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Understanding Smart Grids[*]

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Abstract:

A smart grid is the superposition of one physical electricity network on an information system. "Digitalization" (the growing application of information and communication technologies across the economy) enables electricity to break away from exclusive and centralized generation, opening it up to the increased integration of small-scale renewable sources in distribution networks. Digitalization also facilitates two-way communications between clients and providers, transforming them -progressively into "prosumers". This suggests a new electricity system requiring changes in regulatory and technical norms. Transmission improves, losses decrease, renewables can be better integrated, and demand peaks can be smoothed. On the other hand, there is an important need for investments in smart meters, and IT technology, as well as concerns over the correct treatment of clients' data. The massive introduction of dynamic tariffs is a consequence of smart grid development.

Keywords: Smart Grids; Renewable Energy Sources; Electricity markets

JEL Codes: C14, Q42

1. Introduction

Digitalization can be understood as the increasing interaction and convergence of the traditional economy with digital elements, such as information (data), analysis, and exchange among agents, devices, and machines (IEA, 2017). Growing digitalization is reshaping societies and economies through global social communication platforms, the increased ease of market access through e-commerce, and the growing involvement of consumers in production and distribution chains (Xu, et al., 2018). The "new digital economy" implies innovation in capital goods, the automation of processes, sources of connectivity and data interchange, big data analysis, and artificial intelligence (Sturgeon et al., 2017).

The electricity sector has included information and communication technologies in its functioning. The growing application of information and communication technologies enables electricity to break away from exclusive and centralized generation, opening it up to the increased integration of small-scale renewable sources at different points of the distribution networks. Digitalization also facilitates two-way communications between clients and providers, transforming them progressively from consumers into "prosumers". This suggests a new electricity system requiring changes in regulatory and technical norms changes. Technical and normative changes imply a greater need for investment to enable real-time communication between the different segments which permits the massive introduction of dynamic tariffs and a different bundle of capital goods into the network (Ali and Chou, 2020). It is in this context that new "smart grids" started to replace old "electricity networks".

A smart grid is the superposition of one physical electricity network on an information system, in which devices act as interfaces, and where network components have sensors located in consumer platforms. The smart grid enables consumers to be active participants in the market, where the combination of new technology and a reshaped sector architecture make it possible. The world is adopting smart grids because of digitalization in general -that is its technological component-, as well

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[*] The points of view of the authors are personal, not representing the position of the Universidad del CEMA.

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as their cost efficiency, quality, and environmental benefits. Transmission improves, and supply security and the speed of service recovery in the event of interruptions increase (Rothwell, 2004); OPEX drops and consumers can better integrate their production into the network. In addition, smart grids promote energy efficiency, and integrate renewable sources, thus reducing fossil fuel emissions, and smoothing demand peaks (Moura et al., 2013), permitting more efficient planning of peak capacity investments (Mollahassani-Pour et al., 2017), and the introduction of dynamic tariffication.

Hence, smart grids offer a response to the energy trilemma consisting of the need to reconcile three conflicting objectives: supply security (reliability), environmental protection (sustainability), and minimum supply cost (economic viability) (Oliver and Sovacool, 2017). Nevertheless, collecting those benefits implies overcoming obstacles and facing costs, which means implementing specific policies and regulations to facilitate a smooth transition process (Ghorab, 2019).

The aim of this article is conceptual: to understand the consequences of smart grids' emergence in electricity sector technology (what), and their importance to the progressive transition from fossil fuel energy sources to renewables (why). We also consider some necessary policies and regulations to accelerate and smooth the transition process from traditional electrical networks to smart grids and explore the differences in the production function of old electricity networks compared with new smart grids (how).

The remaining content of the article is structured as follows. Section 2 discusses the characteristics of smart grids. Section 3 refers to the technology of smart grids. Section 4 deals with the policy and governance mechanisms for smart grids. Section 5 devotes to specific regulations of smart grids. Section 6 summarizes the production function changes from traditional electricity networks to smart grids. Section 7 concludes.

2. Characteristics of smart grids

From the technological point of view, a smart grid is an adaptation of the electricity network, which adds the ability of multiple-way communication, incorporates artificial intelligence, and sums up modern control systems to traditional networks (Dileep, 2020). They use digital technology to ameliorate the network's traditional functioning (which operates through comparatively large-scale generators, transportation, and distribution networks), thus giving a growing role to final consumers (often becoming "prosumers"), emphasizing distributed generation, and allowing storage if the electric vehicle fleet is developed enough. An important difference between the old and the new power systems is their architecture. The number of interconnections largely increases in the new smart grids in contrast to traditional networks. Smart grids include power generators, transmission lines, distribution utilities,[4] and customers. The latter category includes the use of renewables to generate their consumption or injection to the grid, the use of electric vehicles, and smart meters.

The electricity industry is adding renewable generation and increasing customer participation in networks, which are evolving from a vertical structure with predictable sources and centralized operations to an increasingly horizontal structure with some intermittent sources and highly distributed generation (DG). Customers can add onsite generation and storage energy in decentralized means (Zame et al., 2018), and their supply to the grid helps to preserve the balance and stability of tension (Cai, 2016). Changes in communications systems, mostly due to the Internet, offer new control and monitoring possibilities, which are expected to lower costs and introduce more flexibility and effectiveness in operations (Dileep, 2020).

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[4] They encompass substations and a control center including switches and meters managed by automatic processes and software.

The term “renewable” is applied to “*non-depletable, inexhaustible, or naturally replenishable energy sources and technologies, which produce electricity, heat, or mechanical energy*”. They are comparatively clean technologies that reduce dependence on fossil fuels. Renewable sources can be situated at locations within both high-voltage and low-voltage grids, favoring the DG (Eid et al., 2016). Renewable sources are considered “sustainable” when they have a negative or neutral CO_2 balance over their life cycle (European Commission, 2012).

All renewables share “front-end-loaded” cost profiles. Consequently, most facilities are funded through project financing, whereby the principal and interest (and profit) are paid from the project’s revenues. The power and capacity contract between the generator and its customers can collateralize the loan. Power purchase contracts for renewables distinguish the producer’s ability, given the characteristics of each source, to meet on-peak, off-peak, baseload, and peaking requirements (Armstrong and Hamrin, 2001). Renewable resources include solar, wind, hydroelectric, geothermal, and biomass. There are also other sources, such as ocean waves, currents, tides, and temperature differences. In Table 1 we describe each technology, its pros and cons, and contracts’ provisions according to the profile of the projects.

Table 1: Renewable energy sources

Source (main costs)	Technology description	Advantages	Disadvantages	Contracts’ provisions
Solar. (equipment and installation)	Photovoltaic (PV) cells are packaged together in a “module” with a transparent cover. Modules can be wired together in “arrays” which convert sunlight into electricity.	PV systems are durable for years, silent, do not yield emissions, and can operate in a variety of climates. A grid-connected client can produce, consume, and sell power.	Most solar power variation is due to clouds. During cloudy weather or periods of excessively hot water use, backup heating is needed.	They can include capacity payments if the facilities deliver consistently on-peak energy. Dispatching provisions should be absent since the operator has limited control of the output.
Wind. (equipment and installation)	A wind turbine with rotating blades converts the kinetic energy of wind into electricity or mechanical energy. Modern wind turbine towers are 30 to 50 meters high with 40 meters in diameter blades. Their maximum power is about 1.5 times the site's average wind speed. The generated energy is proportional to the wind speed cube.	Although wind speed varies over time, it follows daily and seasonal predictable patterns tracked by mathematical models. Wind power plants use no fuel, emit no pollutants, and consume no other exhaustible resources. The wind turbines can operate with fossil-fueled engines in hybrid systems.	The power coefficient reaches not more than half of the airflow energy content, because of aerodynamic losses. Increasing the distance between wind turbines can diminish mutual interference energy losses. Wind plants generate noise and can be visually intrusive. They can disturb wildlife.	They can include capacity payments if the facilities deliver consistently on-peak energy. Dispatching provisions should not be included, since the operator has limited control over the instantaneous output
Hydroelectric. (high initial investments; low operating costs)	A powerhouse converts the potential energy of a water mass, with a certain fall, in electricity. There are two varieties, peaking (storage), and run-of-the-river projects. A peaking hydro unit has a reservoir. “Run-of-the-river” resorts to water flows.	During demand peaks, stored water can be released to support the increased load. The only resource needed is flowing water available at a gradient. Flows are highly predictable. Systems last for decades.	Dams are questioned on an environmental basis. In run-of-the-river projects, predictability varies with annual rainfall patterns, while offering a slow rate of change from day to day.	Contracts covering peaking hydro-units should include high-capacity payments and relatively low energy payments. In run-of-the-river projects, capacity payments can be tied to audits, or to on-peak deliveries.
Geothermal (High initial investments,	Natural heat from within the Earth is captured for producing electricity,	The heat emanating from the Earth is available for power	The best sources are situated in volcanic areas. The thermal	They should include substantial capacity payments and low

low operating costs)	space heating, or industrial steam. Hot water (ranging in temperature from 177° to about 370° C) or steam is pumped from an underground reservoir to the surface. The steam is transferred to a turbine which turns an electricity generator.	generation most of the time. The environmental impact is negligible and can be mitigated by the flow reinjection into the reservoir. Geothermal resources value is based on the enthalpy (heat content) of the fluids.	energy of the Earth is very dispersed, and often at deep depths. Going from the surface of the Earth towards the core, the temperature increases with depth by 3°C, on average, every 100 meters (geothermal gradient).	energy payments, reflecting the cost structure. Capacity testing provisions can be based on the adequacy and regularity of deliveries during on-peak hours
Biomass. (facilities and access to certain fuels)	It is *the biodegradable fraction of products, waste, and residues of biological origin from agriculture, forestry and related industries, industrial and municipal waste* (According to EC). The biofuel converts into energy by direct combustion, anaerobic digestion, gasification, or fermentation and can be burned with similar equipment as a conventional generation.	Bioenergy technologies yield “biofuels” for transport, “bio-heat” or “bioelectricity.” Biofuels can reduce emissions in comparison to other fuels. Since growing biomass absorbs carbon in a similar amount to that emitted when it is combusted, bioenergy systems can produce energy with no net emissions of GHG.	The majority of biomass for bioenergy is solid unprocessed plant material, with around 50 percent of moisture content. The energy content of plant materials decreases linearly with moisture content. Since biofuels have relatively low energy content per ton, facilities must be sited close to the source to minimize transportation costs.	The typical biomass facility runs in a baseload pattern. Biomass projects not operating jointly with an industrial host (co-generators) are “stand-alone” projects. A bioenergy project generally requires a long-term fuel contract to ensure supplies at stable prices, often including a fee to dispose of biomass waste.

Source: Own elaboration from Armstrong and Hamrin (2001), Baghwat et al. (2017), and European Union (2012).

3. Technology of smart grids

The development of a smart grid follows a technological evolution. All new energy technologies have embedded electronic intelligence controlling operations, and linkages with other parts of the grid. A first step towards a smart grid would be *automatic meter reading* (AMR), followed by *advanced meter infrastructure* (AMI), and then network management through smart devices and smart agents. Information technology and new electrical devices with intelligent software inform the network of its operations and needs, collecting information on prices and grid conditions. Thus, demand power management becomes possible for consumers with small-scale and decentralized power production, distribution, and storage. Intelligent appliances with sensors can adjust remotely to grid conditions, and energy storage can be decentralized in thousands of electric vehicles’ batteries (Mazza, 2002).

The new grid configuration modifies the character of the investment needs. Peaks of demand[5] become less frequent (Dileep, 2020). Since capacity in traditional electricity networks was dimensioned to cover peaks of demand plus contingencies, if electricity production and consumption become flattened over time, infrastructure capacity needs will decrease. Moreover, generating electricity near the demand level reduces line losses. New technologies will help to provide a quick and precise response to peaks and contingencies through a gradual increase in power capacity and/or an instantaneous adaptation of clients’ demands, which is coupled with the introduction of dynamic tariffs to create the correct incentives. Customers will receive real-time signals to adjust their consumption. Distributed generation will promote small producers in an integrated network, and economies of scale will make

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[5] The attention to peaking loads began in the 1970s in the USA with the massive diffusion of air-conditioning. This made it imperative to control peak loads, and stabilize and ensure reliable resources (Eid et al., 2016).

DG affordable. Those smaller and sparse suppliers will replace unnecessary traditional generation capacity infrastructure upgrades.

Nevertheless, transforming the electricity sector to absorb more renewables requires upgrades and modernized extensions of old grid systems. Achieving high levels of renewables involves increasing flexibility and responsiveness to electricity systems (Kumpener et al., 2013). Hence, technological requirements reduce the necessity for some investments but increase the need for others. From the financial aspect, the profile of renewable projects is characterized by high initial investments and further low to nil variable costs, contrasting with the different financial profiles of traditional resources, as stated in Table 1 (Mazza, 2002). In the transition, investments could be scarcely attractive to investors without some regulatory or fiscal nudge (Moretti et al., 2017)

Old grids have been designed to operate with dispatchable (not intermittent) generation from gas, oil, carbon, nuclear, or (storage or peaking) hydro plants. The new generation alternatives, such as solar or wind, fluctuate greatly (they are intermittent). Renewables, however, differ in their degree of intermittency. For instance, geothermal and biomass plants provide baseload energy (low or nil intermittency). Run-of-river hydro is intermittent, but variations in its output tend to be slow and predictable. Solar plants range from intermittent to intermediate, and wind power is comparatively more intermittent.

Each electricity system differs, depending on the mix of energy sources and geographical demand profiles. Studies have found that most traditional grids can add an intermittent source of up to 15 percent of their capacity without requiring any modification (Armstrong and Hamrin, 2001). At medium levels of renewables penetration (15 percent to 30 percent), smart grid technologies will become increasingly important. Above 30 percent capacity penetration is considered high for renewables, and usually requires the incorporation of smart grid technologies to ensure reliable grid operation (Kumpener et al., 2013).

The technological change permits customers to interact flexibly with the grid, which, in turn, demands new operational, market, and regulatory structures (Cai, 2016). The smart grids distribute production and control, and each agent optimizes power operations and interactions with the energy network. Smart grids use technologies at all levels (from generation to appliances) to instantly provide information to match supply and demand. Smart meters are needed to decentralize grid management. New transactions arise between agents exchanging information and energy, and new parties appear, such as aggregator companies that can sell power to customers and negotiate with power generators and distributors.

At the same time, new dilemmas surge, namely: who will be responsible for the problems at each stage? how automatically will the grid be run? what difficulties appear when integrating different generation technologies? how safe or unstable will the system be? and how will the new and huge flow of bi-directional information be managed to protect customers' privacy? (Mazza, 2002).

One-way electricity systems have comparatively lower information flowing from consumers to the utility. Smart grids, instead, are fully integrated and interactive systems that include distributed resources, advanced pricing, and other related technologies. Power grids need a system operator to coordinate economic dispatch and to meet demand at the lowest cost subject to operational constraints (Kirchoff’s laws, capacity and stability constraints, safety and line limits, and contingency). The coordinator calculates payments based on locational marginal prices (Cai, 2016). Smart grid technology adoption has a fast rate of technological change in communications and data management technologies (Kumpener et al., 2013).

The implementation of smart grid technologies starts with distribution automation (DA) and demand response (DR). DA refers to automated control techniques that optimize the performance of power distribution networks. DR refers to the ability of the demand side to be flexible, responsive, and adaptive to economic signals (Siano, 2014). DR includes techniques for reducing loads during peaks or when renewables' supply drops. It helps to avoid the most expensive generation, deferring construction of additional capacity, and preventing brownouts and blackouts (Eid, et al., 2016).

There are three general categories of DR: Direct Load Control (DLC), Voluntary Load Reduction (VLR), and Dynamic Demand (DD). DLC gives utilities some control over selected customer loads under contracts, compensating large customers and those using onsite generation. VLR incentivizes customers to reduce consumption voluntarily. DD stabilizes frequency and the loads automatically adjust their power usage by sensing grid frequency (Kumpener et al., 2013).

In distributed generation (DG), unlike central station generation, power plants are smaller than existent ones, and they are situated at more locations along the grid. This reduces transmission costs. Renewables tend to be modular. Solar and wind technologies have a particularly short lead time from installation to operation, and they provide a flexible option for adding generating capacity in decentralized and community-scale applications (Kakran and Chanana, 2018). Biomass, geothermal and run-of-the-river hydro can also be built swiftly.

Inverters are electronic devices that connect most renewable sources and energy storage devices with the electric grid. Inverters can provide reactive power (VARs) to regulate the grid voltage at their point of connection. Smart Inverters, when used to interface renewable sources with the electric grid, can mitigate transient voltage fluctuations. Also, the output from renewable resources can ramp up and down very rapidly, causing difficulties for grid operators. Smart inverters can be controlled to limit the rates at which power ramps up (Kumpener et al., 2013).

Smart grid information technologies can be classified into four categories:

1) Information collectors (sensors).
2) Information assemblers, displayers, and assessors.
3) Information-based controllers.
4) Energy resources that generate, store, or reduce electricity demand (Kumpener et al., 2013).

AMI refers to smart electricity meters and communications and data processing equipment to collect information and deliver it to the grid operator. The transition to smart grids is not possible with AMR systems because of their limitations. AMI, instead, allows utilities to modify service levels because of its instant information gathering of aggregated and individual demands, rationing consumption if necessary, and the possibility of introducing different revenue models to control costs (Dileep, 2020). AMI measures energy usage with high time resolution, sends data to the utility regularly, and establishes two-way communication between the utility and consumers, making real-time pricing possible, which reflects real-time production costs (Kumpener et al., 2013). AMI provides information to consumers and allows them to consume when electricity is cheap (Dileep, 2020). AMI can measure renewable resource output for compensation, control, and planning. They can also integrate distributed resources into DA schemes and can serve as the communication link that enables DR. Among their components, AMI systems comprehend smart meters, automatized home grids, smart thermostats, communication grids from meters to local data concentrators, data management meter systems, and data added to software platforms (Dileep, 2020).

Electricity storage adds flexibility to electric grids because it helps to deal with the variability and unpredictability of renewables. Electricity storage can be divided into bulk (multiple megawatts over hours) and distributed[6] (kilowatts to megawatts over milliseconds to minutes). Storage regulates grid frequency and voltage, contributes to smoothing renewable power variability, allows small-scale energy arbitrage, permits shavings of short-term load peaks, works as backup power, and defers upgrades by improving distribution system asset utilization.

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[6] Some of the technologies in distributed storage include lithium-ion batteries, lead acid batteries, several types of flow batteries, thermal storage, flywheels, super-capacitors, and hydrogen storage.

Batteries of Electric Vehicles (EVs)[7] could be used as distributed storage. Vehicles would have to be able to discharge power back into the grid (known as vehicle-to-grid or V2G). EV batteries can be used as smart loads, even without V2G, by intelligently controlling the charging of an EV (or a group of EVs) (IEA, 2019). Nonetheless, limited storage resources continue to be an issue in electric markets.

Virtual Power Plants (VPP) is a portfolio of energy resources that may not be geographically nearby, or operate independently of the grid, to increase reliability and reduce variability. A VPP may combine power sources, energy storage, and DR, while a central controller or aggregator coordinates. VPP can form a virtual peaking power plant without adding generation capacity.

4. Governance mechanisms for Smart Grids

The challenges to smart grid development imply a series of policies and regulations. Prevailing regulations would not optimize the use of the network, and the transit to a smart grid would not minimize the investment costs. Reshaping the grid would entail some help from policies and regulations, which would send signals of coherence for a smooth transition and avoid wasted resources (Yeager, 2004).

A plausible approach to determine how necessary regulatory intervention is would be to analyze the existence and importance of market failures (that is, externalities, public goods, natural monopolies, and information asymmetries) and to test whether intervention would justify the costs. The regulatory framework for smart grids covers its different components, such as DG, storage and EV, and AMI.

At the highest level, a sector reference framework would be necessary to determine the long-term power sector policy and establish the corresponding regulatory institutions, as well as a roadmap to incorporate renewables into the grid, a more active role of consumers, the distributors redefined role, etc. The general framework is a public good in the sense that it marks the route with “buoys”. A checklist for issues (not exhaustive) would include regulation on DG, regulation on renewable generation, fiscal incentives for renewable generation and AMI incorporation, goals on renewable generation’s share, and regulation of EV penetration.

Once a general framework has been established, another challenge is the market architecture design, which implies integrating renewables, the coordination and optimization of generation, and consumption. The market structure will change according to the distributors’ different roles (Van der Veen and Hakvoort, 2016).

Price regulation should support the economic and financial sustainability of the providers. On the one hand, the profile of the projects implies substantial initial investments with an uncertain recovery horizon. On the other hand, most smart grid projects, especially those that enable renewable energy, have externalities, such as economic gains from greater reliability, improved public health due to lower emissions, and long-term environmental and economic gains from low-carbon electricity generation.

Thus, there are two reasons for intervention: uncertainty and externalities. Externalities from grid reliability and decarbonization should be recognized in tariffs to send the proper price signals. In the absence of these conditions, new capacity needs will be met by conventional projects with the lowest capital costs and the shortest construction terms. In the short term, governments may have to build a bridge to encourage the development of renewable energy projects that deliver long-term benefits, for instance, through long-term energy contracts that offer investors some market guarantee (Armstrong and Hamrin, 2001).

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[7] In 2018, the global electric car fleet exceeded 5.1 million, including battery electric vehicles (BEV), plug-in hybrid electric (PHEV), and fuel-cell electric vehicles (FCEVs).

Regulation should promote and motivate innovation and technical change, modifying the profile of the projects that demand massive initial investments. An essential part of the investments involves replacing and upgrading expensive physical infrastructure for the distribution network, and the implementation of innovative projects. These include pilot projects to improve knowledge of innovative technologies and consumer behavior. Regulatory interventions can incentivize innovation and ensure that new forms of investment are reflected in regulated tariffs (Cambini et al., 2016).

In recent years, regulators have developed mechanisms to stimulate innovation within the distribution systems, supporting innovations that would otherwise be unlikely to develop. The incentives can include higher regulated rates of return (an extra or bonus component to the regulated WACC, such as in Portugal and Italy) or revenue rewards due to performance targets (such as in the United Kingdom and Denmark). The incentive mechanisms can include auction procedures (Cambini et al., 2016). The new regulatory regimes should consider DG and the new “prosumer” role. Since they enter at different locations in the grid, the boundaries between transmission and distribution blur, demanding the harmonization of regulatory treatment.

A governance mechanism is needed to allow free access to the network of new generators and “prosumers”. The objectives of traditional regulation of the electric utility industry have sought to ensure reliable power at the lowest price; to establish processes that produce sufficient revenues to attract additional investment in electricity infrastructure; and to design tariff signals to encourage the wide use of electricity (Baghwat et al., 2017). In the new environment, the public interest is related to the control of emissions and substitution of fossil fuels, using less disruptive mechanisms to finance the transition.

Subsidized technologies have an advantage over unsubsidized technologies, i.e., a solution when externalities are at stake that can compensate for the disadvantage of new technologies to make foot in the market in the face of incumbent technologies. Technologies with front-end-loaded capital costs are also at a disadvantage in an economic regime with a short-term pricing structure (because of uncertainty) (Armstrong and Hamrin, 2001). Regarding this last point, incentives could include a premium for demand uncertainty (Cambini et al., 2016).

To promote market development, access to free information and low-cost communication must be available to boost the skills of the agents to interact with the network and to generate more confidence in consumers by promoting privacy and protection against cyber-attacks, particularly, and against generic fragilities of the smart grids. For privacy reasons, the liberalization or regulation of data collection from smart metering is especially sensitive.

Smart grid development depends on the evolution of other markets, such as digitalization in general, and AMI diffusion in particular. Every advancement in digitalization is fertile soil for new appliances, which can facilitate the DG and DR. Just as the concept of universal service was one step ahead of telecommunication development, some similar criteria can be adopted in digitalization and smart metering, taking into consideration the growth of the smart grid sector.

Different tariff structures promote incentives to consumer behavior through rewards and penalties and are included in the demand management instruments. Until recently, time-based pricing has been applied mainly to industrial users, however, with the growing share of renewables, it would be sensible to extend the criteria to residential clients. Demand response can be induced directly through “controllable” (interruptible) or contract-based, or indirectly by price-based[8] ways (Eid et al., 2016).

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[8] The types of advanced pricing schemes are:

1) Time-of-Use Pricing (TOU), where electricity is cheap at low loads and expensive during peaks. Peak hours and prices tend to be predetermined. It is useful for solar sources.
2) Critical Peak Pricing (CPP), where utilities warn customers when loads are about to reach annual peaks based on forecasts and compensate those who reduce loads. Peak hours are established one day beforehand based on the maximum expected load.

5. Regulation of smart grids

Current regulations are thought for centralized and hierarchic generation systems, without distributed generations and responsive demand, where the costs and benefits of distributed generation and demand participation are not included in the price system (Li, et al., 2015). Before adopting new costly technologies for digitalization, utilities, and regulators need to assess their current conditions and the benefits of adopting them in specific sectors.

Ruester, et al. (2013) suggest four regulatory issues to be addressed if a smart grid is developed: 1) distribution fee, 2) tariff structure, 3) new activities for distribution companies and unbundling, and 4) new responsibilities for distribution and transmission companies. In the first case, some investments are needed to smarter the network, while some short-run efficiency is achieved in the operation of the grid. In the second case, tariffs should orient with proper incentives the behavior of the agents. In the third case, new activities depend on the network and the possibilities of decentralizing, encompassing aspects such as property and management of smart meters or data and operation management. In the fourth case, each segment should be defined, and the information flows between shared activities should be coordinated.

The transition toward digitalized electricity sectors could require market redesign to enable the entry of new stakeholders, as well as the reformulation of their roles and those of current stakeholders. However, there are many services that smart meters can provide even without institutional changes. They include better monitoring of grid status by the distribution company, a reduction in distribution losses, a faster reaction to interruptions, measurements of real-time household consumption, avoiding checking meters and arrear controls, and service restoration at a low cost for the distribution company (Cont, 2021).

Adding institutional changes makes it possible to introduce new plans with new, value-added services for users, demand smoothing, and distributed generation. The required institutional changes involve separating distribution and commercialization stages, with differentiated payment schemes, the emergence of demand aggregators, the new role of a distribution system operator (DSO), and the surge of a data aggregator.

Commercialization firms compete to offer customers different electricity service plans, selling electricity but also issuing and collecting bills. The separation of commercialization from distribution had already started with the bypass of the largest consumers, buying directly from generators, under vertical separation of activities. Introducing separated commercialization firms does not require smart meters. On the other hand, introducing smart meters without separated commercialization firms does not guarantee the benefits of digitalization, since the incentive structure faced by the distribution-commercialization company relies on sales volume rather than on efficient consumption. Combining separate commercialization companies with smart meters will enable the design of adequate plans for different hourly consumption patterns (Romero, 2020; Cont, 2021).

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3) Variable Peak Pricing (VPPr), where peak hours are predetermined, while prices are established one day in advance based on the maximum expected load.

4) Real-time pricing (RTP) or dynamic pricing, where price profile forecasts adjust at intervals throughout the day. Peak hours and prices are variable. It is useful for resources that follow unpredictable patterns.

Regulatory authorities should promote easy comparisons between different consumption plans. Regulations to foster competition include those that prevent companies from refusing contract cancellations by customers and from making it difficult for customers to move to other providers. Regulations to protect consumers include those concerning changes in contract terms and conditions and the availability of last-ditch plans for all customers (Ros et al., 2018). The distribution companies continue to be regulated firms, since the network is monopolistic, and their distribution fee should be charged to end consumers.

Demand aggregators provide services to reduce the cost of contracts and for other services included in customers' electricity bills. Competition in commercialization enables the spontaneous emergence of firms that group electricity consumers to enable demand reductions or increases in exchange for a fee. Demand aggregators optimize consumption flexibility among residential users and small stores, manufacturers, and other firms to offer electrical system reductions in aggregate demand to flatten the short-term cost variations caused by fluctuations in supply and demand (Burger et al., 2017). Aggregators may sell their services to system operators or generation or commercialization companies. Commercialization firms may integrate with an aggregator and offer plans including discounts in exchange for demand-response or storage services (Fischer, 2020). Aggregators negotiate by offering clients alternatives to flatten the cost curves they face.

Alternatively, they can offer their services to distribution market operators (DMO), which add flexibility to the demand and charge the overall electrical system operator for the service of flattening demand. A distribution system operator (DSO) manages the system through a distribution network operator to a DMO within a disintegrated market, centralizing the electricity. If the distribution company also supplies electricity, there is no need for an independent DMO. The DSO can be a unit within the system operator or an independent entity representing the interests of demand agents and suppliers concerning distribution (Keay et al., 2014).

Smart meters generate consumption data that can be useful for system operations and management, for competitive commercialization services, as well as to avoid competition if the data is in the hands of the incumbent distribution company, or to implement price discrimination strategies when there is no competition. Smart meters raise concerns in terms of data privacy. One option to address these problems and risks involves creating a specialized, independent institution that receives data from meters and sends them on to commercialization companies in a non-discriminatory way, subject to rules that protect customer privacy. Customers would fund its services with a small additional fixed fee in their bills. Alternatively, these data could be managed in a decentralized way, which would be an advantage in case of information leaks (Cont, 2021).

6. The production function changes from traditional electricity networks to smart grids

Our previous discussion allows us to characterize the differences between the "traditional" networks and the "smart" grids and the differences in the productive process. Both schemes share almost the same outputs and inputs, but subtle changes modify the character of some of them, as well as their sensitivity to environmental conditions.

Tuballa and Abundo (2016) offer a comparison of traditional networks against smart grids: 1) In traditional networks the technology is mechanical, while in smart grids is digital; 2) communication is one-way against real-time multiple-ways; 3) generation is centralized in the former and distributed in the latter; 4) the network is radial in contrast to a sparse one; 5) recovery and control are manual and slow, *versus* automatic and quick in the other case; 6) traditional grids process comparatively smaller amounts of information, with lower quantity of sensors and scarce considerations for safety and privacy of the data, while in smart grids the information flow is abundant, needing a high quantity of sensors and being safety and privacy a first-order concern; 7) finally, old fashion networks offer a small variety of options for customers, while intelligent networks offer multiple alternatives to clients.

Table 2: A comparison between traditional and smart grids

Comparison criteria	Traditional Network	Smart Grid
Technology	Mechanization	Digitalization
Communication	One-way	Multiple-way in real-time
Generation	Centralized	Distributed
Network	Radial	Sparse
Information	Small amount	Great volumes
Sensors	Low quantity	High quantity
Recovery and control	Manual and slow	Automatic and quick
Safety and privacy	Scarce considerations	First order concern
Options for users	Small number	Multiple numbers

Source: Author's elaboration on Tuballa and Abundo (2016)

The World Energy Council's Energy Trilemma Index ranks countries' energy performance on three dimensions: security, equity, and sustainability. Sound energy systems are secure, equitable, and environmentally sustainable, balancing the three dimensions. At the same time, its growth in size, and balance in shape, implies proper policies and creative approaches (World Energy Council, 2018). Smart grids face and contribute to solving in part the trade-offs of the three goals.

First, smart grids are characterized by comparatively lower energy intensity (because of more efficient appliances in residential clients, and machinery of non-residential clients, plus cleaner economies, with greater services/GDP ratios and clean industries/GDP composition), which, together with a growing share of renewables in the energy matrix, yield less harmful environmental impacts than traditional networks.

Second, the nature of the capital itself shows that smart grids depend comparatively less on transport and distribution networks, and critically on AMI penetration, which allows for two-way communication and a surge in the "prosumer" role, distributing generation and automation (DG and DA).

Third, the level of digitalization is necessary to "smarter" the grid.

The previous discussions suggest some ways to address the design of one highly challenging experiment. The most important is cost treatment because one objective of the transition is to reduce the costs of traditional infrastructure while facing the costs of "smarting" the grid. The environment is preserved by increasing new renewables' share in the energy matrix (as a percentage of total sources), replacing fossil resources, and not accounting for storage-type hydroelectric to concentrate better on distributed generation. Thus, we are considering increases in quality, together with environmental protection, and a drop in costs, which can be proxied by the reduction in losses.

The distribution system can be integrated upstream with generation and transmission, depending on the industrial organization of the electric sector in each country. Its outputs are the energy consumption (in GWh), and quality levels of the service, such as interruptions or losses, which relate to the state of the infrastructure.

The inputs to achieve those outputs, are labor, the traditional proxy of capital, transmission, and distribution network in kilometers (as a raw capital measure of the system), plus AMI penetration (as a key and distinctive input for smart grids because they allow for two-way communication within the grid), and renewables participation in the energy matrix.

Smart grid development requires connectivity to justify the value of the investment, that is, a favorable context to grow. Thus, the environmental variables (both pre-requisites of a smart grid) that we consider are the density of the network (which is a standard contextual variable in the study of traditional networks' efficiency), plus connectivity, measured as the percentage of the internet broadband connections out of total connections.

7. Concluding remarks

Energy efficiency, the introduction of non-conventional renewable energy, the reduction of carbon emissions, the lowering of long-term supply costs, consumption peak smoothing, and the stability of electricity networks are the consequences of smarting power grids. Smart grids promote the growing integration of renewable energy sources, a horizontalization of the roles of producers and consumers, and a flatter demand profile that saves infrastructure investment intended to supply consumption peaks. On the other hand, smart grids require costly investment to modernize information technology, and regulations to face market failures (externalities, public goods, information asymmetries, etc.) that can defer the transit from traditional networks to modern ones and would require some market architecture design and governance procedures which help finance the transition and the development of the new environment. Different dynamic tariff structures promote incentives to consumer behavior through rewards and penalties and are included in the demand management instruments.

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