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ELECTRICITY SERVICES IN A MORE DISTRIBUTED ENERGY SYSTEM

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Abstract

The integration of significant volumes of intermittent renewable generation and distributed energy resources in electric power systems is forcing a debate on what electricity services are needed in a power system, how to price them and what agents are best suited for their provision. This paper defines and justifies the existence of a small set of primary electricity services that must exist in all power systems and regulatory contexts in order for the power system to operate satisfactorily. These services are determined by the placement of constraints on the planning and operation of power systems. As power system technologies evolve, new primary services may emerge, but will always be based on the placement of constraints on system operation and planning.

Keywords: *electricity services; energy; operating reserves; black start; firm capacity; network connection; voltage control; power quality; constraint mitigation; loss reduction; regulation.*

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Executive Summary

The rapidly growing presence of a multiplicity of new and diverse agents in power systems all over the world urgently demands a clarification of the electricity services with economic value. This paper: 1) identifies, in a rigorous and internally consistent manner, the minimum set of services that are necessary for a power system to function satisfactorily. The key messages of this document are summarized as follows:

1. There is a large diversity of electricity services that are provided now and that may be offered in the future. Given this range of current and potential services, it is important to understand the economic basis and rational for these services, which ultimately serve as the backbone of the business models in the electric power industry
2. Despite the enumerable number of services currently offered in the power system, it is possible to define a minimum set of mutually exclusive and collectively exhaustive electricity services that are required – or are indispensable – for the power system to physically function. These service are called "primary services" (or "primary electricity services"), and are defined herein.
3. Each electricity service arises from the imposition of a constraint on power system operations or planning. Associated with each constraint is a dual variable that indicates the marginal price of each constraint, and therefore the marginal price of the service in question. Where a dual variable does not exist due to the physical realities of power system planning and operations, regulated measures may need to be imposed.
4. The energy-related primary services are energy, operating reserves, black-start capability, and firm capacity. The network-related primary services are network connection, voltage control, power quality, mitigation of network constraints, and energy loss reduction.
5. In the face of changing technologies and requirements, the set of primary services may evolve; nonetheless, the methodology for identifying these services should remain as described herein, and should be grounded in economic and mathematical theory.

1 Background and Introduction

Power systems are rapidly evolving towards integrating a substantial participation of a multiplicity of agents that will play a diversity of roles; furthermore, these agents may frequently adopt different roles at different times (e.g. consumer in one hour, producer in another). In the context of the power system, an agent's role is characterized by the *electricity services* that it provides to and obtains from other agents. At their most basic level, electricity services are activities or products with commercial value that are procured by or on behalf of electricity consumers. Electricity services vary widely in their nature; electricity services may be physically-, financially-, or information-based, or they may be other value-creating activities or products. Furthermore, they may vary in their formats, with different durations, levels of commitment, cost allocation methods, and economic implications.

It is impossible to try to enumerate or predict all the services that will develop in the future. Indeed, it is difficult even to enumerate all those that exist today. Human creativity is boundless and established companies, entrepreneurs, and individuals will explore business opportunities around the provision of new and existing services. Some of these business opportunities will be economically sound, while others will be doomed to fail. Given this vast set of current and potential services, it is important to understand the basis for these services, which ultimately serve as the backbone of the business models in the electric power industry. This paper identifies, in a rigorous and internally consistent manner, the minimum set of services that are necessary for a power system to function satisfactorily – regardless of the regulatory context.

This document begins by identifying and describing the key set of electricity services related to energy that must exist in all power systems and regulatory contexts. It then presents the set of electricity services related to networks.

2 Electricity Services

We begin by defining the minimum set of mutually exclusive and collectively exhaustive electricity services that are required for the power system to physically function. We call these indispensable services "primary services" (or "primary electricity services"). Without the primary services defined herein, the power system would not perform its sole function: to provide useful electric energy to consumers. These primary services are therefore indispensable to every power system, regardless of the regulatory or policy context. Each primary service has economic value, and therefore a corresponding price or charge. Some of them, like operating reserves, may be defined differently in different power systems; however, the service itself and the concept behind it do not change. Perhaps in the future, the physical evolution of the power sector and its organization will require the addition of novel primary services to our list; however, we postulate that the set described herein is exhaustive given today's paradigm, and that any potential future additions will adhere to the same philosophy that we describe.

All other services that are not-indispensable from the perspective of a power system's physical operations will be called "secondary services." They may arise from the application of some specific policy or regulatory measures, or they may be derivatives[1] of the primary services, in the same way that one can create many different types of financial instruments associated with an underlying commodity (e.g. forward contracts for oil). For instance, medium and long-term contracts between buyers and sellers of energy can be established, either in organized platforms like power exchanges, in a bilateral and decentralized manner, or in many other possible formats. Moreover, some agents – regardless of whether or not they are physical participants in the production or consumption of electricity – may engage in financial contracts with, for example, the price of electricity in the energy or operating reserves markets as the underlying commodity.

In the supply and demand of electrical energy there are two basic underlying physical services: the *electricity that is produced and consumed* at different times and in different places, and the *provision of the networks* that allows the diverse system agents to deliver and obtain electricity.

For the sake of clarity and with the goal of thinking in concrete rather than in abstract terms, let us consider a standard regulatory framework with competitive wholesale and retail markets for energy, and with the transmission and distribution networks regulated as natural monopolies (and remunerated, in one way or another, in relation to their cost of service). This is the regulatory framework that will be assumed throughout this document, unless indicated otherwise. Other regulatory frameworks are possible, like vertically integrated utilities with a single monopoly owning and managing generation, transmission, distribution and retailing; other options in between these two approaches exist as well. The primary services listed herein exist regardless of the framework, although the entity providing the service may differ from framework to framework. The economic signals –prices or charges– corresponding to each one of the services may also be determined differently in each regulatory framework. The following sections examine energy and network services separately.

2.1 Energy-related services

2.1.1 Electric energy

In an ideal competitive energy market left unfettered by regulation, electricity will be provided by a multiplicity of suppliers, some of them "centralized" – large nuclear, hydro, wind, solar powered stations, or fossil-fired plants connected to a high voltage transmission network – and others "decentralized" – small solar PV on rooftops, residential and commercial micro-cogeneration or micro-turbines, small and medium size solar and wind farms, mini-hydro plants and many others.[2] Mathematical and computational techniques exist such that the price of electricity can be computed at any given time and at any given location within the network [1]. These prices are defined according to the well-established theory of spot pricing, which, conceptually, can be extended to every corner of the

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[1]A derivative is defined as a contract or financial instrument whose value is derived from and is dependent upon the value of an underlying asset or commodity.

[2] We deem these decentralized agents (e.g. small scale solar PV, energy storage, demand response, etc.) "distributed energy resources" (DERs).

electric grid through locational marginal prices.[3] **Electric energy** (referred to herein as simply electricity or energy), at a given location and at a given time, is the first primary service.

Some "complications" may appear with this primary energy service. Depending on the specific organization of each electricity wholesale market, physical energy is frequently bought and sold in more than one market. For example, it is common for a single power system to operate a day-ahead market, several intraday markets, and a balancing market [2]. Energy has different prices in each one of them, and agents may choose in which markets they want to participate[4] (in expectation, prices should be the same in all markets). Energy trading also happens over longer time horizons via physical or financial contracts, with time durations ranging from days or weeks to months or years. Regardless, the physical commodity being traded is the primary service of electric energy.

The energy-related services described in the following paragraphs are created by placing constraints on the provision of energy (we follow the same principle when discussing network-related services in Section 2.2). This arises from a fundamental principle in microeconomics and property of constrained optimization: when an authority such as a market operator, system operator, or regulator imposes a constraint on the delivery of a service in a market,[5] a new commodity is created. The price of the commodity delivered in the market is then equal to the value of the dual variable of the constraint. Take carbon markets as an example: when a limit is imposed on the total amount of CO2 emissions in a power system, a price per ton of CO2 emitted is created as the dual value of this carbon constraint [3]. The same result will occur if a minimum quota is imposed on the total amount of coal production in an electricity market, although, in this case, the extra cost per unit of coal-generated electricity will apply only to coal-fired power plants.

2.1.2 Operating reserves

Energy demand and supply must be in equilibrium at all times to maintain the system's frequency within a narrow band; this tightly-banded frequency is critical to enable connected electricity appliances and devices to function correctly and safely. Changes in electricity supply and demand will occur due to a variety of circumstances: agents switching devices on or off, power plants or lines failing, natural

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[3] Let us ignore here that there may not be a unique way of computing the price of electricity, since, even if the difficulties of computing the spot price of electricity everywhere are overcome, many difficulties remain (such as how to account for the nonlinearities in the start-up costs and the heating rates of thermal power plants) [19], [20]. In many power systems, the spatial differentiation of prices, due to network losses and network constraints, is ignored. Nodal prices (i.e. locational marginal prices, or "LMPs") are computed for transmission nodes in only some power systems, mostly in North and South America and Australia. Zonal prices, with very large zonal definition (e.g. France as one zone, and Germany plus Austria and Luxemburg as another) exist now in Europe. To the knowledge of the authors, nodal prices are presently not used at distribution level in any power system. LMPs used in the distribution system are referred to as distribution level LMPs, or "DLMPs."

[4] The difference in prices between time periods arises from the differing flexibility of different electricity resources and the variability and uncertainty of supply and demand. Some generators, such as coal or nuclear plants, are slower than others, such as storage units or natural gas plants. As markets progress towards real-time, fewer generators are capable of responding rapidly enough to changes in the energy supply-demand balance. A premium – in case of a short-term supply deficit – or a lower electricity price – if there is a surplus of supply – reflects these changing power system conditions.

[5] Note that market operations can be represented as a social-welfare-maximization or system-cost-minimization problem.

variations in wind and solar production, increases or decreases of demand with time, or fluctuations in hydro inflows. Agents selling electric energy *have an inherent economic interest* in responding to these changes. For instance, in the case where demand increases, this creates an opportunity for sellers of electric energy to increase production. They can take measures to be ready to operate on short notice; for example, operators of an uncommitted thermal power plant can keep the boiler warm or crew ready, or committed plants can operate below their rated capacities. Demand and other distributed energy resources may also participate in maintaining this equilibrium by responding to electricity prices or contracting with suppliers to ensure that sufficient means are available in case of an unexpected change in supply or demand conditions. Thus, in an ideal world, the management of the equilibrium of supply and demand of electricity could be entirely left to the agents of the power system.

Still, in this ideal world, some consumers may perceive the risk that system agents by themselves may not be ready or able to cope with the many unforeseen events that may take place in the operation of the power system. Therefore, they may want to guarantee themselves against loss of electricity by contracting with some agents – typically generators – the readiness to respond to unexpected changes. This would create a price for a new type of commodity – operating reserves – in a natural or spontaneous way.

In the real world, given the realities of free riders, imperfect markets, imperfect information, the extremely rapid time scales involved (i.e. fractions of a minute, in some cases), and the critical nature of electricity in modern economies, regulatory intervention has been universally adopted to ensure that supply and demand are balanced at all times (and therefore system frequency is maintained within a narrow band around a specified value: 50 Hertz in Europe and 60 Hertz in the US). System operators, tasked by regulators and policy makers with ensuring that the power system operates within secure limits, set requirements such that the agents in the power system are ready to respond to imbalances between supply and demand of electricity in a pre-specified time range and for a prescribed total volume. The generation mix of power systems is very diverse in different parts of the world, and system operators may therefore establish very different technical requirements for these "operating reserves." Therefore, while the definitions of the operating reserves described herein may differ between power systems, we postulate that other definitions are simply different categorizations or derivatives of those presented in this document (see [4]–[6] for reviews of different reserve definitions).

Changes within a power system occur continuously (due to fluctuations in demand, output of intermittent generation, and sudden loss of generation plants or lines tripping). In order to restore the equilibrium between supply and demand, energy must be provided or curtailed within an appropriately short timeframe (typically within a few seconds to a few minutes). System operators, following regulatory guidelines, establish the conditions that guarantee that a certain amount of capacity is available to supply and/or curtail energy in response to these fluctuations, and, further, that this capacity has the technical specifications required to ramp up and/or down rapidly enough to effectively accommodate these movements.

In most existing power systems, the inertia of the large rotating masses in conventional thermal generation plants and hydro turbines immediately and automatically compensates for the imbalances between supply and demand in a natural way. However, this innate supply of energy cannot be maintained for long, as the frequency excursion – either up or down – would become unacceptable. This instantaneous and natural inertial response has to be followed by explicit control actions in different time ranges with resources that are named "operating reserves." These reserves are subject to tight technical specifications to keep frequency within the required limits.

The fastest reserves are termed "**primary operating reserves**" or "primary frequency response." Conventional thermal and hydro power plants respond to frequency deviations by increasing or decreasing their power output in a matter of seconds by means of what is known as "governor action," the design of which depend on the specific generation technology. Some new technologies like solar PV and wind can also respond to these changes if purposefully equipped to do so (typically at some expense). Further, some resources like battery storage units or properly instrumented demand may effectively provide primary frequency control. Renewables, storage, and demand may therefore provide primary operating reserves, which can be also pictured as "artificial inertia [6]." **Primary frequency control**, or primary operating reserve, is therefore our second candidate to be a primary service. It is created by a requirement imposed by the system operator that can be formulated as a constraint on both the capacity required for primary reserves and the technical specifications of this capacity (e.g. the speed of response)[6].

The rate at which the system frequency excursion happens depends on the volume of inertia in the system. This in turn affects the volume and characteristics of the operating reserves required to control it; furthermore, some of the fastest growing generation technologies – wind and solar – do not contribute a natural inertial response. In those systems where the lack of inertia might result in a potential security problem, the natural inertia of power plants would become a resource with a commercial value.

The resources that can provide the fastest response in any given power system are necessarily limited. Once they become exhausted, other slower operating reserves may take their place. This contribution will be necessary until the balance between supply and demand has been reestablished, the power system has been returned to its nominal frequency, and the flows at the interconnections have been reestablished to their scheduled values. Therefore, the system operator must determine the conditions for "**secondary operating reserves**" or "**secondary frequency control**" by placing a constraint on the magnitude of capacity and the technical specifications thereof to respond to disturbances and restore the system to its nominal frequency. These secondary reserves may respond slower than primary reserves (e.g. on the order one to tens of minutes), and tend to be dispatched centrally by the system operator (although this is not technically required).

[6] This occurs due to the duality theory in constrained optimization, mentioned above.

Furthermore, a final and even slower responding service of "**tertiary operating reserves**" or "**tertiary frequency control**" is defined.[7] In this case the power plants providing the service may not have to be in operation, but they may be able to respond in a short amount of time (e.g. 30 or 60 minutes). System operators usually create a constraint requiring that a certain amount of capacity remain online or ready to start-up in a short time span, such that the system can restore the amount of faster responding resources that have been used up already.

These reserves are named and defined differently in almost every power system.. In some systems, the system operators and the regulators are presently studying modifications in the definition of these operating reserves because of the new challenges that are brought by the strong penetration of the so-called intermittent generation sources (e.g. solar PV and wind) [5]. The growing presence of demand response may also have an impact here [7], [8]. Presently there is a substantial amount of literature advocating the need to define a new commodity vaguely termed "flexibility" [9], [10]. We understand that the flexibility of a power system, i.e. its capacity to respond to changes that may affect the equilibrium between supply and demand, is a consequence of the generation mix that the agents decide to contribute to the system, and the technical requirements on operating reserves that are established by regulation. Therefore, there is no need to define flexibility as a new product or service in its own right, as the value of flexibility should be accounted for in the value of properly defined operating reserves. As indicated before, we anticipate that the current definitions of secondary and tertiary reserves will be gradually adapted to the changing generation mix in each power system, and even a new "quaternary operating reserve" might be needed, but always under the same "philosophy" that has been explained here – e.g. all services – in actual power system practice – emerging from the constraints placed on the system by the physical limits imposed by the system's technologies or by constraints placed to meet certain operational regulatory goals.

2.1.3 Black start

The electric machinery, control equipment, etc. in a traditional power plant require a certain amount of power to enable the plant itself to operate[8]. If the plant is generating electricity during normal operation, this power is provided by the plant's own generators. If the plant is offline due to maintenance or because it was not dispatched, this power is typically drawn from other generators on the network. However, in the case of emergencies that cause wide-area outages, this power supply may not be available. In these instances, **black-start capability (or energy restoration capability)** is required. Black-start is defined as the technical resources that allow a power system to recover normal conditions after a blackout. Historically, black-start capability has been categorized as an "ancillary service" in power systems. In line with this tradition, we propose to consider it as a sort of emergency reserve, with specific technical requirements that allow it to "bootstrap" the power system. These requirements typically specify the volume, technical characteristics and geographical position of the

[7] Primary, secondary, and tertiary operating reserves are corollaries to the European system of Frequency Containment Reserve (FCR), Frequency Restoration Reserves (FRR), and Replacement Reserves (RR) respectively.

[8] Note that this is not a universal truth. Distributed PV plants, for example, are typically capable of operating solely on the power produced when the sun strikes the PV panels.

resources that are needed. In the future, DERs configured as micro-grids with the capability of functioning in an islanded mode from the main grid[9] could contribute significantly to the provision of this service[10].

2.1.4 Firm capacity

Now we enter a more contentious territory that is beyond the realm of system operators, whose technical dictums cannot be contested by non-technical power system stakeholders; this terrain is therefore more prone to be hotly debated by lawyers, economists, politicians, and regulators. Should investments in means of electricity production be incentivized so that the risk of shortages due to a lack of generation is reduced to a socially or politically acceptable level, or should the decision to invest be entirely left to market forces? Note that this issue goes beyond the previous discussion on operating reserves. In the operation realm, the quantity of electricity producing assets is fixed, and cannot be changed in the short term. What is under discussion here is whether or not the regulator should take actions to ensure that there is enough investment in generation assets so that the system can cope with stresses on the supply-demand balance. Moreover, an additional concern is whether the regulator should intervene to make sure that the currently installed generation capacity – or the means of voluntary demand reduction – will be ready whenever a situation of stress in the equilibrium of supply and demand may happen. This readiness cannot be taken for granted. For example, non-firm gas supply contracts do not guarantee the provision of gas to the gas-fired power plants, hydro reservoirs may be empty when their water is needed, or power plants might be on maintenance during the day when system supply and demand are very close.[11] We shall define "adequacy" as the capability of generation investment and demand response to meet the anticipated future peak system demand, and "firmness" as the capability of having enough generation and demand ready to respond when actually needed during the current operating period (see [11] for a review of the motivations behind the creation of adequacy mechanisms, and see [12] for a review of security supply mechanisms).

There is no conceptual agreement on this issue, and experts continue to debate it, although in practice all power systems have some kind of intervention in this regard, resulting in some kind of commodity and associated price (as with all the other services)[12]. Therefore, if the regulator wants to impose a

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[9] Small systems that are able to continue operating while the bulk grid is not operating are considered to be "islandable."

[10] Primary, secondary, and tertiary operating reserve services are created by placing constraints on the power system's operations, while the black-start service is created by placing a constraint on the power system's planning and design. However, we place black-start in the category of reserves, as it is implemented to account for contingencies.

[11] The latter case was a regular occurrence during the California energy crisis in the early 2000's.

[12] The format of these interventions is very varied (capacity payments, capacity markets, strategic reserves, reliability options, adders to energy market prices, etc.). These interventions are generically termed Capacity Remuneration Mechanisms (CRM). There are few truly "energy only" markets. The Australian National Electricity Market (NEM) appears to be the perfect example of an energy only market, with the peculiarity that basically all the demand is hedged against the very high prices that sometimes occur in this market by call option contracts that are signed by the retailing companies, or suppliers. Why these suppliers hedge their consumers, while this does not happen elsewhere in the world, deserves to be examined carefully. Texas is another interesting example. This market, as the UK "electricity pool" in the 1990s, has a regulated component that is added to the day-ahead energy price to "make it right" [21]. This kind of regulatory interventions in the day-ahead market

certain level of capacity reliability (adequacy, firmness or both) in the provision of electricity, a new commodity with a price will be created. A single regulatory instrument can be applied to handle both adequacy and firmness with a single service (e.g., reliability options [13]). If a system is firm, it inherently has adequate capacity. The same can be said about expected future firmness (i.e. a system that has planned capacity to be firm in 5 years will be adequate). We therefore define **firm capacity**[13] as a primary service, which refers to a guaranteed amount of installed capacity or demand response that is committed to be ready to produce or curtail when it is called upon during times of system stress. Capacity that is adequate but not firm has little value; this stems from the fact that capacity services have the provision of electric energy as the ultimate goal, and energy at the time it is desired is the valued service. Given that adequate but not firm capacity does not guarantee energy at the time it is desired, we consider our proposed approach to be preferable and shall maintain our definition.

The presence of large amounts of intermittent generation in power systems demands further consideration of the plain requirement of some amount of "firm capacity", without further qualifications. In a power system with a large proportion of intermittent generation, the requirement of "being available when needed" cannot be met by the "right amount" of inflexible generation capacity. Therefore, as it is also the case with operating reserves, the current or expected generation mix of a specific power system will condition the requirements for firm capacity service – that is, the service will have to comply with some technical requirements besides a simple quantity requirement.

2.2 Network-related services

2.2.1 Network connection

We now proceed to address the network-based electricity services. The most basic primary network service – and the origin for all the others – is **network connection**. Network connection allows the different agents to participate in purchasing and selling of the energy-related services defined above. The service of network connection has a suite of defining characteristics: the simple point of connection, the cost of which is driven primarily by an agent's geographic position with respect to the network; the peak amount of energy that an agent may inject or withdraw at any moment in time (i.e. transfer capacity); the duration and frequency of network-related limits/inabilities to inject or withdraw (i.e. reliability); the aesthetics of the network (e.g. whether the cables are overhead or underground or other characteristics); a minimum required distance to inhabited buildings or environmentally sensitive areas; or many others. The network connection service therefore is defined by the resulting *built* network that minimizes the total cost of providing the service while meeting any prescribed requirements.[14]

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price are perfectly legitimate if they only try to approximate better the true value of the energy price, but they would be CRMs if they go beyond, with the purpose of promoting resource adequacy.

[13] We avoid calling it "generation capacity", because it can be also provided by storage or demand response.

[14] It is preferable to include under the concept of "cost" as many items as possible and to reduce the number of "requirements": besides investment and operation and maintenance costs, there are costs associated to non-served energy, environmental impact, loss of value of property because of the presence of lines, etc. In practice it is often difficult to include these costs explicitly, and constraints, targets or mandated requirements are used instead.

Distribution networks are designed, built, operated and maintained by distribution system operators (DSOs), which – universally, at least until now[15] – also are the owners of the distribution grid. As indicated before, we shall assume that DSOs are regulated as natural monopolies and, for the sake of simplicity, that they are remunerated in relation to their cost of service, although the specific method is immaterial for this discussion.[16] DSOs design and operate the distribution networks in compliance with grid codes that have been approved by the regulatory authorities.

In theory, an omniscient network provider could know the welfare function (including all preferences) for the connection service for every agent within the power system. This network provider would then design a network to perfectly balance the welfare gained by increased access to electricity services (both in terms of the transfer capacity and reliability) and satisfaction of other requirements against the increased costs of these actions. Each user could therefore, in theory, receive the efficient level of capacity and reliability from a network. However, this ideal balance will likely not be achieved given the realities of discrete, lumpy network investments, regulatory mandates for uniform levels of reliability across a network or across a class of consumers or zones, free-rider problems, realistic network providers, etc. More realistically, a network provider would estimate the welfare function for a class of agents (typically quantified as the cost of non-served energy or value of lost load), estimate the current and future demand for injections/ withdrawals, and estimate the potential flows and resulting losses. Based on these factors, the network provider would produce its best estimation of a welfare-maximizing network. These estimates may, however, not accommodate the multiplicity of needs of specific agents. These deviations may lead to certain agents procuring additional network connection characteristics. This is particularly important in the case of reliability; certain consumers (e.g. silicon manufacturers) have extraordinarily high costs of non-served energy and frequently procure "above and beyond" measures of reliability from network providers. We do not, however, consider this to be a new service (e.g. a reliability service), but rather an extension of the characteristics of the provided network connection service. This same concept applies to, for example, a touristic area that requires underground lines, or a residential area that requires lines to be built a certain distance from houses, etc.

As in the case of energy services, new agents may participate in the provision – not only in the utilization – of the network services described below. What is presented here applies both to transmission and distribution networks, although the impulse for change in the design and operation of the power sector is presently arising from new developments at the distribution and retail market levels.

Can parallels be drawn between the identification and treatment of primary energy-related services and network-related services? In the case of energy we added specific services that were needed to meet

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[15] The possibility of unbundling distribution system operation from distribution ownership is presently being considered in some power systems, such as in New York [22]. These discussions are taking place in the context of reforms that try to address the increasing presence of DERs in the power systems. This issue does not affect our definition of electricity services in the present document, and we shall assume for the rest of the document that distribution system operation and distribution network ownership are in the same company.

[16] Within the wide category of "natural monopoly regulation" many different implementation versions exist, as the multiple approaches to performance or incentive-based regulation, straight cost-of-service, RPI-X, RIIO, etc. See [2] for a detailed description.

some technical requirements, plus others to provide operating reserves as well as adequate generation capacity and readiness to be available when needed. Next we see how the same categories of services can be identified for network connection.

2.2.2 Voltage control

Electricity networks have to be operated so that the voltage at the points of connection must be within a certain secure band around the rated or nominal value for each particular network (consequently, all modern appliances are designed to operate on these voltages). This requirement imposes constraints at each node in the network, which creates another primary network service: **voltage control**. This service may also be referred to as voltage constraint mitigation.

The voltage values at the different nodes depend on the electrical characteristics of the networks (lines and transformers), the existing voltage control means (voltage controllers, transformer taps, capacitors) and the patterns of demand and generation connected to the network at each node. It is therefore possible that the network users, by means of demand or generation response, may facilitate that the voltage stays within the required limits at specific nodes [14]. As network use changes or network equipment ages, DSOs typically take actions, such as the installation of additional capacitors, to solve local voltage problems. However, DERs might also provide the same voltage control service, and, if it appears to be economically viable, this opportunity should be made available to these agents. Furthermore, if there are sufficient conditions for a competitive supply, the DSO could establish some kind of market or auction mechanism to determine the most economic way of providing the service. [17]

Voltage control or voltage constraint mitigation takes on two primary forms: short and long term (or operational and investment). In the short term, decisions on the operations of the multitude of voltage control devices within the network must be made to ensure voltage constraints are met. However, in the face of changing (historically growing) demand profiles, operational decisions may not suffice, and investment decisions must be made (alternatively, demand profiles could be static, but technological innovations could present new alternatives to the operational status quo). As noted above, these investment decisions could involve network investments (i.e. reconductoring, new lines, or voltage-related equipment), or non-network DER investments or operational responses. The existing network components that make up the network connection service, combined with the suite of available operational options, define the capability of the system to meet voltage constraints. As network investments are made to mitigate expected future voltage constraints, the investments become part of the built network, and define the built network's ability to manage voltage constraints.

2.2.3 Power quality

In addition to a proper voltage magnitude and a tightly banded frequency, installations, equipment, and appliances connected to the network have other technical requirements related to the characteristics of the voltage wave that should be met to ensure these devices' proper functioning. Under ideal conditions, the voltage wave at each connection point should be perfectly sinusoidal, three-phase balanced, and at

[17] Note that voltage problems are typically very local in nature (i.e. they occur at specific points or areas within a network, but are not interconnection-wide like frequency problems).

its nominal value at all times.[18] However, voltage disturbances that negatively affect the voltage quality on a sub-cycle-basis may occur. These disturbances include harmonics, voltage fluctuations (flicker), voltage unbalances, voltage dips and sags, short-supply interruptions, etc. As with voltage control and the various types of operating reserves, these power quality disturbances have the potential to disrupt the operations of loads or generators. As such, demand and supply resources have a natural incentive to ensure that power quality is maintained so that power can be delivered and consumed. However, rather than trusting unregulated actors to take the necessary steps to ensure power quality, regulators typically require network operators to ensure that voltage disturbances are kept within maximum ranges of variation specified by the corresponding technical standards[19]. As in the case of voltage control, network operators may utilize their own resources to improve power quality (for instance, performing maintenance of network infrastructure), or may rely on other actors (by requiring that network users meet standards for the creation of disturbances such as harmonics or flicker in the network, or limits to their power factor, for example). It is possible to identify a plethora of constraints that are placed on system operation and planning to ensure power quality; there are therefore a portfolio of potential services related to power quality that link network operators and energy users. However, for the sake of simplicity, we will refer simply to the service of **power quality**. In general, the services that comprise power quality are regulated by technical standards that impose minimum obligations to both network operators and users. In particular, if the power quality levels required by a specific user are higher than the system standards, both the network operator and the user may form a bilateral agreement on the supply conditions and the associated economic compensations.

2.2.4 Mitigation of network constraints

An almost identical case to that of voltage control can be made for the **mitigation of network constraints**, which is commonly termed "congestion management." Activation of network constraints on power flows are typically due to hitting line or transformer thermal capacity limits (voltage limits are typically dealt with separately, as discussed above). Stability limits are also important at the transmission network level. These constraints result in a new kind of primary network services: **mitigation of network constraints**.

The network provider or system operator can perform various actions to reduce network constraints, such as: changing network configuration, redispatching generators or loads, and shedding or curtailing loads. Network constraints limit the energy transfer from one part of the network to another, preventing the most economically efficient generating sources from meeting end-user needs. As with voltage control, historically, DSOs invested in network infrastructure to reduce network constraints and bring the network into compliance with the applicable grid code. However, agents other than the DSO may provide constraint relief through a multiplicity of responses, such as the dispatch of DERs or

[18] Note that most residential users in the U.S. are connected to a single phase. Certain circuits in a distribution network may be entirely fed by a single phase. These single phase loads or circuits originate from a larger three phase circuit. The principles of maintaining the quality of the wave form as presented with respect to three-phase wave forms remain for single-phase wave forms.

[19] In Europe, the standard EN-50.160 specifies the voltage characteristics of electricity supplied by public distribution systems. In the US, IEEE/ANSI standards are applied. For instance, IEEE Std. 519 provides guidelines for harmonic control in power systems.

the response of demand [15]. If economically viable and if sufficient competitive conditions exist for the provision of these services, market mechanisms to determine the price should be prepared. Constraint mitigation has both short (operational) and long (investment) components as well, and exhibits the same interplay with the network connection service as voltage control.

2.2.5 Energy loss reduction

Technical losses in electricity networks typically have sufficient volume and associated costs to drive distribution network investments. Network losses happen in the form of heat resulting from electrical resistance in power lines and transformers, and are closely tied to the patterns of network user consumption or injection in specific locations of the network.[20] Depending on the region of the network and the time of the day, these patterns may contribute to increasing or reducing losses. Historically, the network provider would invest in network infrastructure for loss reduction if properly incentivized to do so by regulation. However, there is a trade-off between network investment costs and the costs of energy losses, with some optimal equilibrium value that a properly incentivized and economically rational DSO should ideally try to reach [2]. Network users actively modifying their load or injection profiles to reduce losses can be thought of as a service to the network provider, which may be economically viable if it happens to be less expensive than alternative network investments. Therefore, the DSO may be interested in organizing the decentralized provision of this new primary network service, **energy loss reduction**.[21]

2.2.6 Potential future network services

Voltage control, mitigation of network constraints, and energy loss reduction are services that, if properly priced, should defer network investments in an economically efficient manner. Even if the application of these services may result in network deferral, there is no reason to talk about "network deferral" as a primary service.

Finally, paralleling the structure of energy services, we have to examine if there is any reason to define services such as operating reserves, firmness, or adequacy for the networks. The three of them refer to reliability margins in different time ranges: real time operation security margins, readiness to provide these margins when needed, and sufficiency of the existing or anticipated infrastructure to provide these margins. The issue is whether the grid has to be operated or not with some margin of security between the network capacity – as defined by the network's voltage and thermal constraints – and the actual flows. The answer depends on the requirements imposed by the grid codes, in particular the anticipation with which these margins have to be met, and here it is also relevant whether the DERs can participate or not. For instance, the network operator may accept that part of the security margins that the grid

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[20] There are also, for example, heat losses in the transformer iron cores, but these mostly depend on the voltage level at the transformer connection points.

[21] Is there a constraint associated to this primary network service? Note that the DSO does not have a natural incentive to reduce losses, as they happen in the distribution network, but the cost of losses is incurred by the generators that produce the energy that is lost. Therefore, the regulator has to create a target (constraint) to be met by the DSO, and some sort of penalty or credit associated with meeting the target. This regulatory intervention adopts multiple formats in different power systems, but a target and some economic incentive are always present in one way or another.

code imposes, when operating the system, can be satisfied with DERs if their volume and expected performance are competitive with what the network itself can provide. The same can be said of DERs being relied upon to contribute when the DSO examines the compliance of the network to meet margin requirements for anticipated stressful situations. In summary, if the grid codes establish the need for these margins in any of these three time ranges – real time operating reserves, network capacity committed to be ready to operate, and installed network capacity – and if agents different from the DSO can efficiently participate in the provision of these services, new network services accounting for the short term reliability, firmness, and future adequacy of the network will have to designed.

The provision of operating reserves, firmness, and adequacy for the network by agents – either in a centralized or decentralized manner – other than the network system operators can be seen as a form of what has been vaguely termed in the literature as "network deferrals." We prefer to classify these services with more precision as presented in this document, but it should be clear that the provision of these services by agents other than system operators might avoid or defer the need for network investments.

3 Conclusion and Future Work

The influx of intermittent and distributed resources has caused certain stakeholders to create or claim the need for new electricity services (see, e.g., the California Independent System Operator's "flexiramp" product [16], or other proposals for investment deferral services [17], [18]). In order to enable the efficient planning and operation of the power system, these services must be grounded in the economic and technical fundamentals of the power system. This document defines the limited set of mutually exclusive and collectively exhaustive electricity services that must exist in power systems – primary services. As technologies evolve and regulatory experience builds, new primary services may be required; however, these services must be carefully defined through the creation of constraints on the planning and operation of power systems. The energy-related and network-related services identified above are summarized in **Table 1**.

Table 1 – List of primary electricity services to be priced

Service	Description
Energy-related services	
Electric energy	Electricity at a given location and time, bought and sold via a combination of long-term contracts, and day-ahead, intraday, and balancing markets.
Primary operating reserves	Immediate, automatic, decentralized response to system imbalances to stabilize system frequency.
Secondary and tertiary operating reserves[22]	Up or down regulation service to accommodate normal, random variations in system frequency, and normal variability and uncertainty of load and generation balance.
Firm capacity	A guaranteed amount of installed capacity that is committed to be ready to produce when called upon under system-stress conditions.
Black-start capability	The availability of resources to restore a power system to

[22] As noted above, existing definitions of operating reserves differ significantly amongst power systems, and definitions of secondary and tertiary reserves are expected to be adapted to changing generation mixes.

	normal conditions after a blackout.
Network-related services	
Network connection	Physical connection to the electricity distribution network and access to the associated services.
Voltage control	Maintenance of voltage within regulated limits throughout the distribution system.
Power quality	Minimization of voltage disturbances in delivered power.
Network constraint management	Overcoming network transfer constraints (thermal capacity/line congestion and current and voltage stability limits at the transmission level) through a range of actions such as network reconfiguration, generator re-dispatch/utilization of DG, or modifications to load or generation.
Energy loss reduction	Modification of network user profiles or use of diverse technical measures to reduce losses in the distribution network.

Subsequent work will demonstrate the computation of, characterize the behavior of, and reveal interactions between relevant prices and charges, and assess business models and technology performance characteristics in providing the identified electricity services.

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