configuration market, an existing resource whose continued operation is endangered by low SCED market prices would be eligible to bid into the configuration market at its going-forward costs. Projects whose bids clear in the PRISM analysis would be eligible for a going-forward cost-based hedging contract, which like those for new resources, swap SCED revenues for a stream of fixed payments sufficient to cover as-bid costs. The structural conditions that support bidding above the competitive, going-forward cost level in today's capacity markets would seem likely to support similar bidding in a configuration market. Such resources have incentives to seek revenue hedging contracts at levels above their going-forward costs, but they also may face relatively strong competition from less costly combinations of resources selected by the PRISM clearing mechanism's objective to minimize costs while meeting its carbon and balancing constraints. This competition may be sufficiently intense to constrain their bids to fully competitive levels.

However, the owners of existing resources that produce large amounts of zero-carbon electricity in most hours would anticipate that their resources are likely to clear in the configuration market, due to making significant contributions to low-cost balancing and GHG emission avoidance, even if bid at levels significantly above their going-forward costs. Indeed, such owners have the resources and ability to utilize their own PRISM analysis to project configuration market clearing and to identify the bid thresholds at which their bids would unlikely to clear in the configuration market. Accordingly, they should be expected to bid close to those threshold levels, which could be significantly above their going-forward costs. And while such bids may or may not result in a less efficient configuration of the power system, they would certainly result in it having higher costs and in a transfer of efficiency gains from consumers to producers. For those reasons, the configuration market as proposed here would include a going-forward cost bidding requirement for retirement bids, with each bid containing the justification for its own going-forward cost estimate, or in the alternative, bidding at an administratively-determined going-forward cost level for each resource type. This is equivalent to collapsing both the conduct and the impact analysis into the one datum of whether a bid is above going-forward costs, as would be appropriate under a pay-as-bid, discriminatory price regime.[73]

c. Buyer's side market power. Today's capacity markets can also be subject to buyer's side market power, which can occur when a capacity buyer, such as a large load serving entity or a de facto coalition of load serving entities, finds it can reduce its capacity costs by developing more capacity than is needed and bidding it into the capacity market at a price low enough to ensure it will clear infra-marginally.[74] In a capacity market with a vertical price/quantity schedule or "demand curve", or a downward sloping one that is suitably steep, the resulting reduction in capacity prices can be large enough to more than offset the cost of the new capacity. To mitigate such buyer's side market power, FERC has approved RTO tariffs that impose bidding floors on the capacity bids made by, or in the interests of entities who have a financial interest in lower capacity prices.

For example, PJM's minimum offer price rule (MOPR) was initially designed and proposed to mitigate buyer's side market power. This would prevent the sort of schemes referred to in the case of *Hughes v. FERC,* in which a state provided out-of-market subsidies ensuring fixed cost recovery to a new combined cycle unit, conditional on that unit bidding into the PJM capacity market as a price-taker and clearing in the market, with the purpose of providing lower net capacity costs to consumers within the state.

The same scenario analysis that helped illuminate intertemporal efficiency in part (xx) above can illuminate the effects of such out-of-market support in the configuration market. We saw that relative shares of clean firm and VITL technologies will depend on their costs, as bid into the configuration market and used in the PRISM optimization that determines the winning bids. With lower bids for VITL technologies, the PRISM optimization process selects more of them and fewer clean firm resources, and vice-versa. Accordingly, if states or federal incentives are provided disproportionately for one or the other of these types of resources, the affected resources would be able to achieve their financial returns with lower levels of revenues, and hence would bid at lower levels into the configuration market. If these bids were low enough, relative to other resource types, they would shift the optimal mix of resources needed to meet the PRISM clearing mechanism's carbon and balancing constraints at the lowest cost.

However, it is not necessarily the case that this shift in resource mix would result in lower costs for capacity buyers. That would depend on the change in the total cost of the resource mix selected by the configuration market. It may be that subsidization of VITL technologies, for example, would result in fewer clean firm resources being deployed, but increased balancing costs due to the deployment of significantly more storage capacity, and a higher level of renewable energy curtailment, under a higher VITL regime. The cost impact of this shift in input costs is likely to be indeterminate ex-ante. That is, total configuration market costs could be the same, somewhat higher, or somewhat lower, depending on the system-level impacts of deploying more of the subsidized technologies in a pattern that minimizes total cost while achieving the targeted emission reductions and maintaining full balancing capability.

Given this relatively indeterminate effect, it appears unlikely that buyers with the goal of suppressing configuration market prices would be able to do so by providing non-market financial support for the deployment of certain types of clean technologies.[75] There simply is no easy way to read the price suppression results of resource deployment off of a configuration market chart or graph, as there is with the downward sloping demand curves (including vertical demand curves) of current capacity markets. Accordingly, there would be no justification for blanket prohibitions or bid floors to prevent such intentional outcomes, since in many cases they could not be expected to even occur.

d. MOPR use and abuse. The preceding discussion suggests that a blanket bid floor would likely be neither justified or useful to mitigate buyer's side market power in the configuration market. This leaves the question of whether a bid floor may be needed to prevent inefficient entry by resources receiving non-market revenues. The author's view on this is that the current application of the MOPR to trigger bid floors, based on the full cost of new entry net of SCED market revenues for resources that receive out of market support due to state policies, is unjustified as a matter of economic theory, standard business practice in all other competitive markets, and common sense. In effect, it relies on the argument that economic entry to competitive markets only occurs when the entrant is assured of receiving their full annualized costs in the first year, which is obviously not true. If all entrants waited until markets were in a shortage-based equilibrium to actually build their resources, the result would be an even more intense and destructive boom-bust cycle than we see in most markets for assets with no alternative uses and high levels of fixed costs. Instead, businesses tend to invest based on long-term expectations of supply and demand dynamics, rather than on a tight market in the current period.

Such longer-term expectations arguably underlie the 28,502 megawatts of interconnection requests reported by PJM as of March, 2020.[76] Further, such regular and constant incentives for investment, with comparable competitive pressure across all entrants, are exactly the kind of investment incentives electricity markets should be designed to create. Incentives for such continuous investment are especially important in an era of rapid decarbonization, which will require nearly continuous investment in the most efficient mix of clean new and existing technologies for at least the next two decades, and potentially much longer.

The idea that such investment will only be efficient, and can only be made, when the market is so tight that it is able to clear at or above long-run marginal costs, is little more than a barrier to entry when included in today's market designs. Further, if such tight, near equilibrium conditions were necessary for efficient entry, then a new market design that will continually clear at the long run marginal costs of the least cost array of technologies needed to incrementally meet its carbon and balancing constraints – as the configuration market will -- is needed even more acutely. But such a market should not need a bidding floor that inhibits clean resources from clearing, since it will meet its key constraints by selecting the mix of the resources bid into it which, when paid their as-bid costs, do so at the lowest cost. If a bidding floor is needed at all for attracting and selecting efficient resource mixes, it should be based on the same metric of going forward costs for all technologies, including new projects, rather than discriminatorily requiring new projects to bid at their net cost of entry, while competing against the much lower going-forward costs of existing resources, which baldly discriminates against new resources based on the bizarre administrative fiction that, in competitive markets, entry only occurs when resources can and do receive their annualized, full long-run marginal costs in their first year of existence.[77]

iv. Identifying input requirement sets and the impact of non-convex technologies

i. Applying Varian's concept of the *input requirement set* to the decarbonization problem. This discussion follows Varian (1992), which was at the time a widely used graduate level text in mathematical economics programs.[1] In the first chapter, Varian lays out the essential steps in applying mathematical models to the analysis of how firms choose to deploy specific technologies, considered in terms of their ability to transform specific inputs into specific outputs. At the outset, Varian warns

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[1] Varian's book, along with Silverberg's *Structure of Economics,* were the course textbooks on the master's level microeconomics class that was a prerequisite for the author's acceptance into the University of Minnesota's Ph.D program in applied economics in 1992.

against the errors that often result from treating of inputs and outputs simply as aggregate stocks that do not depend on time, and suggests instead that both inputs and outputs be specified as flows, in terms of the quantity used and produced per time period, and that the flows be defined in terms of the specific calendar time when they are available, and if relevant, their location, as well.

This advice is particularly relevant to analyzing the efficient choice of inputs consisting of clean energy technologies and their underlying prime movers in the power sector, since their availability can vary dramatically by the hour and by location. Further, due to the very short period of time during which stored electric energy can be used at the full power rating of current storage media, the vast majority of electricity must be produced at the time it is consumed. Adding the critical requirement that, for reliability, the amount of electricity produced must also always the amount consumed, makes Varian's admonition to treat the time dimension with the appropriate level of precision particularly relevant to the analysis of efficient choices of clean energy technologies by firms in the power sector.

Varian then lays out several steps to help analyze the rational economic selection of inputs by firms. The first is to identify all technologically feasible input and output combinations. By inputs he means the amounts of inputs, including both long-run inputs of capital invested in various types of equipment and short-run inputs of fuel, supplies, and labor, used in each relevant time period. Outputs are simply the relevant amount of product produced in each relevant time period by the use of each combination or level of inputs. These input plus output bundles comprise the set of all *feasible production plans* facing the firm, in that the various output levels identified could actually be produced from the specified inputs in the relevant time intervals.

The next step is to identify any relevant restrictions on these levels of inputs and outputs, and to select from the feasible set of production plans the subset that meets these restrictions. The resulting subset is called the *input requirement set.* It consists of all the combinations of inputs that the firm could actually use to meet its specified restrictions on inputs and outputs. As an example of a such a restriction, Varian offers the case of a firm that requires the inputs it uses to be able to produce at least a specified amount of output in each relevant time period. The resulting input requirement set consists of just those input bundles that are capable of producing the specified amount of output.

In the power sector, for example, the restrictions would, among other things, specify that the inputs must be available, in each dispatch interval, in sufficient quantities to meet the expected level of electricity consumed, plus reserves, in that interval. A firm using fossil fuel technologies would satisfy this input requirement by ensuring the availability of enough firm generating capacity, at all times, and enough fuel, at all times to meet any level of demand up to peak demand levels and reserve needs. Fuel availability would typically be assured either with firm real-time fuel delivery (e.g., in the case of natural gas) or periodic delivery with substantial on-site storage (e.g., in the case of liquid fuels and coal). Most power sector firms face an additional input restriction of cost-minimization, as well, which could be met through the screening curve approach described in Section I above. Notice that, due to the constant availability of fuel and the use of highly dispatchable or firm generation technologies in combinations that minimize their commitment costs, the time dimension used in identifying the input requirement set is simply the one datum of peak load, plus load levels in each of 8760 hours.

By contrast, a power sector firm switching from fossil resources to fully clean energy resources will have the same restrictions on its inputs, but will need a very different approach to identifying its input requirement set. To always balance its load and generation, this firm needs to identify enough locations with enough available wind and sunshine, and enough storage and other zero or low carbon resources, whether existing or to be constructed, to be able to meet its actual load in every dispatch interval. But the complexity of determining the likely availability, in each dispatch interval, of many different combinations of project type and locations, under many different weather patterns, suggest the firm will need to use some type of mathematical programming model, with small granularity in its data regarding wind speed and solar irradiance at many potential sites, over many years of different weather patterns, to identify its actual input requirement set.[2]

Further, because most of these resources have not yet been deployed, the firm will need to not only identify the potential locations for wind and solar, and the relevant data, but to find a way to get accurate information on the feasibility and cost of development at each of those locations, before it can identify the optimal mix of resources to deploy. One way to do this would be to elicit bids to develop wind and solar projects, along with a wide variety of other clean energy technologies, prior to modelling all potential sites, and to use the cost, technology and performance characteristics indicated by these bids to improve the accuracy, and potentially reduce the computational complexity, of the process it uses to identify its input requirement set. It could then issue power purchase agreements to the developers whose offers passed the mathematical programming screen and were thus identified as being in the input requirement set, as is already being done by several utilities.[3] Such precursors to the configuration market can thus be seen as an outgrowth of the attention to the time dimension of the choice of input and output requirements recommended in Varian (1993).

ii. The concept of non-convex technologies as applied to the input requirement set.

Varian also offers an interesting way to characterize the different ways to analyze the specific technologies can be combined in developing the input requirement set. For example, technologies that allow any linear combinations of inputs to produce at least the required level of output in the relevant time period are characterized as *convex technologies.*[4]

This characteristic of technologies appears to be closely related to the concept of complementary and substitute inputs in production discussed in the main body of this paper. Specifically, the ability of many linear combinations of one or several fossil fuel inputs, processed through various quantities of different fossil fuel generating technologies, to always satisfy the requirement that electricity generation must

[2] For a real-world example of just such a process, see Hawaiian Electric Company discussion of their use of E3's RESOLVE model, at 1-8, 2-16, and 3-4 et seq. in HECO (2016) in developing their plans to meet Hawaii's statutory mandate to reach 100% renewable electricity by 2045.

[3] See examples of such existing practices at the utility level in the cases of HECO and Xcel cited at endnote 4, supra.

[4] See Varian (1993), Section 1.5 pp. 7-9. Specifically, if inputs **x** and **x'** can each produce the required output level *y,* then both bundles the bundles (**x**, *y*) and (**x'**, *y*) are in the input requirement set *V(y)*. If any linear combination of these inputs $s\mathbf{x} + (1-s)\mathbf{x'}$, $0 \leq s \leq 1$, also produces *y*, then the technologies that convert **x** and **x'** to *y* are convex technologies, and the input requirement set comprised of **x** and **x'** itself is also convex as a result. Note that, if the underlying technologies are not convex, the bundles (**x**, *y*) and (**x'**, *y*) would still be in the input requirement set, due to the fact that either of them alone, by assumption can produce *y.* They would also be in the input requirement set if they only are able to produce *y* in certain complementary combinations, but not in all linear combinations. But in both of these cases, despite being included in the input requirement set, they would not be convex technologies, and the input requirement set, if composed just of these resources, would itself not be convex. It would, instead, require specific proportions of **x** and **x'**, and of the technologies that convert them to *y.*

equal consumption in each dispatch interval, is a clear example of the convexity of these specific technologies. For example, 50 ten-megawatt reciprocating engine generators and 25 twenty-megawatt aeroderivative turbine generators could each meet any amount of load between 20 and 500 MW, so they would both be in the feasible set for a firm with maximum load plus reserves of 500 MW. In combination, they could meet 975 MW of load, and hold 25 MW in reserve, so the combination of both would be in the feasible set for a firm with a maximum load of 975 MW and an expectation of at most one generator outage at time of peak load. Further, many approximately linear combinations of them could be used to meet any level of load between 10 MW and 975 MW, so they are still effectively convex technologies. Similarly, many different combinations of these and other fossil technologies could be substituted, and still meet the input requirement of balancing load in all dispatch intervals.

By contrast, no combination of wind and solar resources would be sufficient to meet all load in any dispatch intervals in which potential insolation and wind speed is insufficient to produce enough electricity to match consumption. Identifying the best combination of wind and solar will require identifying those sites whose combinations of probably wind speeds and solar irradiance in each dispatch interval best approximates the probable level of load in each such interval. While a number of different combinations may approximate this optimal level, many potential combinations will not. Adding battery, thermal or mechanical energy storage technologies could allow the underlying inputs of wind speed and sunshine to meet the required output level at all times, but the input combinations that satisfy the input requirement will again be relatively specific, rather than a broad set of linear combinations.[5] Accordingly, all these technologies are not convex technologies in Varian's terminology, and must instead be used in relatively limited complementary combinations to meet the firm's input requirement.

These observations suggest that it may be useful, in further developing the microeconomic analysis of the efficient adoption of technologies needed for decarbonizing the power sector, to explore the concept of convex and non-convex technologies, specifically in terms of the search, information and transaction costs associated with decarbonization, and the investigation of mechanisms that would minimize those costs.

There may also be larger scale implications of these different technology characteristics. For example, Varian distinguishes between the implications of convex technologies at the relatively small scale of the firm-level the input requirement set, and the implications of convex production sets at the typically much larger scale of an industry's or a market's production set. Convex technologies in the input requirement set are important primarily in terms of their ability to replicate, in various combinations, a specific production requirement a single firm may face. By contrast, convex production sets, which typically span an entire industry, not only allow various combinations of inputs to produce a given level of output, but have additional, and more complex implications, such as ruling out increasing returns and

[5] And, at current storage costs, the amount of storage required in the input requirement set would likely be prohibitively expensive. Costs could be reduced creating a placeholder for a clean firm or a clean flexible technology to substitute for the most expensive storage, wind and solar resources, and by continuing to use a limited amount of natural gas generation until those clean technologies become more cost effective. But any such new clean technologies would be optimally used only in specific amounts and combinations with the other clean energy resources, rather than in any number of linear combinations, especially if achieving a declining level of carbon emissions is also part of the firm's requirement set.

a wide variety of other macro-level non-convexities, which can include externalities in production or consumption, inefficient or non-existent equilibria, and other market-level pathologies.

These differences in scale may be less relevant in the power sector, where the input requirement set is ultimately determined and met at the level of the electrical interconnection, which is the locus at which all internal generation must accurately match all internal consumption at each moment. This macro input requirement set is, therefore, of a scale at least as large as each electricity market in the US. It thus determines not only the structure of each subsidiary control area's input requirement, but that of the entire industry within each interconnection. Accordingly, the increasing deployment of non-convex technologies in relatively fixed complementary combinations, at the level of the aggregate production function within electricity markets and entire interconnections, may have important implications at the macro level of market efficiency, which may be more appropriate to address from a mechanism design perspective than through highly decentralized market prices alone.

In light of the potentially weighty implications of Varian's concept of non-convex technologies, the author has attempted to find other instances of the use of the concept in applied economics, with only limited success. The most relevant publications encountered are Kerstens et al. (2005) and Aoki (1987). Both of these bear, to some degree, on the balancing problem faced by electricity market operators.

Kerstens et al. evaluates, from an applied resource economics perspective, the implications of non-convex fishing technology. Fishing ships are characterized as a non-convex technology, since for existing ships, their hold capacity is fixed and lumpy, and thus various combinations of existing ships cannot efficiently achieve all intermediate production levels assumed by a convex model of optimal fishing quotas. This divergence between the convex assumptions of economic policy analysis and the actual non-convex nature of the technologies subject to those policies is evaluated for its implications for the efficiency of various fisheries management policies. The authors argue those policies would be considerably more efficient if based on the actual, non-convex, technologies rather than on a counterfactual assumption of convexity.

Aoki evaluates, from a mechanism design perspective, the efficient allocation of production among two agents using two different technologies, each of which is non-convex but which are both needed to achieve the required level of output. Aoki further assumes that the output of the two technologies cannot be stored, but must instead be consumed as it is produced. These assumptions make Aoki's analysis and mechanism design concept potentially more relevant to the electricity sector, with its strong underlying similarities of non-convex clean energy resources and limited economic storage. Aoki asserts that the inability to store the output and the need to produce it as it is consumed makes it impossible to convexify the overall production function. This condition, in the small world of his two-agent, one-product model, ensures the conditions of increasing returns and production externalities against which he evaluates various mechanisms for their ability to produce a relatively efficient Nash-like solution.

Of course, neither Aoki nor Kerstens et al. demonstrate anything about the electricity sector itself. But both papers do show that explicitly recognizing and modeling the non-convexity of the technologies being adopted by an industry can be critical for developing effective means to ensure the efficiency of the industry as the use of those technologies becomes, or needs to become, prevalent.

End-notes

[1] See, for example, the many studies available on the websites of E-Three, Evolved Energy Research, and Vibrant Clean Energy, respectively at: https://www.ethree.com/projects/ ; https://www.evolved.energy/research ; and https://www.vibrantcleanenergy.com/media/reports/ .

[2] A swap is defined as a financial contract through which two parties exchange the cash flows or liabilities from two different financial instruments. Here, cash flow A is the project's settlements for spot market energy and ancillary service sales, while cash flow B is the project's levelized payments to cover its fixed and operating costs. Normally, A flows from load, through the spot energy market, to the project and B flows from the project to the suppliers of its inputs. Under the swap envisioned here, A would flow to load through the configuration market's settlement process, and B would flow from load, through the configuration market's settlement process, to the project, and hence to its suppliers of inputs. The levelized cost flow B would be adjusted according to bvarious performance requirements in each project's contract to provide appropriate incentives to perform and operate efficiently.

[3] A comprehensive and accessible description of such a model is Sepulveda and Jenkins (2017), which describes the GenX model's seven distinct elements that are co-optimized in its cost-minimizing objective function, which include system expansion (including retirements), dispatch and operating costs, provision of reserves, and expansions of both the transmission and distribution systems. This cost minimization is subject to two overall constraints, namely to balance generation (including discharges from storage) and load in each hour; and for total CO2 emissions from the dispatch of the various technologies to not exceed a total cap on CO2 emissions. It also gives a good overview of how the GenX capabilities can be used in various configurations to analyze different aspects of the decarbonization problem, and the various tradeoffs, as of 2017, between its computational complexity, precision and accuracy. Other examples of PRISM analysis and model descriptions are found in McDonald et al. (2016), Haley et al. (2019); Aas et al. (2020).

[4] See, e.g., Wilson et al. (2020) for a description of Xcel's use of a system expansion model to evaluate clean energy resource bids as part of its implementation of Colorado's integrated planning process, and HECO's description of its integrated planning process, which includes competitive procurement rounds, at https://www.hawaiianelectric.com/clean-energy-hawaii/integrated-grid-planning . (Accessed October 25, 2020).

[5] Haeringer, (2017), p. 3, observes that economists are divided regarding the definition of markets. One group sees a market as "an institution in which goods and services are traded (or assigned, exchanged, etc.)" The other sees it as "a protocol or mechanism that helps elicit prices." The configuration market would meet the first definition, without question, and since it would establish prices at which competing projects are accepted and paid, it appears to meet the second, as well.

[6] Following Corneli (2018).

[7] Reicher et al. (2017) observes that, according to the International Energy Agency, successful decarbonization will require some $2.3 trillion per year to be invested globally in clean energy. They show this would use 67% of the total annual cash inflows currently available globally to blue-chip investors, and argue that, to achieve costs low enough to compete with new and existing fossil fuels, clean energy investments need to achieve risk profiles that will attract enough blue-chip investment to supply this additional flow of low-cost capital. The authors observe that key factors in this de-risking will involve increased revenue stability for clean energy resources, e.g., through power purchase agreements and new wholesale market designs.

[8] 60 Herz is the standard frequency in the US, 50 Herz is the standard in Europe and a number of other countries.

[9] Useful and accessible overviews of balancing, maintaining frequency and synchronized operation are Babazadeh (2015), and the more basic overview provided at https://www.electronicshub.org/synchronization-of-generators/ (Accessed October 15, 2020).

[10] See NERC Standard PRC-006-3 (Automatic Underfrequency Load Shedding) at https://www.nerc.com/_layouts/15/PrintStandard.aspx?standardnumber=PRC-006-3&title=Automatic%20Underfrequency%20Load%20Shedding&jurisdiction=United%20States . (Accessed October 15, 2020.)

[11] North America's Eastern Interconnection, for example, includes all the interconnected alternating current transmission, generation and load between the High Plains, the Gulf of Mexico, the Maritime provinces and Hudson Bay. Within this broader region, Quebec and the ERCOT zone of Texas are not part of the Eastern Interconnection, but instead each have their own synchronized interconnection, with no alternating current

connection to the Eastern Interconnection. See, e.g., map at https://www.e-education.psu.edu/geog469/node/222. (Accessed October 20, 2020).

[12] For example, rotating clean energy generators such as nuclear, CCS, or zero-carbon fueled combustion technologies will continue to require a constant grid frequency to synchronize and operate safely. The inverters that wind, solar and batteries rely on to synchronize themselves with the grid also require a strong frequency signal from the grid to function. Further, a constant frequency is also critical for fault protection and related system security and safety requirements, and to produce a constant velocity in three-phase electric motors on the demand side of the system.

[13] This decomposition follows Varian (1992). See Appendix part III.

[14] This is true even though boiler-based technologies have significant start-up times before they can synchronize to the grid and produce power. Despite this, when the historical concept of "base load service" still made sense, they could typically be counted on to be committed and already operating at most times when up to their full output could be needed to balance increases in consumption. Similarly, intermediate and even peaking service were -- and still are -- provided by boiler-based technologies, by pre-committing the units according to expected daily load levels, so they would be up and running at their lower limits, with their ramping capacity available when needed to follow load or meet peaks. By minimizing the number of starts for plants used for "base load" service, this reduced the contribution to total cost of their (non-convex) start-up, minimum run time and shutdown costs. The introduction of large amounts of VITL technologies has the effect of cutting up the time periods during which such plants are optimal to operate, causing them to cycle on and off more frequently, and making it more difficult to minimize their non-convex costs, and more expensive to own, operate and maintain them. This is the primary reason why "base load" levels become more intermittent and less suited to being served by "baseload generation" when there are high levels of renewables, and especially of wind on power systems. See n. 17 and Appendix I.

[15] See the Appendix for an illustration of screening curves and load duration curves and their historic use in basic resource planning.

[16] For a more detailed discussion of the positive and negative dynamics associated with different mixes of non-firm technologies, see Schlag et al. (2020).

[17] Many existing nuclear plants are not well-suited to reduce their output or operate intermittently, and so must run around the clock, around the year. Because electricity demand is often higher during the day, adding up to the amount of solar power to meet expected daytime demand levels will not impinge on the demand "headroom" nuclear plants need to run around the clock. But adding even a more modest amount of wind, which often produces electricity at night when demand is low, could lead to overproduction at night, and hence the need to curtail either the wind or the nuclear plant production to avoid increasing system frequency above the acceptable 60 Herz. Despite its lower marginal production cost, curtailing wind could be more efficient, since frequent curtailment of nuclear output could potentially lead to the retirement of the entire facility, dramatically increasing overall costs.

[18] Sepulveda et al. (2018), especially Fig. 1, p. 6; Jenkins et al. (2018); NJBPU (2019), Appendix A, pp. 252 – 285, especially the comparison of the least cost scenario and variant 5, in which existing nuclear plants retire at the end of their current license periods.

[19] Further, competitive market dynamics are formally analogous to the simple linear optimization processes used for fossil fuel planning. See, e.g., Arrow and Hurwicz (undated). This suggests that the added information and computational burden associated with optimizing the long-term mix of clean energy resources may exceed the ability of today's wholesale energy markets to support the fully decentralized development of an optimal clean energy supply portfolio.

[20] The metallurgical "recipes" for turning iron into various forms of steel are widely known and closely followed, but the "recipes" for whatever distinguishes a BMW from a Ford may be hard to reproduce, and intentionally so.

[21] Vegetable canners and freezers offer planting date- and variety-specific contracts to multiple independent, competing vegetable growers, based on LP-optimized planting schedules that will provide the continuous flow of fresh vegetables needed to maximize the value of capital-intensive processing facilities. RTOs use LP-based SCED to identify and dispatch the optimal mix of available generation, owned by independent and competing non-regulated entities, to match load within system security constraints every five minutes. In both cases, the critical dynamic matching of input supplier production with input utilization can't be achieved as efficiently without the centralized optimization process, even though both sectors are highly competitive and take place in the context of competitive markets for capital, equipment, labor, fuel, land and other essential inputs.

[22] The author was active in numerous debates in the early years of this century over the merits of SCED or "nodal" wholesale electricity markets vs. those of "zonal" markets, which do not use centralized SCED algorithms to dispatch or price generation. At that time, a common argument used *against* SCED market proponents was that they were advocating central planning rather than truly competitive markets, since SCED dispatch decisions and prices were generated by a Soviet-style, centrally operated linear programming tool, not by decentralized voluntary buying and selling decisions of many independent agents. It is interesting to hear some proponents of SCED markets make the same argument today against the configuration market and related concepts.

[23] For example, shipping firms use combinatorial auctions to procure the least-cost combination of trucking routes and providers between a company's manufacturing and distribution facilities. See Caplice and Sheffi (2006).

[24] In combinatorial auctions to procure trucking services, the sellers (the trucking firms) have information about complementary routes that the buyer (the shipper) does not have, and the combinatorial auction elicits that information efficiently. In the configuration market, neither the seller (the energy project developers) nor the buyer (the market host and load) has information on the complementarities of the possible inputs, so the PRISM tools are needed to extract that information from the bids and the other data.

[25] Perhaps the most relevant example for the configuration market is the so-called *incentive auction* by which the FCC simultaneously procured unused or undervalued TV frequencies and sold them to mobile telephony providers, as described in Leyton-Brown, Milgrom and Segal (2017). In that auction, certain bids to sell TV spectrum could not be accepted without checking a very large number of permutations of bids for the potential to create broadcast interference with each other. This was a risk because winning sellers were granted replacement frequencies on another band not used by mobile telephony, but if winners were geographically close to other users of the same frequency, the two stations' broadcasts would interfere with each other. Thus, as part of the auction winner selection process, those potential combinations had to be identified and rejected before the bids could be cleared on the basis of their prices. This near-simultaneous feasibility determination required a large and rapid set of algorithms to check for interference as part of the bid clearing process, much as the configuration market would use PRISM analysis to check for positive rather than negative synergies among bids from clean energy resources as part of the bid-clearing process.

[26] Mechanism design is used to develop game-theoretic procedures that will induce independent economic agents to solve allocation problems in the most efficient feasible manner, when those allocations cannot be provided efficiently by a decentralized process. Ordinary auctions are examples of very simple mechanism design. An accessible overview of mechanism design is Haeringer (2017), Appendix B.

[27] Recalling Kenneth Arrow's insight, cited in Williamson (1981) at p. 551: "Market failure is not absolute; it is better to consider a broader category, that of transaction costs, which in general impede and in particular cases completely block the formation of markets." The transaction cost literature is likely to be increasingly important in solving electric market and institutional design problems in the era of rapid decarbonization, especially those problems beyond the reach of marginalist price theory and Pigovian taxes.

[28] Alova (2020) analyzes investment in energy technologies by 3,311 regulated utilities from around the world over the last two decades, and found that 75 percent of the global, non-hydro renewable capacity is owned by non-utility independent power producers (IPPs), while only 19 percent is owned by regulated utilities. Further, among regulated utilities, 75 percent (owning 50 percent of all capacity) added neither fossil nor renewable technologies; 10 percent of utilities (with 26 percent of all capacity) added renewables comprising, on average, 14 percent of their capacity, But of this 10 percent that added renewables, 57 percent continued to grow their fossil fuel assets by roughly 5 percent during the same period, the majority of it natural gas-fired. Generally, even the utilities that are growing renewable energy capacity appear to couple that growth with new fossil fuel capacity, rather than transitioning entirely to low or no carbon generation. It is striking that the power sector entities subject to the balancing requirements lag so far behind those that do not in terms of investment in variably intermittent resources.

[29] For insights based on significant real-world deviations the necessary conditions of economic theory, see Joskow and Tirole (2007). On a non-theoretical level, Corneli, Gimon and Pierpont (2019) offer a thought-experiment showing the potential elusiveness and instability of an efficient price-driven equilibrium level of VITL technologies.

[30] Existing capacity markets would either be replaced by, or transform into, a configuration market.

[31] See, e.g., Steinberg, L. (2015). Changing the Game: The Rise of Sports Analytics. *Forbes,* August 15, 2015. Available at: https://www.forbes.com/sites/leighsteinberg/2015/08/18/changing-the-game-the-rise-of-sports-analytics/?sh=50bf0b884c1f . (Accessed October 20, 2020).

[32] See Arthur (1989) for the seminal paper on path dependency, increasing returns due to experience and use, and technology lock-in, including the lock-in of inferior technologies. Two familiar examples of path dependence in the paper are the persistence of the QWERTY keyboard and of AC power, whose increasing returns are attributed to coordination externalities, as amply illustrated in the case of AC power in the balancing discussion above.
[33] Going-forward costs are generally defined as cash outlays, including needed maintenance and repairs, that would be avoided if a plant were to cease operations.
[34] See EIA chart of capacity additions by type and by year, 1940 -2016 in Appendix
[35] FPA Section 209(b) is codified as Section 824(a) of the US Code. The state board provision and its potential use in clean electricity policy is explored in Dennis, Kelly et al. (2016).
[36] Optimization challenges and details, including the role of intertemporal optimization and projections of future efficient resource mixes, are discussed in the Appendix, part III.
[37] E.g., IPCC (2018).
[38] See, e.g., https://www.forbes.com/sites/scottcarpenter/2020/10/15/us-utility-companies-rush-to-declare-net-zero-targets/#2ea02549693b . (Accessed October 25, 2020).
[39] See, e.g., Carbon Pricing in Organized Wholesale Electricity Markets, 173 FERC ¶ 61,062. FERC Notice of Proposed Policy Statement, October 15, 2020.
[40] See Section 3(b)(v).
[41] Such a swap should provide a high-power incentive, since the project retains the residual of fixed cost recovery, including the earnings of its equity owners, subject to meeting the performance requirements. There may be additional efficiency gains, not explored here, from more sophisticated approaches to establishing incentive contracts, such as those proposed by Laffont and Tirole (1993).
[42] The proposed swap has many of the characteristics of tolling agreements widely used between independent power producers (IPPs) and load serving entities (LSEs), in which the LSE pays a fixed cost payment to the IPP in return for the LSE gaining the right to call on its plant as needed and retain all energy market revenues earned by the plant, while also taking on the obligation to pay for the fuel used.
[43] Projects that choose to bid into the configuration market are trading the possibility of occasional extraordinary rents from energy market scarcity for the certainty of a fixed, and potentially lower, stream of payments from load, while laying off the risk of long periods without scarcity prices in which they could not meet their debt obligations. Load is trading this fixed outflow, which it can afford even in the absence of scarcity prices, for the varying, and potentially very large, inflow of revenues when there are scarcity prices. This lays off load's risk of very high costs at the time of high scarcity prices. If secondary markets are able to offer more attractive hedges to new resources than these swaps, e.g., that allow the resources to retain some of the scarcity rents while still supporting attractive debt financing, those new resources would simply choose not to participate in the configuration market.
[44] Krishna (2010), ch.13.
[45] See n. 47 regarding problems with the use of ELCC as a common product definition in the configuration market.
[46] Krishna (2010), id..
[47] A reviewer suggested that with new approaches to the capacity metric of expected load carrying capability (ELCC), the configuration market could perhaps be more efficient and use a single, market-clearing price. However, the ELCC of any particular resource varies by resource type and location, and with actual insolation and wind speeds, and also varies dynamically with the deployment of varying mixes of clean energy resources. Further, it generally declines with growth in overall deployment of clean energy resources. See, e.g., MISO (2020), Figure 2-3 and Schlag et al. (2020). As both cited analyses show, using such a metric in a capacity market involves a number of serious, rate-making like administrative compromises between a variety of efficiency and fairness concerns, and thus could create a number of efficiency and participation challenges in a capacity market. By contrast, the configuration market's as-bid payments for incrementally optimized elements of a power system that be able to balance and carry sufficient reserves in all dispatch intervals, avoids all these problems. Hence ELCC is not recommended for use as the traded product in the configuration market.
[48] Haley et al (2019) at p. 66, "Our modeling of optimized pathways [to reduce atmospheric GHG concentrations to 350 ppm by 2050] shows little change to gas capacity relative to today but the eventual retirement of all other fossil electricity generation"; and Phadke, Paliwall, et al., (2020) at p. 4, "[adding 1,100 GW of new wind and solar generation while] "retaining existing hydropower and nuclear capacity [except planned retirements], and much of the existing natural gas capacity combined with new battery storage, is sufficient to meet U.S. electricity demand dependably (i.e., every hour of the year) with a 90% clean [energy] grid in 2035. … Generation from natural gas

plants constitutes about 10% of total annual electricity generation, which is about 70% lower than their generation in 2019." NJBPU (2020) shows broadly similar results regarding gas capacity retention with dramatically falling natural gas-fired generation.

[49] NERC's Glossary of Terms (at http://www.nerc.com/files/Glossary_of_Terms.pdf) defines adequacy as "an electric system's ability to supply aggregate electrical demand and energy requirements of end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements". In practice, achieving adequacy involves each of NERC's regional reliability organizations (RROs) setting its own standard for overall or "planning" reserve margins, above and beyond peak demand. RROs select a reserve margin that is estimated through sophisticated probabilistic electric supply and demand models to be sufficient to result in an expectation of emergency load shedding events of no more than during one day in ten years. The frequency of expected load shedding frequency is called the loss-of-load expectation (LOLE), for example, an LOLE of 1 day with load shedding in 10 years. Depending on the specifics of each RRO and their analysis, this typically produces a planning reserve margin in the neighborhood of 15%, which is equivalent to installed capacity of 115% of projected peak load. For a useful, accessible but rigorous exploration of LOLE and related issues, see Brattle (2018).

[50] The widespread view that states have, or had and can "take back" authority over resource adequacy (RA) is somewhat misleading, since resource adequacy can only be achieved by, and across, an electric interconnection, by coordinated and comparable requirements for each balancing authority, load serving utility and generator within the interconnection. Under the Federal Power Act, states clearly have the authority to regulate the construction and cost recovery of generation resources, if they choose to exercise it. Where exercised comprehensively, this authority allows states to ensure that their regulated utilities meet RA requirements that are consistent with, and contribute to, achieving regional resource adequacy standard. States with a single state ISO can and do exercise some RA authority at the state level. E.g., the California PUC's RA program requires utilities to contract with enough generators to meet 115 percent of their peak load, which is intended to ensure enough capacity to meet each utility's share of the single-state CAISO's resource adequacy responsibilities. The New York State Reliability Council (NYSRC) sets resource adequacy requirements for the single state NYISO, within the Eastern Interconnection – with the explicit requirement in the NYSRC's rules and agreements that NYISO and its market participants also comply with NERC and NPCC standards and criteria. The ERCOT interconnection is fully within Texas and not synchronized with other US interconnections, and therefore its electricity companies cannot participate in interstate commerce. Hence, they are statutorily exempt from most FERC jurisdiction. The ERCOT board sets a planning reserve margin target of 13.75%, however ERCOT, and its regulator, the Public Utilities Commission of Texas, take this target as a non-binding benchmark, and rely on ERCOT's energy-only SCED market prices to induce an appropriate level of investment in new and existing resources. By contrast, the resource adequacy standards administered through capacity requirements and each RTO's capacity procurement process in the multi-state RTOs of ISO-NE, NYISO, PJM, MISO and SPP are designed to meet broader regional reserve margin requirements designed to produce a specific loss of load expectation. These regional standards may be approved by FERC (e.g., Order 747, approving the Reliability First regional standard affecting PJM), or may instead be taken as advisory by the RTO in developing its own (e.g., in ISO-NE).

[51] See, e.g., Brattle (2018), pp. 33-39.

[52] Id.

[53] A price on carbon cannot be relied on to always fix this situation, either. In SCED-based markets, the cost of emitting a ton of carbon can always be recovered if the emitting plant, or one like it, is on the margin (i.e., setting the LMP). Plants with marginal costs and carbon emissions that are lower than those of the marginal plant will make earn additional quasi-rents, since the marginal plant emits more CO2 per MWH than they do, and thus has higher marginal compliance costs that are included in the market clearing price. This explains why merchant power companies with large fleets of combined cycle gas turbines have generally supported carbon pricing policies. Their combined cycle units will recover their carbon costs when they are themselves on the margin, and will earn additional carbon-related quasi-rents, above and beyond their own fuel and carbon costs, when either combustion turbines or less efficient coal plants are setting the price when the combined cycle units are operating infra-marginally. Erosion of these quasi-rents would require, in addition to a carbon price, the rapid entry of large amounts of clean resources that can effectively displace substantial shares of both the combined cycle unit's energy production, and the dispatch of combustion turbines and thermal plants providing various ramping and peaking services above them in the dispatch merit order. Even so, if the new clean resources are predominantly VITL technologies, then SCED prices will be suppressed in the many hours with net surplus VITL resources, and

scarcity will occur, and gas plants will primarily be needed, in hours with low levels of wind and sun and depleted time-limited resources. During these hours, gas-fired electricity will be in very high demand and receiving scarcity prices on the order of $10,000 or more per MWH. Under such circumstances, even relatively inefficient gas plants could operate profitably while paying very high carbon prices. Indeed, gas-fired resources, on both the supply and the demand side of the market, could be the preferred resource for hedging the risk of such longer periods of inadequate VITL energy, even with very high carbon prices. Ensuring such gas use does not conflict with the required levels of deep decarbonization may require the development of zero-carbon gas substitutes, as well as the deployment of substantial amounts of clean firm technologies, e.g., new nuclear and CCS.

[54] The interaction of the resource adequacy approach used in the configuration market and the retirement incentives will need to be considered carefully, and the details of each will need to be designed so as to achieve both goals efficiently.

[55] For example, the PRISM mechanisms balancing and carbon constraints may overestimate the energy market revenues that certain of these resources receive in the real world, and those revenues may be further suppressed by slow retirements of other resources, lower fuel prices, and changing transmission topologies, relative to those in the PRISM analysis.

[56] Hogan and Pope (2017) offer particularly relevant insights into the inefficient balance between transmission and generation in ERCOT's otherwise highly competitive energy-only market.

[57] The level of savings associated with such a projection would have to be determined through the transmission planning and transmission tariff approval process(es) of the governing jurisdiction(s) involved in approving cost-recovery for transmission projects in the region where the configuration market operates.

[58] Hogan and Pope (2017) at pp. 75-77.

[59] Jenkins and Sepulveda (2017) explains how the GenX model includes DERs in its optimization.

[60] E.g., PJM's Fixed Revenue Requirement (FRR), as provided for in Section 8 of PJM's *Reliability Assurance Agreement.*

[61] Blank (2020) is a well-known guide to such parallel and iterative development of product and customers.

[62] NJBPU (2020), VCE / MISO (2017) and Aas et al. (2020).

[63] See n. 4, above.

[64] The concept was central to Schumpeter (1942)'s view of economic history. It was given a strong practical application by Samuel Insull, who in developing his first integrated, scale-optimizing electric utility, claimed to measure his success in large part by the size of his junk pile of scrapped earlier investments in smaller scale technologies. Bradley (2011) at p.125.

[65] Sepulveda et al. (2018), figure S8 in the supplemental material.

[66] The GenX model appears to have used stepwise myopia in this study, based on the discussion in Jenkins and Sepulveda (2017). Specifically, the model seems to have been run separately but incrementally for each specified, incremental annual period producing the levels of decarbonization reported in the many graphs of Sepulveda et al. (2018), while using perfect foresight within each annual run to better capture unit commitment and other inter-temporal processes within that year.

[67] The main difference is that typical prospective PRISM analysis is based on current assumptions about future costs and availability of the various clean energy resource, while the configuration market will get its data on cost and available quantities of resources from bids submitted by real developers who know their costs and their project's prospect of successful development.

[68] Due to their high fixed costs, low serial number risks, and inherent risks associated with nuclear fuels and reactors, new nuclear generating technologies in particular are likely to depend on much longer-term revenue hedging agreements for successful development than wind and solar projects. These less capital intensive and well-proven technologies are likely to be viable with substantially shorter length hedges, especially if the configuration market is used to provide a relatively high LOLE, and hence support relatively high SCED market prices, as discussed under resource adequacy in part 3(b)(iii) above.

[69] For example, ETF needs to integrate into the fuel supply and delivery systems, as well as the bulk power system and electricity markets. DERs need to integrate into customer value propositions and local electric distribution systems, as well as electricity markets, and may have the ability to use dramatically innovative new coordination and dispatch optimizing tools to do so. EV charging networks need to integrate into the transportation system, customer value propositions, and distribution systems. Achieving the full value of such resources depends on this multi-sector integration, much of which cannot proceed rationally without clarity on how these technologies and

business models will actually provide value to, and be able to coordinate with, a rapidly decarbonizing power system.

[70] Haeringer (2017), pp. 29-34.

[71] Krishna (2010), pp. 13-17.

[72] See, e.g., Monitoring Analytics (2020).

[73] Non-competitive conduct would be self-evident in a bid above going-forward costs; while the impact would be automatic if the bid cleared and so received a hedging contract at the as-bid level.

[74] An early analysis of the possibility of buyer's side market power and potential means to mitigate it is the testimony of Corneli (2005) in the LICAP hearing phase of the Devon II proceeding at FERC. Note that one of the four criteria proposed for mitigation of buyer's side market power was that the buyer who develops the price-suppressing new capacity must be able to reasonably expect to receive more benefits from the price suppression than the total cost of the new capacity. In extending PJM's MOPR from addressing buyer's side market power to acting as a deterrent to state-supported clean energy investment, FERC's section 206 order completely ignored this critical criterion for determining whether buyer's side market power exists and warrants mitigation.

[75] Out-of-market support for GHG emitting technologies would not increase GHG emissions, since the carbon constraint is binding. It could potentially increase the shadow price of carbon in the model, forcing more zero carbon resources into the market, and at a higher cost, to overcome any incentives to operate at a lower cost, or remain in operation longer, the GHG emission incentives provide.

[76] Of the total 28,502 MW interconnection requests reported in March of 2020, 436 MW os were for natural gas resources, 2,683 MW were for wind resources, 4,572 MW for storage, and 20,674 MW for solar resources. PJM Interconnection Queue Status Update, May 12, 2020. Available at: https://www.pjm.com/-/media/committees-groups/committees/pc/2020/20200512/20200512-pc-info-only-pjm-queue-status-update.ashx . (Accessed October 20, 2020).

[77] For a reasoned and thoughtful example of such a non-discriminatory, going-forward-cost based bidding floor for use in today's capacity markets, see the sustainable market rule (SMR) proposal of Bowring (2018). Dr. Bowring serves as the market monitor for PJM.