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Getting Smart (Grids). An Efficiency Frontier Assessment[1]

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Abstract:

Information and communication technology are reshaping the electricity industry, with economic, environmental, and regulatory consequences. Smart grids allow the growing integration of renewable energy sources, a horizontalization of the roles of producers and consumers, a flatter demand profile which save investments intended to supply peaks of consumption, idle at great extent off-peaks. On the other hand, smart grids require important investments for modernizing technology.

Concerning our objectives, firstly, we seek to understand the conceptual consequences of the irruption of smart grids on the electricity sector, and its importance for renewables adoption. Secondly, we discuss policies and regulations needed to accelerate the transformation of the electricity network in a smart grid, and to increase the renewables' share on total energy. Thirdly, our empirical approach runs a Data Envelopment Analysis (DEA) model to estimate the efficiency gains in the transition between traditional and smart grids. Our results show the efficiency levels of those countries whose objective is to deliver electricity with high levels of quality of services, and at the same time, using more renewables (with fewer carbon emissions), and low cost of supply. We conclude discussing the implications of our empirical model, the limitations, and next stages in polishing the results.

Keywords: Smart Grids; Renewable Energy Sources; Efficiency; Data Envelopment Analysis

JEL Codes: C14, Q42

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1. Introduction

The concept of “digitalization” describes the growing application of information and communication technologies across the economy, which is an integral part of the “Fourth Industrial Revolution,” according to Schwab (2016). Digitalization can be understood as the increasing interaction and convergence of traditional economy with digital elements, such as information (data), its 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 commerce and distribution platforms, and the growing involvement of consumers in production and distribution chains (Xu, et al., 2018). The “new digital economy” implies innovation in capital goods, processes’ automation, sources of connectivity and data interchange, big data analysis, and artificial intelligence (Sturgeon et al., 2017).

Digitalization permits that electricity to cease to be exclusively and centrally generated, opening room for increased integration of renewables in different nodes of the network and at a wide range of scales (because digitalization allows incorporating meaningfully renewable sources, by connecting them to the distribution network), and permits two-way communications between clients and providers, the former increasingly becoming “prosumers.”

Since many years ago, the electric sector had adopted information and communication technologies for its functioning. This suggests the progressive surge of a new electrical system, which would require, among others, regulatory and technical norms’ refreshing. Together, technical, and normative change imply the greater need for investments for real-time communication of the different segments (Ali and Chou, 2020).

A smart grid is the superposition of one physical electricity network with an information system, which interfaces devices, and where network components have sensors located in consumer platforms. The world is adopting smart grids because of digitalization in general, as well as because of cost efficiency, quality, and environmental reasons. Transmission improves, and both supply security and speed of service recovery before interruptions increase, OPEX lower, and consumers can integrate better their production into the network. Besides, smart grids promote energy efficiency, integrate renewable sources reducing carbon emissions, and smooth demand peaks (Moura et al., 2013). Smart grids help mitigation and adaptation to climate change and permit more efficient planning of peak capacity investments (Mollahassani-pour et al., 2017).

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

The first aim of this article is conceptual: to understand the consequences of smart grids irruption in the electricity sector technology (what and how), and its importance for the progressive replacement of fossil sources of energy to renewables (why). A second objective is, based on previous assessments, to make some considerations about policies and regulations needed to accelerate and smooth the transition process from traditional electrical networks to smart grids. The third aim is empirical in its scope and focuses on determining the efficiency frontier of achievements in the trilemma’s objectives. To address that, we estimate a Data Envelopment Analysis (DEA) model considering variables relevant for the analysis of smart grids.

This document is structured in the following way: after this introduction, section 2 characterizes smart grids, section 3 discusses smart grids technologies, policies and regulations, section 4 is the empirical section, composed by database, method and models, section 5 is for results’ discussion, and section 6 concludes.

2. Smart Grids Characteristics

From the technological point of view, a smart grid is an adaptation of the electricity network, which adds to traditional networks the ability of multiple-way communication, artificial intelligence, and modern control systems (Dileep, 2020). They use digital technology to ameliorate the network's traditional functioning (through big-scale generators, transportation, and distribution networks), giving a growing role to final consumers, distributed generation, and storage. Smart grids include power generators, transmission, and distribution utilities[5], and customers[6].

The electricity industry is adding renewable generation and increasing customer participation in grid operations, which are evolving from a vertical structure with predictable resources and centralized operations to a horizontal structure with some intermittent resources and distributed generation. Customers can add onsite generation and storage energy in decentralized means, 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 over the whole electricity system, which in turn could lead in the long run to lower costs, and introduce more flexibility and effectiveness in operations (Dileep, 2020).

The term "renewable" is applied to non-depletable, inexhaustible, or naturally replenishable energy resources and technologies, which produce electricity, heat, or mechanical energy. They are comparatively clean technologies with limited impact on the environment, and they consequently reduce dependence on fossil fuel. Renewable resources can be situated at locations within both high-voltage and low-voltage grids, favoring the Distributed Generation (DG) (Eid et al., 2016). Renewable sources are considered "sustainable" when they have a negative or neutral CO2 balance over its life cycle. A basic rule for ecological sustainability is that energy may be extracted from production/consumption systems, but nutrients must be recycled (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 proceeds of the project. The power and capacity contract between the generator and its customers can collateralize the loan. Power purchase contracts for renewables should reflect the producer's ability to meet on-peak, off-peak, baseload, and peaking requirements (Armstrong and Hamrin, 2001). Renewable resources include solar, wind, hydroelectric, geothermal, biomass, and there are also other sources, with less diffusion, such as ocean waves, currents, tides, and temperature differences. The Table A1, in Appendix, shows a scheme of every source of the list, considering main costs, a brief description of the technology, its advantages, disadvantages, and provisions needed in contracts to promote the source.

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. From a traditional one-way communication, a first step would be automatic metering reading (AMR), followed by advanced metering infrastructure (AMI), and next, 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 and collect information on prices and grid conditions. Thus, demand power management is allowed at the consumer level with small-scale and decentralized power production, distribution, and storage. Intelligent appliances with sensors can adjust remotely to grid conditions. Energy storage can be decentralized in thousands of car batteries (Mazza, 2002).

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[5] Comprehending substations, and a control center including switches and meters managed by automatic processes and software.

[6] Including within this category, the generation using renewables for own consumption or injection to the grid, the use of electric vehicles, and smart meters.

The new grid configuration modifies the character of the investment needs. Peak demand attainment becomes less frequent; thus, a system design based on peak demand becomes oversized (Dileep, 2020). The attention to peaking loads started in the 1970s in the USA with the massive diffusion of air-conditioned. This required to control peak loads, to stabilize and made resources reliable (Eid et al., 2016). One supply-side element of the diversification of resources is the inability of generation to cope with huge investments needed to sustained growth in peak demand, plus the problems due to the price volatility of fossil resources (Dileep, 2020). Since capacity is dimensioned to cover peaks of demand plus contingencies, if electricity production and consumption become flattered over time, infrastructure capacity needs will decrease.

Moreover, generating electricity near to the demand point reduces line losses. New technologies will help to provide a quick and precise response to peaks and contingences through a gradual increase in power capacity and/or an instantaneous adaption of clients' demand. Distributed generation will promote small producers in an integrated network, and economies of scale will make distributed generation affordable. Those smaller and distributed suppliers will replace no more needed traditional generation capacity infrastructure upgrades. Flatten peaks will reduce the transmission and distribution lines' investment needs and their associated losses.

Nevertheless, transforming the electricity sector to absorb more renewables requires upgrades and modernized extensions of old grid systems. Achieving high levels of renewables requires increasing flexibility and responsiveness to electricity systems (Kumpener et al., 2013). Thus, technological requirements modify the character of the investments needed. In the financial aspect, the profile of the projects is also different: renewable projects are characterized by high initial investments and further low to nil variable costs, contrasting with the different financial profiles of traditional resources (Mazza, 2002). In the transition, investments could be scarcely attractive to investors without some intervention (Moretti et al., 2017)

Old grids have been designed to operate with dispatchable (not intermittent) generation from gas, oil, carbon, nuclear or hydro plants. The new generation alternatives, such as solar or wind, are very fluctuating (intermittent). An explanation for each source is developed in the following section. Within renewals, they differ in their degree of intermittency. For instance, geothermal and most hydro, and biomass plants provide baseload energy (low or nil intermittency), to peaking. 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 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). Less than 15 percent penetration on any section of the grid is considered a low level of renewables, which are generally feasible without any smart grid technologies. At medium levels of renewables penetration (15 percent to 30 percent), smart grid technologies will become increasingly important. Above 30 percent capacity penetration are considered high for renewables, and usually require the use 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 traditional network is a hierarchical system in which electricity delivery to consumers (at the bottom of the chain) is the responsibility of power generators (at the top of the chain), in a one-way "pipeline" with centralized control (Dileep, 2020). The smart grids instead 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 with demand. Smart meters are needed to decentralize grid management. New transactions arise between agents exchanging information and energy.

Also, new parties appear, such as aggregator companies that can sell power to customers and negotiate with power generators and distributors. Thence, new troubles arise, namely, who will be responsible for each stage's problems, how automatically will be the grid run, which difficulties appear in integrating different generation technologies, or how unstable and safe will be the system (Mazza, 2002).

One-way electricity systems have little or no information flowing from consumers to the utility. Smart grids, instead, are fully integrated systems that include several types of distributed resources, advanced pricing, and other related technologies. However, there are many possibilities between these two extremes (Kumpener et al., 2013). The success of smart grids depends on the application of efficient and cost-effective communication systems for measuring, monitoring, and controlling aims (Dileep, 2020). Power grids need a system operator to coordinate economic dispatch and to meet demand at least cost subject to operational constraints (Kirchoff's laws, capacity constraints, safety limits, contingency, stability constraints, and line limits). 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).

3. Smart grids technologies and regulations

3.1 Technologies

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 drop. DR permits avoiding 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 (VLD), and Dynamic Demand (DD). DLC gives utilities some control of selected customer loads under contracts, compensating large customers, and those using onsite generation. VLR incentivizes customers to reduce consumption voluntarily. DD stabilizes frequency and loads automatically adjust their power usage by sensing grid frequency (Kumpener et al., 2013).

In distributed generation (DG), as opposed to central station generation, power plants are smaller than existent, and they situate at more locations along the grid. This reduces transmission costs. Renewables tend to be modular. Solar and wind technologies, particularly, have a 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 hydro (that which does not require a dam) can also be constructed swiftly. The resources are different, and policymakers should know similarities and variations among renewable energy resources (Armstrong and Hamrin, 2001).

A smart grid makes it possible to integrate renewables with a wide range of diverse electricity resources. These technologies can also promote greater use of distributed renewable generation. They can provide system operators with real-time information on how these systems are operating to control them, to maintain reliability, match load, or to control voltage. The utility's role is one of standard-setting and distribution system. 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).

Tuballa and Abundo (2016) offer a comparison of traditional against smart grids: i) In traditional grids the technology is mechanical, while in smart grids is digital; ii) communication is one-way against real-time multiple-ways; iii) generation is centralized in the former and distributed in the latter; iv) the network is radial in contrast to a sparse one; v) recovery and control are manual and slow, *versus* automatic and quick in the other case; vi) traditional grids process small amounts of information, with low 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; vii) finally, old fashion networks offer a small variety of options for customers, while intelligent networks offer multiple alternatives to clients.

Table 1: A comparison among traditional and smart grids

Comparison criteria	Traditional Grids	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 number

Source: Own elaboration on Tuballa and Abundo (2016)

Smart grid technologies can be classified into four categories:

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

AMI refers to smart electricity meters and the communications and data processing equipment for collecting information and delivering it to the grid operator. The transition to smart grids is not possible with AMR systems, because of its limitation to control at all levels. AMI permits utilities for modifying service levels because of instantaneous information gathering of aggregated and individual demands, rationing consumption if needed, and performing different revenue models to control costs (Dileep, 2020). The 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 possible real-time pricing, which reflects real-time production costs (Kumpener et al., 2013). AMI provides information to the consumers allowing them to consume when electricity is cheap (Dileep, 2020). AMI can measure renewable resource output for compensation, control, and planning. They also can 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 is handy for adding 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 storage[7] (kilowatts to megawatts over milliseconds to minutes). They regulate grid frequency and voltage, contribute to smooth renewable power variability, allow small-scale energy arbitrage, permit shavings of short-term

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

load peaks, work as backup power, and defer upgrades by the improvement of distribution system asset utilization. Batteries of Electric Vehicles (EV)[8] could be used as distributed storage. This would require the vehicles 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 group of EVs) (IEA, 2019).

Virtual Power Plants (VPP) is a portfolio of energy resources that may not be geographically next, nor operate independently from the grid, to increase reliability and to 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.

Smart grid technologies at bulk power generation and transmission level include (Kumpener et al., 2013):

1) Flexible Alternating Current Transmission Systems (FACTS), which regulate grid voltage or power factor, improving dynamic grid stability and power quality.
2) Bulk (long-term) Energy Storage used to store electricity at off-peak times and release it during peak. Stored hydropower accounts for most storage capacity. Several other forms of bulk energy storage are being piloted as sodium-sulfur batteries, flow batteries, molten salt thermal energy storage, or lithium-ion batteries.
3) Dynamic Line Rating (DLR) technology allows real-time line rating, optimizing the capacity of line transmission. Traditionally, power lines are given a single power rating based on the worst-case weather scenario. The capacity of power lines to carry current decreases with higher conductor temperature, increases with ambient temperature and solar radiation, and decreases with wind speed. DLR is complementary with wind power because it cools lines.
4) Synchrophasors (Phasor Measurement Units PMUs), measure the magnitude and phase of transmission line current, facilitating advanced grid control and optimization methods.

3.2 Policies and regulation

The challenges for the smart grids' development imply a series of policies and regulations. Current regulation would not optimize the use of the network, and the transit to a smart grid would not minimize the investment costs. The reshaping of the grid would need some help of policy and regulation, which gives signals of coherence for a smooth transition and to avoid the waste of resources (Yeager, 2004). The golden rule for determining the need for regulatory intervention is analyzing the existence and importance of market failures (that is, externalities, public goods, natural monopolies, and information asymmetries), and testing benefits of interventions overcomes costs. The regulatory framework for smart grids builds based on a set of regulations over its different components, such as DG, storage and EV, and AMI.

Firstly, at the highest level, it seems necessary a sector reference framework, with a definition of power sector policy in the long run and the establishment of according regulatory institutions, and a roadmap for renewables incorporation to the grid, the role of consumers, distributors, etc. The general framework is a public good, in the sense it marks with "buoys" the route. A checklist for issues (not exhaustive) would include regulation on DG, regulation on renewables' generation, fiscal incentives to renewables' generation and AMI incorporation, goals on renewables' generation share and regulation on EV penetration.

Secondly, once established a general framework, a challenge is the market design, which implies the integration of renewables and the coordination and optimization of generation and consumption. The market structure will change with different roles for distributors. Investments

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

in smart grids must make economic sense. 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. Utilities were traditionally rewarded for providing reliable service and they have few, if any, incentives for implementing new technologies somehow risky of any sort (Kumpener et al., 2013). Externalities from grid reliability and decarbonization should be recognized in tariffs to set 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 run, governments may have to build a bridge to encourage the development of renewable energy projects that deliver long-term benefits. A bridge to that future is long-run energy contracts that guarantee buyers (Armstrong and Hamrin, 2001).

Thirdly, the transition from fossil to renewables resources is expensive and needs the development of regulatory schemes to incentivize investments in the smart grids. Regulation should promote and motivate innovation and technical change, modifying the profile of the projects which demand massive initial investments. An essential part of the investments is replacing and upgrading physical infrastructure for the distribution network, and through the implementation of innovative projects. These include pilot projects to improve knowledge of innovative technologies and consumer behavior. Regulatory interventions should 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 for stimulating innovation within the distribution systems, supporting innovations otherwise unlikely to undertake. The incentives can include higher regulated rates of return (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 some tendering procedures (Cambini et al., 2016). The new regulatory regimes should consider DG and the new “prosumer” role. Since they enter in different places of the grid, the boundaries between transmission and distribution blur, demanding harmonization of regulatory treatment.

Fourthly, it demands the development of the rules of the game to allow network free access for new generators and “prosumers” in the same sense that when decades behind, the telecommunication sector was vertically disintegrated. In developing regulation, the primary tasks are: identifying the public’s interest that is being protected (environmental considerations, fuel imports substitution); and identifying the least disrupting and more cost-efficient mechanisms and tools (subsidies, financing) that can accomplish this task. The objectives of traditional regulation of the electric utility industry have been to ensure reliable power at the lowest price; established processes that result in sufficient revenues to attract additional investment in electricity infrastructure as required to ensure reliable power at a reasonable price; and design tariff structures and price signals to encourage the wide use of electricity. Some rules of thumb are that new technologies are seldom on an equal footing with established technologies (replicating the incumbent-newcomer problem). Subsidized technologies have an advantage over unsubsidized technologies (a solution when externalities are at stake). Technologies with front-end-loaded capital costs are disadvantaged in an economic regime with a short-term pricing structure (because of uncertainty) (Armstrong and Hamrin, 2001). In this last respect, incentives could include a premium for demand uncertainty (Cambini et al., 2016).

Fifth, to promote the participation in the markets, it is necessary to allow access to free information and low-cost communication, to impulse the skills of the agents to interact with the network and to generate more confidence in consumers promoting privacy and protection against cyber-attacks and in general against those fragilities of the smart grids. A sensitive issue, because of privacy, is the liberalization or regulation of data collection from smart metering.

Sixthly, smart grids development depends on the evolution of other markets, such as digitalization in general and of AMI diffusion particularly. Every progress in digitalization is fertile soil for new appliances, which can facilitate the DG and DR. As the universal service concept was in the past one step ahead to telecommunication development, some similar criteria can be adopted in digitalization and smart metering, having in mind the smart grid sector growth.

Finally, different tariffs promote incentives to consumers' 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, but it is expected that, with the growing share of renewables, the residential flexibility will become more common. Demand response can be induced directly through "controllable" (interruptible) or contract-based, or indirectly by price-based ways (Eid et al., 2016). The types of advanced pricing schemes are:

1) Time-of-Use Pricing (TOU), under which electricity is cheap at low loads and expensive during peak times, being a useful device for solar sources. Peak hours and prices tend to be predetermined.
2) Critical Peak Pricing (CPP), under which utilities warn customers when loads are to reach annual peaks, based on forecasts, and compensate those who reduce loads. Peak hours are established with one day of anticipation, based on the maximum expected load. Price is static and predetermined.
3) Variable Peak Pricing (VPPr), under which peak hours are predetermined, while prices are established with a day in advance, based on the maximum expected load.
4) Real-Time Pricing (RTP) or dynamic pricing, under which price profile forecasts adjust at intervals throughout the day, being useful for resources that follow patterns not easily predictable. Peak hours and prices are variable.

4 Methodological Approach: Data, Estimation Method and Models

The objective of this empirical section is to estimate the efficiency of countries to achieve the outputs of the electricity sector (supply consumption needs, under certain quality standards, at reasonable costs, and with certain environmental impact), with certain inputs (capital, labor and energy intensity), given environmental conditions (non-controllable inputs).

Our present discussion allows us to characterize the differences among the "traditional" and the "smart" grids and the differences in the productive process. In fact, both schemes share the same outputs, and the same inputs, but subtle changes modify the character of some of them as well as the environmental conditions.

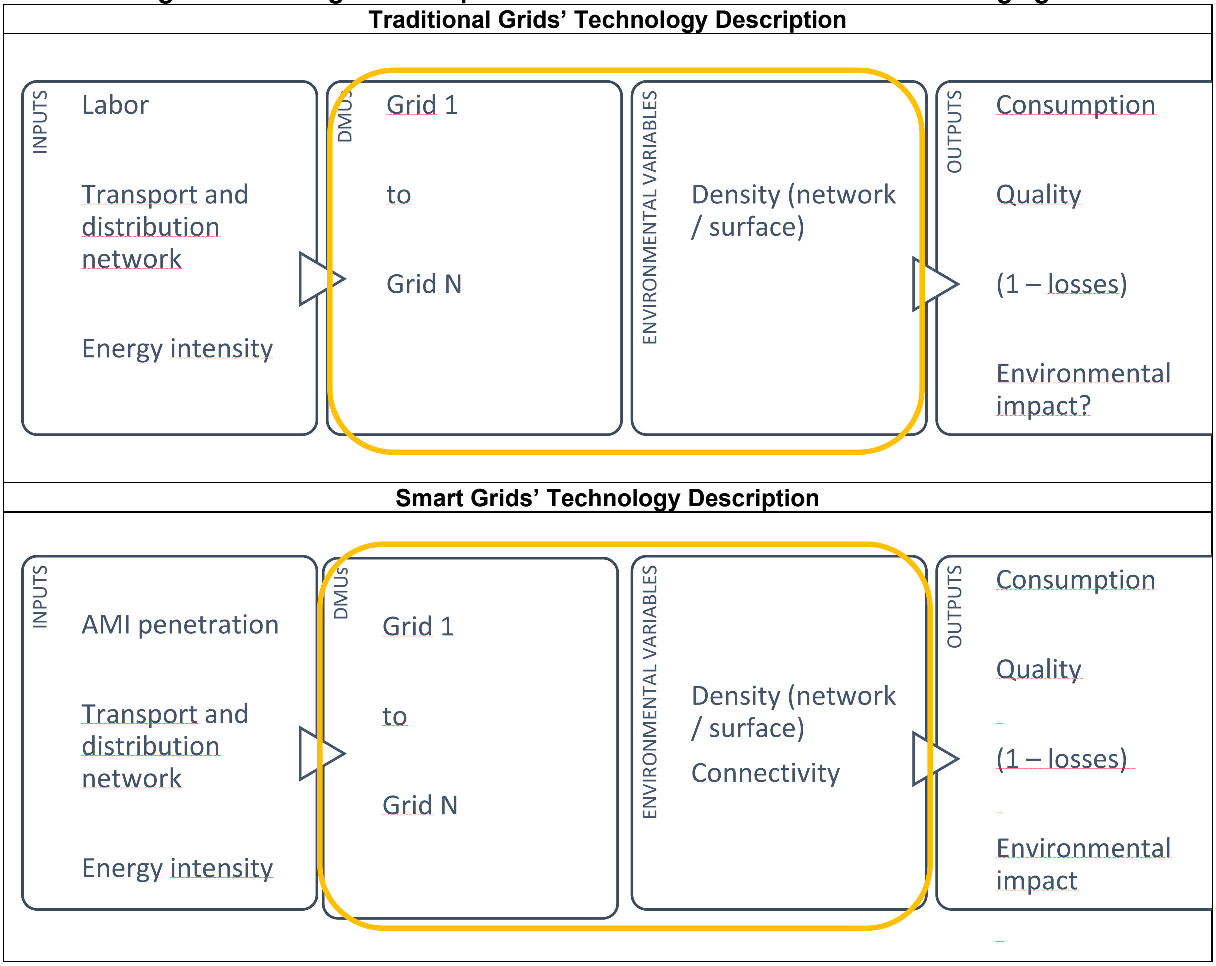
Smart grids are characterized firstly by lower energy intensity (because of more efficient appliances in residences and machinery in non-residential clients, plus cleaner economies - probably with more services/GDP and less dirty industries/GDP-) and less damaging environmental impact as a result of the former plus growing participation of renewables in the energy matrix.

Secondly, the nature of the capital: smart grids depend comparatively less in transport and distribution network and probably much less of labor inputs, and depends critically on AMI penetration, which permits double way communication and the surge of the "prosumer", DG and DA.

Thirdly, the environmental characteristic is less the electricity physical coverage, and more the level of digitalization, a necessary condition to "smartize" the grid. The process we have in mind is synthesized in Diagram 1.

The previous sections give clues to design one experiment which faces many challenges. The most important is cost treatment, because the effect of the transition is to decrease costs of traditional infrastructure, while increasing costs of “smartizing” the grid. The environment is preserved with increasing new renewables participation in the energy matrix (as a percentage of total sources), replacing fossil and not accounting-for storage-type hydroelectric, to concentrate better in distributed generation. We are considering then increases in quality, together with environmental protection, and reducing costs, measured by losses reduction. The inputs to achieve those outputs, which are correlated with smart grids, are energy consumption (in GWh, to denote the size of the market), transmission and distribution network in kilometers (as a raw capital measure of the system), and AMI penetration (as a key and distinctive input for smart grids, because smart meters allow double-way communication in the grid). The latter requires connectivity to make sense and worth the investment, that is, a favorable context to progress. Thus, the environmental variables (both pre-requisites of a smart grid) we consider are density in terms of network / surface, and connectivity, measured as the percentage of the internet broad band connections on total connections.

Diagram 1: Changes in the production function because of “smartizing” grids



Source: Own elaboration.

4.1 Data

Our dataset comprises information from 37 countries for 2018. To operationalize the efficiency frontier of a productive process of a smart grid (Diagram 1) we need meaningful proxies for each output, input, and environmental variable (the names in CAPITAL letters).

With respect to outputs, CONSUMPTION is measured in GWh. We proxy cost-supply reduction by the inverse of losses, in transmission and distribution, measured by the percent of energy lost: our variable is called (1 – LOSSES). We proxy quality by (1 – SAIDI) (System Average Interruption Duration Index, length of interruptions per year per clients served). The fourth output related to the environmental impact, is measured by NEWRENEWABLES penetration (excluding fossil fuel sources and hydroelectricity).

The inputs of the process we consider are NETWORK (in kilometers) and AMI (in percentage of total meters), the latter a distinctive input of smart grids. We suppose labor input as constant, and we do not include it in the estimates. ENERGY INTENSITY combines structural situations (the energy matrix of the country, partly dependent on resources, partly on past investments and policy decisions, as well as the economic structure) with efforts to save energy through energy efficiency policies.

The environmental conditions, finally, are CONNECTIVITY, measured as an indicator of internet broad band penetration, which in turn is a critical condition for the development of the two-way communication needed for smart grids. Moreover, since we are including countries of varied extension, we need to provide alternatives to the core model. Thus, we consider DENSITY, which is important for distributed generation diffusion, as kilometers of networks divided square kilometers.

In the Table 2 we present and define our outputs, inputs, and environmental variables.

Table 2: Variable definition and character

Variable	Character	Definition
CONSUMPTION	Output	GWh
(1 – LOSSES)	Output	In transmission and distribution, as a percent of production
SAIDI	Output	Length of interruptions per year per client
NEWRENEWABLES	Output	Renewable electricity output (as percentage of total electricity output, excluding hydroelectricity)
NETWORK	Input	In kilometers of transmission and distribution
AMI	Input	Advanced metering infrastructure. Penetration as a percent of total meters
ENERGY INTENSITY	Input	Energy consumption / GDP
DIGITALIZATION	Environmental	Percentage of broad band connections
DENSITY	Environmental	Km of Power Network / Surface in Square Kilometers

Source: Own elaboration.

The information is analyzed considering 37 countries as decision-making units. We present the descriptive statistics of the database in the Table 3, together with some contextual information.

Table 3: Descriptive statistics of the sample (2018 values)

Variable	Mean	Std Dev	Max	Min	Mean Dev
CONSUMPTION (GWh)	256,139	647,254	3,885,440	4,592	3
1-SAIDI	85.689	2.687	87.570	75.005	0.031
NEWRENEWABLES	0.176	0.132	0.683	0.024	0.749
(1-LOSSES)	0.922	0.043	0.980	0.782	0.047
NETWORK	30292	47920	257495	298	2
AMI	0.281	0.335	1.000	0.000	1.191
ENERGYINTENSITY	1.425	0.610	3.526	0.526	0.428
DENSITY	81.702	54.489	225.642	3.005	0.667

CONNECTIVITY	30.327	9.299	44.776	7.347	0.307
Contextual information					
Variable	**Mean**	**Std Dev**	**Max**	**Min**	**Total**
PRODUCTION (GWh)	298,075	743,383	4,455,355	2,201	11,028,776
LOSSES (GWh)	20,898	44,917	253,733	154	773,221
POPULATION	40,770,428	65,304,372	326,687,501	607,950	1,508,505,849
SURFACE KM2 000	1,323	2,792	9,985	3	48,961
COVERAGE ELECTRICITY / POPULATION %	99.87%	0.79%	100.00%	95.20%	
MOBILE/100 INHABITANTS %	119.07%	25.23%	163.87%	0.00%	
GDP per capita 000	32.995	21.827	110.702	6.454	
GDP US$ million	1,389,110	3,083,791	17,900,989	26,373	51,397,088

Source: Own elaboration on World Bank, European Commission, and national data.

4.2 Method

We use Data Envelopment Analysis (DEA), which objective is to measure the efficiency of resource utilization in different organizations and technologies in use, to yield a measure to evaluate performance, for every decision-making unit (countries) with the resources assigned to it, that is, devoted to “smartize” the grid (Charnes et al. 1978). DEA employs mathematical programming to evaluate the relative efficiency of decision-making units (Banker, et al., 1984). Lacking any characterization of the underlying technology, DEA method determines relative efficiency of each decision-making unit, by reference to rankings of the observed results (Charnes et al. 1978). Because individual inputs and outputs need to be suitably and meaningfully aggregated, in the absence of market prices, which are the natural weights, DEA endogenously generates weights which are implicit “shadow prices” of inputs and outputs for aggregation.

A DEA model evaluates the efficiency performance of *n* decision-making units (countries in this case), in the production of *s* outputs using *m* inputs. For each country, DEA solves an optimization problem seeking the optimal weights for the inputs, and for the outputs, which maximize the ratio among the weighted sum of output divided on the weighted sum of inputs (a total factor productivity measure), subject to similar ratios for every decision-making unit ≤ 1.

For *n* decision-making units ($j = 1, \ldots, n$), *s* outputs and *m* inputs the problem is:

$$Max\ \theta = \frac{\sum_{r=1}^{s} u_r\, y_{r0}}{\sum_{i=1}^{m} v_i\, x_{i0}} \tag{1}$$

Subject to:

$$\frac{\sum_{r=1}^{s} u_r\, y_{rj}}{\sum_{i=1}^{m} v_i\, x_{ij}} \leq 1; j = 1, \ldots, n \tag{2}$$

$$u_r, v_i \geq 0;$$
$$r = 1, \ldots, s;$$
$$i = 1, \ldots, m$$

Where θ is the maximum ratio for decision-making unit 0, y_r are the outputs (for $r = 1, \ldots, s$), and x_i are the inputs (for $i = 1, \ldots, m$), both outputs and inputs being positive. The u_r, $v_i \geq 0$ are the weights which solve the problem, from the data on all units, which are being used as a reference set.

The efficiency of one decision-making unit of the sample is to be rated relative to the others, distinguishing it by "*0*" in the functional (but preserving its original subscript in the constraints). This decision-making unit has the most favorable weighting allowed by the constraints (Charnes et al., 1978). An optimal $\theta^* = max\ \theta$ will always satisfy $0 \leq \theta^* \leq 1$ with optimal solution values $u_r^*, v_i^* > 0$ (Banker et al., 1984). Efficiency is defined as the score $E_r = y_r/Y_r$, where y_r is the actual output r produced by the decision-making unit under analysis, and Y_r is the maximum feasible output in the sample, obtained by the same input set, where $0 \leq E_r \leq 1$.

In the CCR Model (Charnes et al., 1978), the set of efficient decision-making units form an envelope relative to observational data from all j = 1, …, n decision-making units. Productivity and technical efficiency are equivalent only when the technology exhibits constant returns to scale (CRS), and the model yields an "overall efficiency" rating. BCC Model applies to variable returns to scale (VRS) technologies, allowing to compare the maximum average productivity attained at the most productive scale, with the average productivity at the actual productive scale to measure scale efficiency (Banker et al., 1984).

4.3 Models

We run four models, named A to D in Table 4, under CRS. Model A is the Core, without environmental variables, with four outputs and three inputs, Model B includes CONNECTIVITY as environmental, Model C incorporates instead DENSITY as environmental, and Model D uses both environmental conditions. In Models B to D, the environmental variables enter with orientation to input assumption, which seems reasonable, they are uncontrollable from the point of view of the sector, but they facilitate the accomplishment of increased levels of efficiency.

Table 4: Models

Variables	Model A CRS (CORE)	Model B CRS z IO (CONNECTIVITY)	Model C CRS z IO (DENSITY)	Model D CRS z IO (DENSITY AND CONNECTIVITY)
Outputs	CONSUMPTION	CONSUMPTION	CONSUMPTION	CONSUMPTION
	1-SAIDI	1-SAIDI	1-SAIDI	1-SAIDI
	NEWRENEWABLES	NEWRENEWABLES	NEWRENEWABLES	NEWRENEWABLES
	(1-LOSSES)	(1-LOSSES)	(1-LOSSES)	(1-LOSSES)
Inputs	NETWORK	NETWORK	NETWORK	NETWORK
	AMI	AMI	AMI	AMI
	ENERGYINTENSITY	ENERGYINTENSITY	ENERGYINTENSITY	ENERGYINTENSITY
Environmental		CONNECTIVITY	DENSITY	CONNECTIVITY
				DENSITY

Source: Own elaboration

5 Discussion of results

The Table 5 presents the results by model and the Table 6 shows the results by country, identifying the efficient decision-making units. The four models are integrated by 37 countries.

Model A permits identifying 9 countries as efficient, Model B has 20 efficient countries, Model C has 22, while Models D increase the identification to 27 countries, combining both environmental conditions. Each one of these points is linked to different aspects of getting smart grids: connectivity is a pre-condition to double way communication within the network, while density is essential for the introduction of DG.

Average efficiency is monotonically increasing from Models A to D, while standard deviation is reduced monotonically from Models A to D. Models A and C has the same minimum, while Models B and D shares a slightly high common minimum, apparently connected to the connectivity effect.

The correlation between the scores of Models A and B is 0.45, between Models A and C is 0.56, and between Models A and D is 0.32, while the correlation among Models B and C is 0.32, and among Models C and D is 0.63 (considering connectivity in both of them).

Table 5: Results by model

Statistics	**Model A CRS (Core)**	**Model B CRS z IO (connectivity)**	**Model C CRS z IO (density)**	**Model D CRS z IO (density and connectivity)**
Observations	37	37	37	37
# efficient	9	20	22	27
% efficient	24.32%	54.05%	59.46%	72.97%
Mean	0.686	0.884	0.869	0.941
Max	1.000	1.000	1.000	1.000
Min	0.227	0.320	0.227	0.320
Std. Dev.	0.223	0.170	0.210	0.137
Mean Dev.	0.325	0.192	0.241	0.145
Correlations	**Model A CRS (Core)**	**Model B CRS z IO (connectivity)**	**Model C CRS z IO (density)**	**Model D CRS z IO (density and connectivity)**
Model A CRS (Core)	1.000			
Model B CRS z IO (connectivity)	0.450	1.000		
Model C CRS z IO (density)	0.561	0.322	1.000	
Model D CRS z IO (density and connectivity)	0.323	0.692	0.632	1.000

Source: Own elaboration

The Table 6 presents the results by country. The order is decreasing in the table following the mean score of the four models. Only nine countries are consistently efficiency in all models: Cyprus, Japan, Denmark, Germany, Lithuania, Luxembourg, the United Kingdom, the United States and Belgium.

Table 7: Results by country

Country	**Model A CRS (Core)**	**Model B CRS z IO (connectivity)**	**Model C CRS z IO (density)**	**Model D CRS z IO (density and connectivity)**	**Average**
Cyprus	1.000	1.000	1.000	1.000	1.000
Japan	1.000	1.000	1.000	1.000	1.000
Denmark	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000	1.000
Lithuania	1.000	1.000	1.000	1.000	1.000
Luxembourg	1.000	1.000	1.000	1.000	1.000
United Kingdom	1.000	1.000	1.000	1.000	1.000

United States	1.000	1.000	1.000	1.000	1.000
Belgium	1.000	1.000	1.000	1.000	1.000
Austria	0.885	1.000	1.000	1.000	0.971
Czech Republic	0.779	1.000	0.959	1.000	0.935
Slovak Republic	0.688	1.000	1.000	1.000	0.922
Hungary	0.663	1.000	1.000	1.000	0.916
Colombia	0.619	1.000	1.000	1.000	0.905
Brazil	0.572	1.000	1.000	1.000	0.893
Peru	0.530	1.000	1.000	1.000	0.883
Poland	0.560	1.000	0.900	1.000	0.865
Italy	0.695	1.000	0.695	1.000	0.848
France	0.847	0.847	0.847	0.847	0.847
Argentina	0.382	0.997	1.000	1.000	0.845
Canada	0.680	0.680	1.000	1.000	0.840
Australia	0.630	0.719	1.000	1.000	0.837
Latvia	0.551	1.000	0.746	1.000	0.824
Romania	0.486	0.796	1.000	1.000	0.821
Finland	0.502	0.709	1.000	1.000	0.803
Sweden	0.560	0.616	1.000	1.000	0.794
Mexico	0.532	0.931	0.743	0.931	0.784
Croatia	0.583	0.951	0.583	0.951	0.767
New Zealand	0.507	0.546	1.000	1.000	0.763
Chile	0.499	0.815	0.846	0.864	0.756
Spain	0.606	0.747	0.755	0.829	0.734
Greece	0.719	0.737	0.719	0.737	0.728
Slovenia	0.487	0.947	0.487	0.947	0.717
Netherlands	0.698	0.698	0.698	0.698	0.698
Portugal	0.644	0.659	0.691	0.691	0.671
Bulgaria	0.239	1.000	0.239	1.000	0.619
Estonia	0.227	0.320	0.227	0.320	0.273

Source: Own elaboration.

The results at the country level must be analyzed on a case-by-case basis, which exceeds the objectives of this work. For example, among the countries with efficiency levels less than one, we can mention the cases of Argentina and France. For model A, Argentina has a low score given mainly by its low renewables penetration rate and poor service quality. The inefficiency of France is probably linked with its high share of nuclear energy (clean energy in terms of carbon emissions), that our model does not capture it. In the same vein we can make a comparison among Portugal and the Netherlands. Although they display similar efficiency performance, their supply energy matrix really differs. While Portugal has almost 20 percent of new renewables generation, in the Netherlands still predominates traditional non-renewables sources. Thus, the lack of more precise environmental variables related with GHG emissions could introduce difference in their countries' performance, which are not captured here, and should be also addressed.

6 Conclusion

The electricity sector is undergoing a process of large-scale technological change, which affects its production function. These changes challenge the criteria for analysis to study the relative performance of the electricity sector. In this sense, our study aims to generate discussion about the reference model to evaluate the operation of the electricity sector between countries. For this, the set of products and inputs is discussed in a context where energy efficiency, the introduction of non-conventional renewable energy, the reduction of carbon emissions, the reduction of long-term supply costs and the quality of services are unavoidable ingredients.

To illustrate the operation of a new analytical model for the electricity sector, information was collected on outputs, inputs, and environmental conditions (old and new), and a database was built to allow an exercise on efficiency frontiers. The results of this exercise should be thought of as a first attempt to operationalize a modern production frontier. Thus, our results show the efficiency levels of those countries whose objective is to deliver electricity with high levels of quality of services and at the same time with fewer carbon emissions and low cost of supply.

The limitations of the results are mainly based on two aspects: i) the quality of the information, and ii) the scarcity of information on some key variables. Unfortunately, these aspects appear as constraints in searching for alternative production frontiers, such as the consideration of distributed generation.

Our results allow us to analyze the role of two environmental variables: the connectivity of the internet and the density of the networks. Beyond the discussion about pertinent environmental variables for adequate efficiency results, our exercise allowed estimating significant changes in the average efficiency levels for the electricity sector.

Appendix

Table A1: Renewable energy sources

Source (main costs)	Technology description	Advantages	Disadvantages	Contracts' provisions
Solar. (equipment and installation)	Photovoltaics (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 and work effectively for years, they are 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 should be used.	Contracts can include capacity payments if the facilities deliver consistently on-peak energy. Dispatching provisions should be avoided since the operator has limited control on 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 at the "rated wind speed" is about 1.5 times the site average wind speed. Generated energy is proportional to the wind speed cube.	Although wind speed varies over time, it follows daily and seasonal predictable patterns that can be tracked through mathematical models. The wind turbines can operate with fossil-fueled engines in hybrid systems. Wind power plants use no fuel, emit no pollutants, and consume no other exhaustible resources.	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 energy loss. A well-designed wind farm can reduce mutual interference losses. Wind plants generate noise and can be visually intrusive. They also can disturb wildlife.	Contracts 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 for a hydropower plant 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 offers a slow rate of change from day to day.	Contracts covering peaking hydro-units, output should include high capacity payments and relatively low energy payments. In run-of-the-river projects, capacity payments can be tied to audits of the facility, or to on-peak deliveries.
Geothermal (High initial investments, low operating costs)	Natural heat from within the Earth, is captured for producing electricity, 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.	The heat emanating from the Earth is available for power 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. The best sources are situated in volcanic areas.	The thermal energy of the Earth is very dispersed, and often at deep depths. Going from the surface of the Earth towards the core, the temperature progressively increases with depth by 3°C, on average, every 100 meters. This is called the geothermal gradient.	The power contract should include substantial capacity payments and low energy payments, reflecting the typical cost structure of these projects. 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 from biological origin from agriculture, forestry and related industries, industrial and municipal waste* (According EC). They convert biofuels in energy by direct combustion, anaerobic digestion, gasification, or fermentation and can be	Bioenergy technologies yield "bio-fuels" for transport, "bio-heat" or "bio-electricity." Biofuels can significantly reduce emissions by comparison to other fuels. Since growing biomass absorbs carbon in similar amount to that emitted when it is combusted,	The majority of biomass for bioenergy is solid unprocessed plant material, with around 50 percent of moisture content. The energy content of plant materials increases with the wood density and decreases linearly with moisture content. Since biofuels have relatively low energy	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

	burned with similar equipment as conventional generation.	bioenergy systems can produce energy with no net emissions of carbon dioxide. Waste undergoes decomposition.	content per ton, facilities must be sited close to source to minimize transportation costs.	including a fee to dispose of biomass waste.

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

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