

DESIGNING ELECTRICITY MARKETS FOR FLEXIBILITY: HOW TRANSMISSION EXPANSION, DEMAND RESPONSE, AND OPERATIONAL RESERVES SHAPE POWER SYSTEM PERFORMANCE UNDER INCREASING VARIABILITY

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Abstract

The quick rate of scale of the variable renewable energy (VRE) has considerably changed the nature of electricity systems operation and economic bases. Short run dispatch, long run investment and regulatory design are now influenced by variability and uncertainty which were previously subsidiary factors. The classical markets of electricity that were constructed based on stable supply and demand that are mostly inelastic are becoming more and more unsuited to suit the needs of the systems that are dominated by wind and solar production. The arguments presented in this paper are that electricity markets need to be transformed into non-energy-based trading platforms, i.e. integrated flexibility procurement systems. Flexibility here is described as the capacity of the power system to react in an effective way to spatial variations, more so, temporal variations, as well as, stochastic variations.

The paper dwells on three fundamental mechanisms of flexibility which include transmission expansion, demand response and operating reserves. Transmission expansion allows structural flexibility by allowing a renewable resource and load geographic diversification, which decreases congestion and reserve requirements. Demand response offers both behavioral and operational flexibility through conversion of electricity consumption into an active balancing provision. Operating reserves avail probable insuring to unpredictability as a financial benefit. The paper presents interdisciplinary literature of the power system engineering, energy economics and regulatory literature, in that these mechanisms are deeply interdependent and have to be structured as a coordinated portfolio and not as stand-alone market products.

The discussion points out that reserve markets should be analysed as stochastic insurance market, the price of congestion, shortage of reserves has to be used to make transmission planning and demand response should be included in the wholesale market symmetrically and supported by credible measurement and verification. The paper also emphasizes the significance of the frameworks of high-resolution, stochastic and network constrained modeling which determine the flexibility value and guide the market design. In general, it is concluded that flexibility needs to be considered as the main power system infrastructure. The electricity markets will then need to transform not only to be institutions trading energy but also institutions that coordinate uncertainty management, making sure the electricity is reliable, efficient, and deeply decarbonated and more variable.

1. Introduction

Those power systems undergoing a rapid decarbonization process experience a shift in the operational and economic logic. The massive scale implementation of the wind and solar production causes variability and uncertainty, which is fundamentally dissimilar to the nature of traditional thermal and hydro resources. Although the traditional systems were based on manageable generation in the wake of fairly predictable demand, the new systems are operating hits on us a reminder that even the supply itself is no longer predictable but rather time-dependent. Some reversal in control over systems overturns flexibility as a peripheral issue to become a central organizing principle of the market design and infrastructure planning.

The key flexibility resources in the electricity markets that have received significant focus have been the battery storage, demand response and the fast-ramping generation, but the electricity markets are still basically set up around the trading of energy instead of acquiring flexibility. This will result in the inefficiency of marketing institutions and physical system requirements. The value of uncertainty management, geographic diversification, or quick response ability can not be communicated through the energy prices alone. Consequently most of the most economically valuable system services have ended up being under-priced, under-provisioned, or as an administrative, instead of a competitive process.

The measure of efficiency of the power system to react to three dimensions of variability can be termed as flexibility. Geographic variations in the renewable output and demand create spatial variability, which is controlled by the transmission networks. Intra-day and seasonal variability leads to the temporal variability and demand response and fast-ramping resources address it. Stochastic variability comes about due to forecast errors and unforeseen downturns and it is handled using operating reserves. These dimensions are characterized by specific technical and economic features, and each of them needs specific market design.

Transmission expansion gives flexibility in terms of structures and expands the possible functioning range of the system. Transmission increases the ability to transport power between areas with varying renewable characteristics and demands smooths the overall demand shape, helps mitigate congestion, reduces balancing costs, and reduces the reliance on the domestic reserves. It is demonstrated by Jabr (2013) and Roh, Shahidehpour, and Wu (2009), that the concept of investing in the network in case of uncertainty may contribute significantly to the overall system cost by sharing variability in space. Transmission is not just one of the assets of energy transportation; it is a long life flexibility resource which alters the statisticality of the uncertainty encountered by the system.

Demand response offers both operational and behavioral flexibility since it converts demand on electricity into a manageable system resource. Albadi and El-Saadany (2008) and Siano (2014) prove that demand response may provide a variety of services, such as peak shaving, alleviation of congestion, and provision of reserves. Designed based on institutional arrangement, pricing and consumer behaviour, demand response, contrary to generation or network infrastructure, is dependent on these factors. Allcott (2011) accentuates that allocative efficiency can be enhanced by exposing the consumers to the actual prices in real time, however, the author also points to the existence of behavioral obstacles limiting responsiveness. Market design should be effective therefore employing automation, aggregation, and incentive compatibility.

The economic basis of short term reliability is operating reserves. As demonstrated by Morales et al. (2009) and Papavasiliou, Oren, and O'Neill (2011), reserves are stochastic insurance tools which are used to hedge against uncertainty. Instead of being carded, technical requirements, reserve quantities and prices ought to be endogenous outcomes of the distribution of a probability of forecast errors and the cost of flexibility resources. As pointed out by Rebours et al, 2007a and 2007b, reserves are technologically differentiated goods and have varying times of response and economic functions.

Although they are central mechanisms in all electricity markets, they are seen as supplementary services, not as prime products. The primary center of attention continues to be energy trading with flexibility being obtained in piecemeal and in many cases, bureaucratically restricted processes. This type of institutional organization exposes itself to long-term underinvestment in flexibility, capital misallocation in resources that fail to perform well in a context of uncertainty. As revealed by Stoft (2003) and Wang et al (2011), reserve market scarcity pricing is critical in communicating stress in the system and providing guidance on long-run investment. In a case of interrupted such signals, market results are not in line with system requirements.

The thesis presented in this paper is that electricity markets should be remodeled in the form of integrated flexibility procurement systems. The transmission expansion, demand response, and operating reserves are to be regarded to represent constituents of the common portfolio of flexibility. They are not valued in isolation and instead, their value is determined through substitution and complementary. At times of sparse transmission, the demand response and value of local reserves increases. In the event of high demand response, the reserve requirements reduce. Structural investment of networks would be more appealing when reserves are costly. Papavasiliou et al. (2011), and Poncelet et al. (2016) demonstrate that planning models that do not take into account these interactions make a predictable artificially low estimate of the cost and reliability of a system.

The article continues in the following way. Section 2 analyzes the demotions of expansion of transmission as a type of structural flexibility, along with its relationship with a lack of knowledge and reserves requirements. Section 3 examines market-based flexibility resources, i.e., demand response with three main points of focus, namely, baseline design, behavioral uncertainty, and institutional integration. Section 4 discusses operating reserves as stochastic insurance markets, and emphasizes on the significance of co-optimization and scarcity pricing. Section 5 establishes a portfolio view, which incorporates transmission, demand response and reserves. Section 6 dwells upon the policy/regulation implication of flexibility based market design. Section 7 discusses the issues of modeling and best practices. Section 8 finishes by putting the concept of flexibility within the context of core power systems infrastructure as opposed to a secondary market product.

2. Transmission Expansion as Structural Flexibility

Transmission networks are closely connected with the effectiveness of power systems to utilize spatial variability in renewable loading and generation. In high penetration wind and solar power systems, production is both location-specific and generally loosely correlated region to region. Geographic diversification is possible through transmission expansion, which means that excess production in one location can be shipped to another location with a deficit. This way, it alleviates curtailing, alleviates the congestion and decreases the localized balancing resources that are required. Economically, transmission hence acts as a long term structural flexibility that reformulates the uncertainty that the system is subjected to.

Jabr (2013) develops transmission expansion planning with uncertainty based on powerful optimization model. His findings indicate that renewable variability and load uncertainty are very sensitive in the network investment decisions. In cases where the uncertainty is carefully

accounted, optimal expansion of transmission is usually greater in size and more geographically diversified than in deterministic models. This indicates how much the transmission is risk-insured: the more robust networks are, the less a system is exposed to extreme operating conditions as there is a way of getting alternative power flows and risk-sharing of regions. Transmission thereby reduces average operating costs as well as likelihood and severity of reliability events.

Similar findings are established by Roh, Shahidehpour and Wu (2009) who prove that coordinated generation and transmission planning incurs lower system total cost and higher reliability than sequential or fragmented planning. This is demonstrated by their market-based coordination structure that transmission expansion causes price volatility decrease and low-cost on reserves procurement because it decreases congestion and permits better utilization of generation resources. This coordination is even more significant in systems that operate under VRE since spatial diversity is among the most effective instruments of variability control.

Of special interest is the association that exists between transmission and operating reserves. Research indicates that there is an increment of reserve requirements with uncertainty in the net load. Weakly connected regions all require local reserves to control local forecast error and contingency because there will be no time to transport them across the regions. Transmission expansion enables sharing of reserves across regions and this decreases the amount that is needed. In this sense, transmission can be called a substitute of reserve capacity, which lessens the loss of balance of the aggregate systems.

This point is supported by Papavasiliou, Oren and O'Neill (2011), who use a stochastic programming framework that is based on scenarios. Their model indicates that reserve procuring and transmission constraints are closely intertwined. In the case of limited transmission, the reserve prices are localized and may increase drastically with the deliverability constraints. Using the network to make the network flatter enhances these price curves and makes the price of reliability low. This shows that reserve markets cannot be planned without transmission planning; locational deliverability is an essential factor determining the reserve value.

Congestion pricing is another concept that is influenced by transmission expansion as a major signal of network sufficiency. Continuous congestion means that the marginal value of network capacity is greater than the marginal cost of network capacity. In most regulatory regimes however, congestion revenues do not cover new transmission investment and planning decisions are achieved by means of the administrative processes. This provides a possibility of a lack of connection between market signals and infrastructure development. Jabr (2013) and Roh et al. (2009) are implying that regulatory bodies would be required to strengthen the regulatory feedback between congestion prices and the transmission planning, as a way of effective long run results.

Transmission and demand response interaction is also an important dimension. Problem In the congested areas, planners have a trade-off to scale between the demand-side flexibility that is locally based and the expansion of the network capacity. Transmission expansion eliminates congestion through raising physical transfer capacity and demand response eliminates congestion by decreasing the local consumption. The two mechanisms are flexible with varying

costs structures and risks profiles. Demand response involves continuous behavioral involvement and institutional assistance when compared to transmission that comes at high initial investment but offers long-term stable benefits. The market design needs them to come up with alternatives that would compete on equal economic terms.

It has been pointed out in the modeling literature that transmission value is underestimated systematically in simplified planning systems. It is demonstrated by Poncelet et al. (2016) that coarse temporal and spatial resolution masks off the patterns of congestion, and understates the benefits of investment in a network in terms of operation. Models of aggregation by regions have the artificial effect of smoothing variation and decreasing apparent transmission frugality. Consequently, the outcome planning was biased in the plan to not expand the network but rather to favour the local capacity to balance resources.

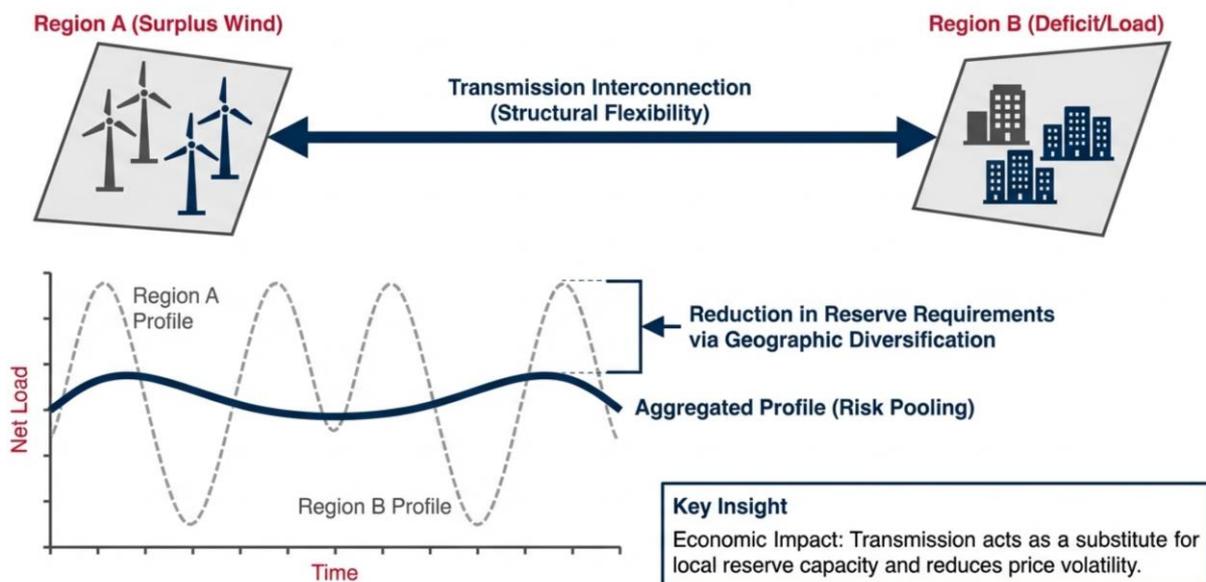
It has been extended by further research that reveals that the interaction between transmission, generation flexibility and policy diversity is misrepresented in models that are not operationally detailed. With explicit representations of network requirements and ramping constraints, the notion of transmission investment can be used as an important catalyst to decarbonization pathways. Lack of transmission will excessive dependence on local supply and peak generation rate, increase costs and emissions.

Considering the economic perspective, transmission growth is to be considered an infrastructural investment through which the statistical form of uncertainty in the system may be altered. Compared to operating reserves, which offer short-term insurance, or demand response, which offers adaptive consumption, transmission redefines the possible power system operation at the expense of dozens of capabilities. It makes the output of renewables correlated across space, flattens the distributions of prices, and decreases the chance of the occurrence of extreme scarcities. These advantages cannot be well represented by a short-run market and revenues, but they are long-run benefits obtained at a system scale.

According to Joskow (2007), infrastructure investment both in electricity markets should be informed by the market and the regulatory control. Transmission is a natural monopoly that has significant features of public good. Its flexibility parameter, particularly at the high VRE penetration, reinforces the argument of the proactive regulatory planning that in-house uncertainty and long-term system sustainability instead of the single guiding principle of short-run profitability.

Conclusively, the expansion of the transmission is not only a facilitator of energy trade but a pillar in the power system design with regards to flexibility. It replaces operating reserves by diversifying uncertainty space, augments demand response by geographical extension of balancing mote activities, and grants long lived security against structural variability. The market design and regulation frameworks should, then, be able to take note of the transmission as a basic flexibility commodity, and incorporate the congestion pricing and reserve deliverability and infrastructure planning into a single economic rationale.

Transmission Expansion as Structural Flexibility and Risk Pooling



3. Demand Response as a Market-Based Flexibility Resource

Demand response (DR) is one of the most diverse and economically qualified flexibility sources in the contemporary electricity networks. In comparison to either the generation or transmission infrastructure (which are more capital-intensive and require longer development times), the demand response uses the already existing consumption assets to make the demand of electricity responsive to system conditions. In systems where VRE penetration is increasing, in most cases where variation in supply is becoming the main problem, the capacity to vary demand on short notice or close to real time makes the consumption per renewable resource and network limiting aspect much more aligned.

The basic typology of demand response programs that are given by Albadi and El-Saadany (2008) is based on the classification of price-based and incentive-based mechanisms. The price-based demand response makes consumers vulnerable to fluctuating prices experience like real-time pricing, critical peak pricing or time-of-use tariff, which is aimed at inducing load shifting where marginal cost of the system is large. The incentive demand response pays the consumers directly to lower consumption when the systems go into emergency or peak demand. Although two mechanisms are flexible, their economic reasoning is different. Prices based programs incorporate demand response into market clearing internalizing indicators of scarcity and congestion, and incentive based programs consider demand response as a contracted reserve capacity.

Siano (2014) tells that the demand response system can provide several services at a time, such as peak shaving, managing traffic congestion, frequency, and contingency reserves. This multifunctionality renders DR distinctively useful in market design that is flexible. The key to its system value however relies on market rules that permit demand response to join generation and storage on an equal basis. Provided that DR is limited to the emergency programs or administratively-procured capacity, the full economic potential is not exploited.

Allcott (2011) compiles the view of demand response based on consumer behavior and allocative efficiency. He makes the point that showing the consumer real time prices can simplify the system costs a great deal as it can cause consumption to be out of peak times. He further notes though that there are behavioral frictions like inattention, limited information, and transaction costs undermining responsiveness. All of these frictions suggest that market design should integrate price signals and automation, aggregation, and default enrollment mechanisms so as to achieve all the benefits of demand-side flexibility.

One key issue of deploying demand response into wholesale markets, is how to build customer baselines. Chao (2011) demonstrates that baselines--the counterfactual estimate of what consumption would have been without a DR occasion--are not specifically technical measures, but central economic measurements. When the baselines are too high with regard to real consumption, the market results in overpayment of demand response, making them manipulated in a strategic way. When consumption is understated by baselines, then participation becomes non-optimal and the flexibility will be supplied insufficiently. Baseline design then identifies the result of demand response being efficiency-enhancing or integrity-destroying to the market.

Chao and DePillis (2013) also show that where the demand response is compensated at prices set on the wholesale market, perverse incentives may be created in the case of poorly designed baselines. Consumers can also stock up or stock away ahead of an event with the aim of gaining profit in later cuts in order to provide false flexibility that undermines reliability in a system. In their analysis, credible measurement and verification are some of the requirements in order to treat demand response as a reliable system resource.

Eid et al. (2016) argue that demand response is a space between wholesale and retail, and coordination in the regulatory domain is needed. Although wholesale markets may be sensitive to flexibility, it may not work because price signals may not be communicated to the end users due to retail tariff structures, absence of advanced metering, and consumer protection laws. This is one of the primary causes why demand response has not been developed in most jurisdictions. Market design that is flexible-oriented thus needs reforms both at wholesale level and regulation of the retail and metering infrastructure.

Operating reserves are also highly interacted with demand response. As demonstrated by Albadi and El-Saadany (2008) and Siano (2014), some of the loads are capable of responding fast enough to offer regulation and contingency reserve services. Industrial loads, commercial structures, and aggregated residential loads can be able to regulate consumption within seconds or minutes, and are technically comparable to spinning reserves. It is known that the reserve value, in the cases of uncertainty, leads to an increase in the reserve value and there is therefore a high system value of a demand response to decrease the net-load uncertainty mostly in VRE-dominated systems.

In terms of portfolio, demand response replaces the transmission and reserves. Localized DR in congested areas helps decrease the power flows over constrained areas, as an alternative to network expansion. DR mitigates the net load variance and decreases the reserve requirements in a system with a large forecast error. Though, such as opposed to transmission or generation

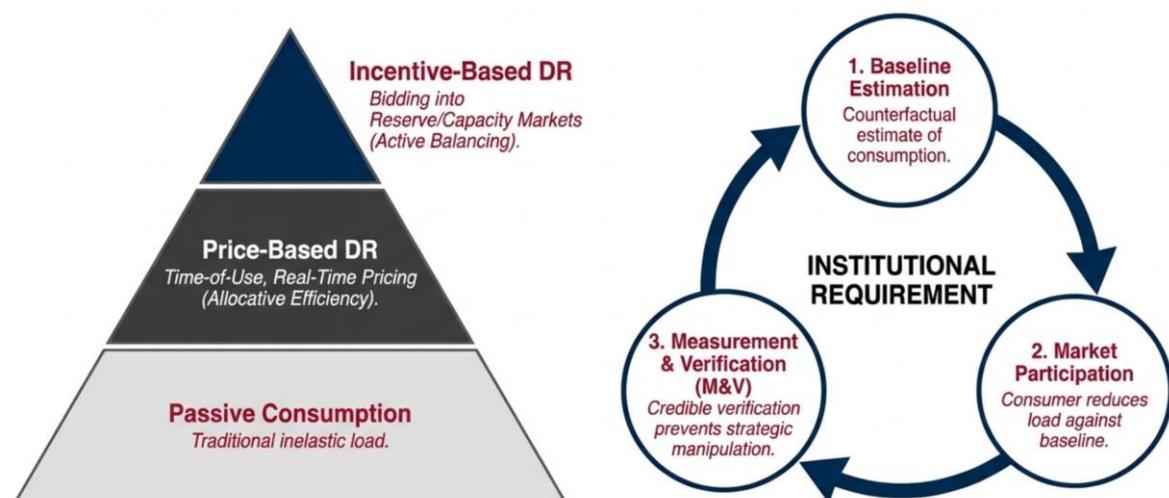
assets, demand response can only be available most of the time, based on human behavior. Market design should also not only be used to price but also performance reliability.

As it is demonstrated by Levin and Botterud (2015), the role of ancillary services revenues grows with a decrease in energy prices in the renewable-concentrated systems. Demand response, which also enters into reserve and regulation markets hence, not only helps in operational efficiency but also in revenue adequacy among the flexibility providers. This adds more weight to the argument of the equal access of the market to both demand-side resources and supply resources.

Regardless of the benefits of demand response, it institutionally is still weak. The barrier to its implementation is its use of baseline disputes, consumer trust, regulatory complexity and political resistance to dynamic pricing. Eid et al. (2016) opine that effective integration of DR must have clear guidelines, consistent compensation systems, and co-existence of wholesale and retail fairness.

Summing up, demand response converts the electricity usage into a system asset of flexibility. It offers low capital, scaling and multi-purpose flexibility which complements transmission growth, as well as operating reserve. Market design, reduction to base credibility, coordination of rules and the realism of behaviour are however critical to its economic value. The demand response in a flexibility-oriented electricity market should not be considered as an emergency response process but rather it should be regarded as regular operating infrastructure, and it should have active role in energy supply, reserve response and congestion management.

Demand Response Topology: Market Integration and Baseline Integrity



Key Insight: Poor baseline design creates perverse incentives; credible M&V is required to treat DR as a reliable system resource.

4. Operating Reserves as Stochastic Insurance Markets

The major way, through which electricity systems cope with short term uncertainty, is by operating reserves. With traditional generation, the reserves in the system have historically been considered as engineering requirements, which are established in an administrative manner to address the maximum plausible contingency. At very high VRE penetrations though, continuous forecast error in wind and solar power takes the place of discrete outages as the

dominant influence on uncertainty. This changes reserves into more of an economic tool to deal with the probabilistic risk rather than a technical tool.

Rebours et al. (2007a) note that the operating reserves cannot be taken as a single homogeneous product but a type of services that are varied by the speed of response time, duration, and the probability of activation. Control of frequency touches upon short-to-minute variations, spinning capacity deals with short-term emergencies, and non-spinning or replacement capacity deals with imbalance over longer periods. The cost structures as well as the technological requirements of the individual categories vary. The efficient market design thus involves the existence of differentiated products and not undifferentiated reserve obligation.

It is demonstrated by Rebours et al. (2007b) that opportunity cost is overpowering in the determination of reserve pricing instead of marginal cost of production. Reserves in the form of a generator have to be off-line or not sold to the energy market as they can generate more energy than allowed. The cost of this opportunity decreases rapidly when the system is tight hence the tremendous volatility that is usually witnessed in reserve prices. Reserve prices are the major transmitters of scarcity signals in the VRE dominated systems in which the energy prices can be low because of the large quantity of zero-marginal-cost generation.

This opinion is formalized by Morales et al. (2009), who model reserves as stochastic insurance instruments. Their model would imply a lower cost of load shedding expected and imbalance penalties by hedging the net load uncertainty. The marginal value of reserves grows non-linearly with the uncertainty, meaning that the reserve scarcity becomes economically central with high forecast error systems. There are two implications of this outcome. First, a clearance of reserve markets at scarce prices has to be permitted. Second, reserve prices do give first-hand information concerning the social cost of uncertainty.

Papavasiliou, Oren, and O'Neill (2011) build on this based on a scenario-generated stochastic programming model of wind integration. Their model would have reserve requirement developing endogenously as the cost minimizing reaction to uncertainty instead of exogenously. This is the opposite of the deterministic reserve rules that provide a set of fixed margins irrespective of the state of that system. Stochastic reserve procurement is closer to the reality of economic trade-off between reserve cost and the risk of failure.

Galiana et al. (2005) indicate that the market clearing requires the co-optimization of reserves with energy in the market. The opportunity costs are neglected as well as price distortion when the scheduling of energy and reserves is done independently. Co-optimization is the way to make sure that the reserve prices correspond to the cost of incurred loss of energy production and the dispatch cost to the cost of reliability. In conditions of high variability, co-optimization will be necessary since the reserve requirement changes quickly due to the renewable forecast conditions.

Stoft (2003) reveals that electricity markets send the message of necessity in investment in flexibility through reserve scarcity pricing as the primary instrument. Once the reserves are low, the prices will increase at a high rate, which will provide incentive to invest in fast ramping generation, storage, demand response, and transmission. When regulators take off the price hikes by administrative measures, they destroy the market with regards to the coordination of long-run reliability investment.

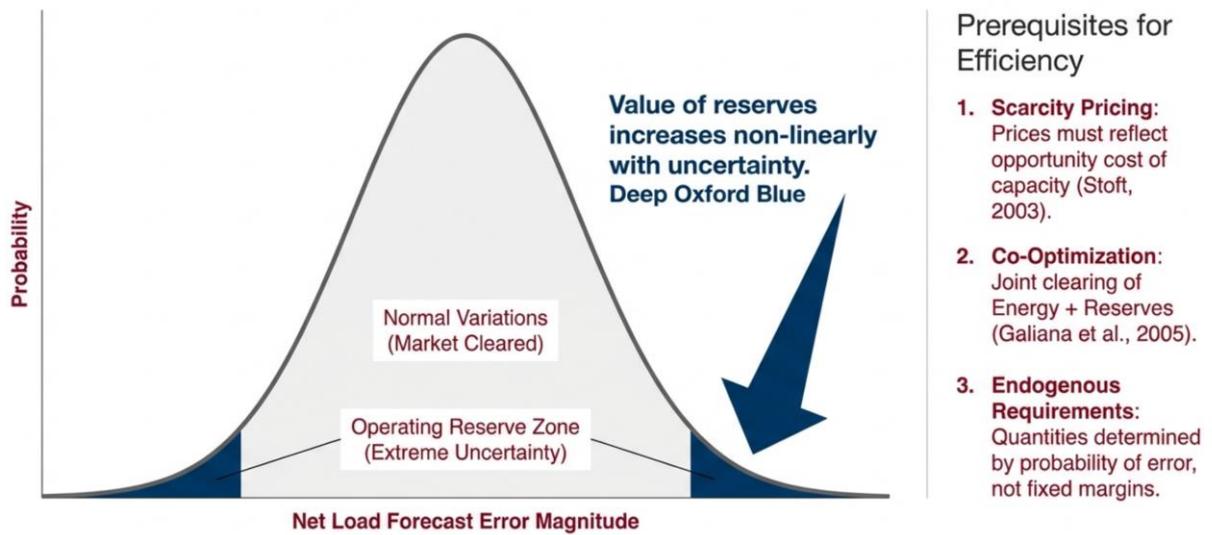
Wang et al. (2011) determine empirically that there are information in ancillary services prices that cannot be derived by the prices of energy. They demonstrate that renewable variability, high load and generator outages are strong signals of system stress that is responded to by reserve and regulation prices. In the systems with the predominance of VRE, the market of ancillary services is becoming the main markets, where the manifestations of scarcity occur. Network bottlenecks are very important in the theory of reserves. Papavasiliou et al. (2011) report that in case reservoir supply is unavailable over congested transmission routes, such reservoirs are sourced locally, which increases the cost. Transmission expansion thus replaces the reserve procurement by enhancing the deliverability and pooling of flexibility in the regions. This confirms that the network planning cannot be disconnected with the reserve market design.

Reserve markets are also directly related to demand response. According to Albadi and El-Saadany (2008) and Siano (2014), fast-responding loads have the ability to regulate and provide contingency reserves. Nevertheless, Chao (2011) and Chao and DePillis (2013) caution that demand response adds to the reserves can only be credible when baselines are correct and performance s can be verified. Otherwise, the reserves are illusions of contracts, but not physical sources of reliability.

On the revenue sufficiency front, Levin and Botterud (2015) reveal that the despondence in energy prices in renewable-based systems makes generators turn to the revenues of ancillary services in order to offset generation costs. Reserve markets thus serve two purposes of guaranteeing the reliability of the operations as well as promote incentive on long-term investments. When the reserve prices are not set at a high rate, the two functions will fail.

In short, operating reserves are to be thought of as stochastic insurance markets that are priced to be reliable in conditions of uncertainty. They transform probabilistic system level risk into economic signals which inform operating in the real-time and long-term investment. The design of the reserve market must be technologically differentiated, energy co-optimized with energy, scarce priced, locational deliverable constrained, and non-traditional resources such as demand response must have open access. With growing variability, reserve markets turn out to be the main element of the economy of reliability rather than a sidelining auxiliary activity.

Operating Reserves as Stochastic Insurance Markets



5. Integrated Flexibility Portfolios and Substitution Effects

The systems of electricity do not use a single mechanism to handle the variability. Instead, they perform with sets of flexibility resources that combine expertise of spatial, temporal and stochastic uncertainty. Economic interdependence exists between transmission expansion, demand and operating reserves. The one can generally be replaced by the others and a marginal value of any resource is determined by the availability of the others. The technical aspects of these substitution and complementarity relationships are necessary in order to have the design of electricity markets which would minimize the total cost of the system and yet remain reliable with increasing variability.

Papavasiliou, Oren, and O'Neill (2011) demonstrate that the reserve requirements are both a factor of uncertainty in the forecast, as well as a factor of the system flexibility portfolio structure. In the case where there are many flexibility channels, uncertainty can be taken up in several ways, which lowers the marginal value of any of the channels. On the other hand, in cases in which the flexibility is low, the reserve prices will soar, indicating the high social cost of the imbalance risk. This is an indication that reserves, transmission and demand response are not free-standing design issues that are part of a system of economic systems.

Transmission expansion replaces operating reserves since it decreases the level of aggregate system imbalance. As demonstrated by Jabr (2013), the huge networks make it possible to cancel forecast errors in areas with uncorrelated renewable production. In a study by Roh et al. (2009), coordinated transmission and generation planning saves costs on price volatility and the cost of acquiring reserves. In loosely interconnected systems, every region is required to have its met reserves on hand the net result being a vastly higher system cost. Transmission hence is a structural means of risk pooling that reduces the need of short term insurance via reserves.

The demand response brings about a new substitution process. As the consumption becomes less concentrated around the risky times, demand response will decrease peak load and net-load uncertainty. Albadi and El-Saadany (2008) and Siano (2014) demonstrate that demand

response may be a participant in the energy market and a reserve provider. It is indicated that system value is particularly elevated in the case of demand response, the decrease of uncertainty increases reserve value (Morales et al., 2009). In this respect demand response replaces the reserves in terms of the quantity of probabilistic insurance needed.

The congested systems also replace the transmission and demand response to each other. In case of acute congestion, planners may either develop additional capacity in a network or promote localized diminishing of loads. Expansion of transmission advances transfer capacity, whereas the demand response decreases demand of transfers. They both offer flexibility, yet have varying levels of risk and cost profile. Transmission involves heavy initial investment but has long-lasting benefits that are stable. Demand response involves constant behavioral involvement and coordination of regulations. These alternatives have to be permitted to compete on the same economic terms by efficient market design.

At a coarse temporal or spatial down to Poncelet et al. (2016) demonstrates, these substitution effects are obscured. Models that average over time or geography fail to capture congestion and variability and give biased conclusions which preserve operational solutions within one particular area at the expense of structural investment in the network. It is also necessary to have high-resolution modeling to determine effective flexibility portfolios.

Bistline et al. (2020) also prove that operational detail also has an impressive impact on investment results. Models that have ramping constraints, reserve requirements and network restrictions represented explicitly prefer portfolios combining transmission expansion and fast response resources and demand-side flexibility. Simple models which neglect these constraints have the tendency of investing excessively in generation capacity and underestimating structural and behavior flexibility.

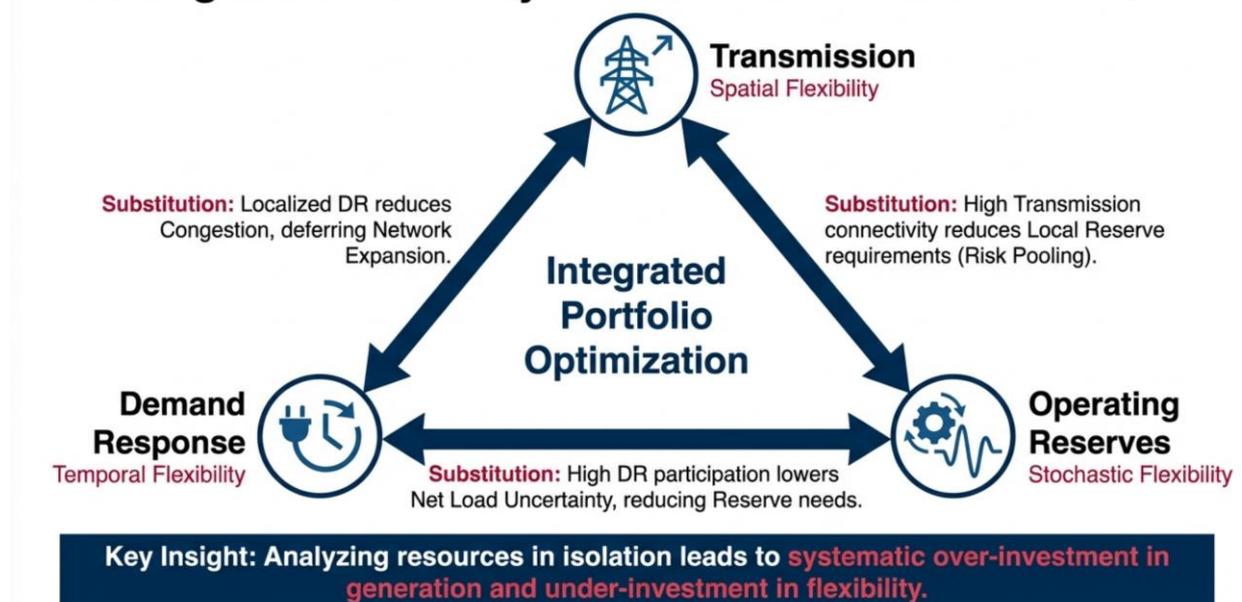
The existence of reserve markets, itself, sends information on the sufficiency of the wider flexibility portfolio. Wang et al. (2011) demonstrate that reserve prices jump between stressed periods of the system. Continued reserve prices beyond normal operating level can be a symptom of a state of both operational scarcity and structural inadequacy, including inadequate flexibility in transmission or on the demand side. According to Stoft (2003), scarcity pricing is critical in making known the long-run investment requirements. Nevertheless, reserve prices should be treated with caution since prices which are high could imply expansion of infrastructure instead of buying new reserves in the short term.

Performance risk has an interaction with reserve markets. Chao (2011) and Chao and DePillis (2013) demonstrate how bad baselines may lead to demand response seeming to be cheaper than it is, and distort portfolio decisions. When there is over-compensation in demand response, the response depending on the compensation can overcompensate, thereby causing a crowding out effect on the transmission investment or generation-based reserves even in a situation where such alternatives are socially cheaper. It is thus important that the integrity of the flexibility portfolios is maintained through proper measurement and verification.

Investment-wise, Levin and Botterud (2015) indicate that the sufficiency of revenues is progressively becoming reliant on the market of ancillary services. With reduction of energy prices, rivalry relocates to providing reserves, congesting, and participation of demand

responses as well. Offering a design of the market that undervalues any of the elements of the flexibility portfolio may cause the development of imbalanced investment incentives. Joskow (2007) states that reliability is a good of a single pool that is to be coordinated through planning and market forces. This is operationalized in flexibility portfolios when there is uncertainty. Instead of having one adequacy margin, systems need to integrate numerous resources that will co-operate in risk management. Transmission offers spatial insurance, demand response offers temporal adjustment and reserves offers stochastic insurance. Overall, it can be observed that flexibility is portfolio-based. Three of these resources are transmission expansion, demand response, and operating reserves that are interdependent. Their best combination is a factor of renewable penetration, geographic diversity, consumer responsiveness, and uncertainty nature. The design of markets should therefore match these resources by trying to provide coordinated pricing with high resolution modeling and institutional frameworks that take into consideration both substitution and complementary effect. Flexibility as a system-level portfolio is vital when it comes to reliability and efficiency as it becomes more and more variant.

The Integrated Flexibility Portfolio: Substitution Effects



6. Policy and Regulatory Design Implications

The switch to a paradigm of electricity systems based on variable renewable energy demands the same direct change in regulating philosophy. Historical electricity regulation models were developed on a system that the reliability was achievable on the basis of dispatchable generation and deterministic planning margins. Energy markets were the core of such systems and ancillary services and demand-side programs served as ancillary roles. This hierarchy is no longer valid as variability increases. The major system aim is flexibility and the regulation should shift to the model of flexibility-oriented governance instead of energy-focused governance.

One of the most important regulatory functions is to bring the market prices to the level of complete socialization of flexibility. Morales, et al, and Papavasiliou, Oren and O'Neil (2009

and 2011) demonstrate that operating reserves are stochastic insurance instruments and hedge uncertainty. In case the price caps or administrative interventions are used to artificially suppress the reserve prices, the economic value of uncertainty management has not been communicated to economic actors in the market. It will cause noninvestment in flexible resources like fast-ramping generation, demand response and storage, unless such investments would be socially optimal.

According to Stoft (2003), costly pricing is a basic principle of an efficient electricity market. Scarcity prices indicate how much it costs us to operate in a situation where we do not have reliability and are the major indication of long-run investment. Price suppressions by regulation can alleviate short-run volatility but will impair the effectiveness of the system at organizing expansion of capacity in the future. The reserve markets are even more significant in a high-VRE system that has frequently low energy prices, given that generation at zero marginal costs produces zero marginal costs.

Joskow (2007) suggests that reliability is such a public good that it would be imprudent to delegate it to the forces of decentralized markets. Even well functioning markets can fail to offer reliability since the internalization of the entire social cost of system failure is not being done by individuals actors. It is a more severe coordination problem as the level of uncertainty increases. Regulatory frameworks should in turn supplement market process in a manner that ensures that there are clear reliability standards, e.g. reserve adequacy requirements or resource adequacy obligations. Such standards must however be applied in a manner that maintains a competition in the market among the suppliers of flexibilities and not dictate on a particular technology of flexibility.

Another important aspect of the market design of flexibility is transmission regulation. Jabr (2013) and Roh, Shahidehpour, and Wu (2009) demonstrate that through expansion of transmission, not only the operational cost and reserve demand are lowered but also, geographic output and load diversification of renewable power becomes possible. However, transmission investment is normally regulated by planned processes as opposed to a market competition. This has the risk of losing the factor of congestion pricing and its reflection in a development of infrastructure. The continued congestion and excessive price of location reserve must lead to the regulatory appraisal of network expansion as a long-term measure instead of ongoing extravagant operational versatility.

The regulators should hence, enhance the feedback mechanism between the wholesale market performance and transmission planning. The congestion prices, the lack of locational reserve, and the reliability events give information concerning the locations with inadequate structural flexibility. The signals should be systematized in planning processes instead of making transmission development an exogenous administrative operation. This mandates strong liaisons between the operators, regulators and planning authorities of systems.

There are especially tough problems in the regulation of demand response since it is at the point of intersection between the wholesale efficiency and retail equity. Neither Albadi and El-Saadany (2008) nor Siano (2014) demonstrate that demand response can offer significant system value except in cases where consumers get exposed to significant price signals and given a chance to engage symmetrically in markets. Eid et al. (2016) stress that such integration

is frequently not possible due to retail tariff structures, the absence of sophisticated metering, and fears on the volatility of bills. The regulators should thus decide whether to prioritize consumer protection or effectiveness gains through dynamic pricing.

A fundamental regulation requirement is to design a baseline of demand response compensation. According to Chao (2011), baselines have a direct impact on the economic efficiency and incentive compatibility. Strategic load inflation is one of the perverse incentives that are demonstrated by Chao and DePillis (2013) to be generated by poorly designed baselines. The regulatory bodies should hence initiate open, standard and verifiable base practices. The demand response can not be classified as a credible flexibility resource either in the energy or reserve markets without credible baselines.

The other significant regulation issue is revenue sufficiency. As renewable penetration grows, Levin and Botterud (2015) demonstrate that this causes energy prices to decrease and become more volatile, hence limiting the capacity of generators to undertake fixed costs by selling energy only. The reserves and regulation as an ancillary service market become more valuable sources of income. Unless such markets are underestimated or limited, then there will not be sufficient investment of flexibility resources, even when the energy market seems competitive. This puts more general concerns on resource adequate practices. Though the concept of capacity markets is not explicitly discussed in the existing literature, based on the discussion by Joskow (2007), the quality of the capacity either in terms of flexibility and reliability during uncertain conditions should also be considered by any administered adequacy mechanism. In high-VRE systems there are slow or unresponsive resources that add slower contribution to the resilience of the system than responsive ones, and market rules need to be responsive to this difference.

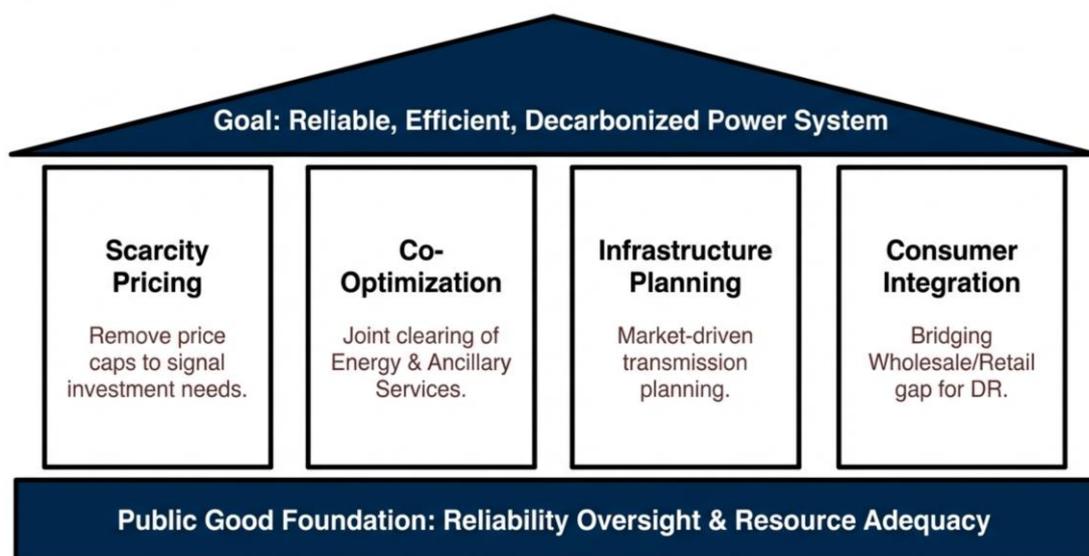
Planning and policy evaluation modeling practices should also be the focus of regulatory policy. Poncelet et al. (2016) and Bistline et al. (2020) demonstrate that simplified models have systematic observations of low values of flexibility due to the disregard of temporal expressions, network capacity, and reserve needs. Infrastructure investment becomes skewed in terms of capacity addition and not structural and operational flexibility when such models are used to influence regulatory decisions. Long-term planning should therefore be mandated to use high-resolution network-constrained and high-resolution dependent models.

Furthermore, the modernization of institutional frameworks relies on leveraging data and artificial intelligence to create sustained competitive advantages and foster organizational resilience (Akbar et al., 2023; Begum, 2022). In the age of digital transformation, it is essential that these AI-driven systems embed ethical analytics prioritizing privacy, fairness, and transparency to build the stakeholder trust necessary for successful policy implementation (Hassaan et al., 2023).

Last but not least, the flexibility-based regulation has to consider the distributional issue. Dynamic pricing, reserve scarcity pricing and congestion pricing augment price volatility. Although this volatility is economically efficient it has concern over affordability and political acceptability. Eid et al. (2016) clarify that the market-based flexibility pricing is complemented with the consumption-protection systems like the smoothing of the bills, targeted subsidies, or

opt-out possibilities. This means that regulation has to work more in a complex environment than traditional systems based on energy alone and achieve efficiency, reliance, and equity. To conclude, the electricity market should be made flexible, which ought to be the main focus of the regulatory priorities. Markets should be left to value uncertainty and scarcity, infrastructure planning should then reflect market indications, demand response should be accommodated credibly and justifiably and modeling practices should be informed by operational reality. Regulation turns into the driving force that harmonizes energy markets, flexibilities purchase, investment in the infrastructure and the goals of society in the growing variability.

Regulatory Foundations for a Flexibility-Oriented Market



7. Modeling Challenges and Best Practices for Flexibility-Oriented Market Design

The professionalism of the flexibility-oriented market design is determined by the frameworks of modeling the performance of the system, investment requirements, and the policies influencing the system where they are evaluated critically. The conventional planning and market models were created to apply when the system consisted of controllable generation and comparatively predictable demand. These models have fundamental constraints as variability and uncertainty become the new reality of power system operation. Without representing uncertainty, network constraints, and operational dynamics with the needed level of fidelity, models are systematically poor approximations of the value of flexibility resources and poor predictors of market design.

The temporal resolution is one of the most significant modeling problems. Poncelet et al. (2016) demonstrate that rough time aggregation blurs short-term fluctuation and overstates the constraint of ramping, the requirement of the reserve, and the price fluctuations. Where representative hours or mean load and generation profiles are used in models, those conditions which help to determine economic value of flexibility are not known. Balancing in high-VRE systems is usually priced by few hours with extreme scarcity. Any disregard of these hours is a distortion in favor of investments in responsive resources, and transmission and demand response.

Bistline et al. (2020) elaborate on this insight by showing how the detail on operations in long-term planning models turns out to be a fundamental alteration in optimal investment results. Models that do not include ramping constraints, reserve constraints and network constraints are more inclined to prioritize generation capacity increase over flexible investment. The introduction of such constraints reflects in portfolios in terms of a mix of transmission expansion, fast-ramping resources and demand side flexibility. This indicates that operational realism cannot be thought of without flexibility valuation.

Another major modeling requirement is stochastic representation of the uncertainty. Papavasiliou, Oren, and O'Neill (2011) demonstrate that the appearance of reserve requirements can be seen as an endogenous result of the uncertainty being represented by scenarios through the use of scenario-based stochastic programming. Deterministic models have the administrative imposition of reserve margins, which do not vary with shifts in the distribution of forecast errors and system states. In contrast, the stochastic models can be used to optimize reserves as economic hedging instruments and their marginal value can be realized. According to Morales et al. (2009), the idea of reserves is supposed to be seen as an insurance against uncertainty rather than technical restrictions. Stochastic dispatch models that model the stochastic reserves integrate the probabilistic contribution reserves make in the cost-effective optimization of system dispatch and enable planners to trade reserves acquisition against other uncertainty-reducing portfolios such as transmission expansion or demand response. Models that do not factor in this view have a systematic tendency to underemphasize the economic significance of reserves.

The spatial resolution is also important. As demonstrated by Jabr (2013) and Roh, Shahidehpour and Wu (2009), network constraints and transmission deliverability has a major impact on the cost of operation and investment decisions. Aggregated network models conceal congestion, smooth out locational price disparities and falsify the alternative between transmission expansion and localized flexibilities. There is thus a need to have high resolution network modelling to assess the actual worth of transmission as structural flexibility.

Wang et al. (2011) demonstrate that prices of ancillary services differ significantly across locations and conditions of systems. Regional average reserve pricing models disregard the locational scarcity and overemphasize the significance of the deliverability limits. There should therefore be an incorporation of locational reserve markets or explicit reserve deliverability requirements in the best practices modeling to earn out the physical realities.

There are further complications when it comes to demand response modeling. According to Albadi and El-Saadany (2008) and Siano (2014), the demand response performance is contingent on the speed of response, the participation rate, and the design of the programs. Demand response is a highly unreliable resource that is being treated as such. According to Chao (2011) and Chao and DePillis (2013), the ability of a model to generate artificial flexibility due to baseline error can give unrealistic evaluations of the demand response potential. Uncertainty in the availability of demand response as well as performance must therefore be included in the best practice modeling.

According to Allcott (2011), behavioral frictions are aspects that restrain consumer sensitivity to price signals. Perfectly rational and fully responsive consumer models overstate the power

of real time pricing. Participation constraints, automation penetration and heterogeneity of behavior should be introduced in realistic modeling.

The other significant issue is that of combining the market operations in the short-run with the long-run analysis of investments. Levin and Botterud (2015) demonstrate that the element of revenue sufficiency is heavily reliant on the markets of ancillary services more than the energy prices per se. Models that purely plan energy revenues falsely reflect the incentive to invest in flexibility resources, and panic underinvestment in the same. The best practice modeling should thus be known to incorporate energy and ancillary service revenue streams in assessing financial viability.

Galia et al. (2005) indicate that energy and reserves have to be co-optimized in order to harness opportunity costs precisely. Separate types of models, where energy and reserves are not considered together, under estimate the prices of reserves and manipulate the results of the dispatch. At that, co-optimization is not only a market design principle but a modeling requirement as well.

Joskow (2007) outlines that reliability is a social good that needs to be modeled in the planning structures. In systems with high VRE, reliability turns into the probability and not a deterministic one. Modeling frameworks should thus have probabilistic reliability constraints or objective functions that represent societal risk indulgence and not mere capacity margins.

Rebours et al. (2007a, 2007b) demonstrate that the technologically differentiated products are ancillary services. Models that combine all the reserves to one category do not get the economic distinction of regulation, spinning reserves and contingency reserves. Best practice modelling demands that there are different products (reserve) with varying response times with different cost frameworks.

Lastly, modeling principles required are transparency and reproducibility. With the complexity of market designs, stakeholders should have the capacity to comprehend on how conclusions will be drawn. The black-box models lead to lack of confidence in policy suggestions and the hindrance to institutional learning. Good flexibility modelling should then be able to be both technical and transparent and understandable.

Overall, modeling approaches determine the intellectual premise of the flexibility-focused electricity markets. Stochastic modeling of uncertainty, high spatial and temporal resolution, explicit reserve modeling, realistic representation of demand response, and a combination of operational and an investment perspective are not option. They are preconditions in designing markets that can effectively and reliably deal with rising variability.

Modeling Challenges: The Gap Between Simplification and Reality

Modeling Dimension	Traditional Simplification	Required Best Practice
Temporal Resolution	Time-averaging / Representative hours. (Underestimates ramping needs)	Chronological simulation with ramping constraints.
Spatial Resolution	Copperplate or Zonal aggregation. (Masks congestion/Undervalues Tx)	Nodal network-constrained modeling.
Uncertainty Representation	Deterministic margins (Fixed %). (Fails to value hedging utility)	Stochastic programming with endogenous reserves.

8. Conclusion: Flexibility as Core Power System Infrastructure

Electricity markets were traditionally geared towards regimes where reliability might be attained largely with the help of dispatchable generation and deterministic planning makes up. In that case, the energy trading has naturally become the prevailing structure of the market design. The fact that the variable renewable energy has been rapidly developing has fundamentally changed this base. Unpredictability and change are not anymore marginal operation issues but characteristics of system performance. Consequently, the flexibility should not be viewed as a service that accompanies the power systems, but as the essential power system infrastructure.

This paper has contended that three processes which include expansion of transmissions, demand response and operation reserve are the pillars of flexibilities in the contemporary electricity frameworks. The two deal with two aspects of uncertainty. Transmission expansion can be used to address variability in space to be able to pursue spatial diversification of renewable production and demand. Demand response eliminates the aggregate variability through conversion of consumption into proactive balancing resource. The stochastic variability is handled by stochastic reserves which are priced as probabilistic insurance. None of these systems is self sufficient. The value of their interaction, substitution, and complementary aspect comes in an integrated portfolio of flexibility.

The literature indicates that electricity markets should no longer be energy-focused trading platforms but they should be institutions that help in coordinating uncertainty management. Galiana et. al (2005), Morales et al. (2009) and Papavasiliou et al. (2011) show that to price flexibility, a combination of energy and reserves co-optimization is needed. The research articles by Stoft (2003) and Wang et al. (2011) indicate scarcity pricing in reserve markets as the major signal in investment towards balancing resources. On the occasion of occurrence of such blindness, markets can no longer steer long-run reliable investment.

The expansion of the transmission becomes a kind of structural flexibility over a long period of time. Jabr (2013) and Roh et al. (2009) demonstrate that good networks reduce congestion, reduction in the reserve requirement and the fluctuation of prices due to a pooling of uncertainty

in space. The process of transmission is thus a restructuring of the statistical phenomenon of system risk. It has much wider potential than the energy transportation phenomenon and should be stated clearly as a component of market design and regulation planning.

Demand response is a form of low-capital scalable flexibility. As demonstrated by Albadi and El-Saadany (2008), Siano (2014) and Allcott (2011) responsive demand is capable of minimizing peak load, congestion, and providing reserve services. Nevertheless, Chao (2011) and Chao and DePillis (2013) show that baseline design and performance verification are essential in deriving the economic plausibility of demand response. Eid et al. (2016) highlight that institutional barriers on the retail-wholesale interface are also a significant barrier to total integration. Demand response can at best serve as infrastructure with the presence of transparent, stable and reasonable participation of regulating frameworks.

The economic foundation of the short-term reliability is represented by operating reserves. Rebours et al. (2007a, 2007b); demonstrates that, reserves are technologically differentiated products whose prices have an opportunity cost and scarcity. The works by Morales et al. (2009) and Papavasiliou et al. (2011) demonstrate that the reserves must be modelled and priced as stochastic insurance instruments. As Levin and Botterud (2015) further reveal, in the case of renewable-dominated systems, ancillary service revenue has taken center stage in the sufficiency of revenue when than the energy prices fall. Reserve markets thus serve two functions namely, a safeguard of reliability and coordinates investment incentives.

One important lesson that this paper will provide is that flexibility is portfolio based in nature. Transmission, demand response and operating reserves are replacements and complements of each other. In situations of low transmission, both the value of localized reserves and demand response increases. In cases where demand response is rich, the reserve requirements will decrease. Structural investment to networks becomes more attractive in cases where reserves are expensive. Papavasiliou et al. (2011), Poncelet et al. (2016), and Bistline et al. (2020) demonstrate that disregard of these interactions is affecting the systematic mispricing in the flexibility and distorting investment performance outcomes.

This logic of portfolio can have significant effects on regulation. According to Joskow (2007), reliability is a public good that has to be supported by the cooperative efforts of institutions. With the rising variability, regulatory systems should assume that the market prices should correspond to the social cost of risk management, congestion and reserve shortage messages should guide the transmission plans, and that the demand response is correlated with the generation-based resources on a symmetrical basis. Levin and Botterud (2015) demonstrate that the increase of revenue sufficiency through ancillary services is unlikely to rely on energy markets as it is, which reinforces the necessity of flexibility-based regulation.

The importance of modeling is also brought out in the paper. Poncelet et al. (2016) and Bistline et al. (2020) demonstrate that the conclusions regarding the cost and reliability of the system are mostly based on the temporal resolution, spatial detail, reserve representation, and stochastic representation of uncertainty. Simplified models put too low a value on the flexibility and too high a value on the traditional capacity expansion. Market design based on flexibility hence demands flexibility oriented modeling.

Conclusively, the concept of flexibility in electricity markets should not be a fringe benefit of the existing institutions. It is a process of change in the governance of power systems. Transmission expansion, demand response, and operating reserves should be regarded as fundamental infrastructure components that can be used to collectively deal with spatial, temporal, and stochastic uncertainty. Electricity markets should transform to be in the form of a platform where energy is traded to one that organizes the management of uncertainty. It is only through this flexibility-based paradigm that power systems will be reliable, efficient and be able to accommodate deep decarbonization as variability increases.

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