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Smart Grids:
Technologies and Project Assessment

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Vienna, April 18th, 2017

Affidavit

I, **José David Alvarez Privado**, hereby declare

1. that I am the sole author of the present Master's Thesis, "Smart Electric Grids: Technologies and Project Assessment", 71 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

In the last few years, smart grids technologies have been deployed in electricity networks through national and regional initiatives, worldwide. Currently, a smart grid body of knowledge is being built around the outcomes of projects sponsored by these initiatives. Now, the impacts and benefits of demonstration projects might be measured and decision makers are able to evaluate the possibility to deploy those types of technologies on a large scale.

This thesis reviews the smart grid technologies deployed on electricity networks of two important regions: U.S. and Europe; and it condenses the principal statistics around smart grids investments in those two regions. It gives an introduction of smart grid architecture model (SGAM), which is used to analyze the smart grid systems in technology-neutral manner.

In smart grid systems, information and communication technologies will become the central nervous system of the power network. Due to this situation, cybersecurity will play a significant role in the electricity grid landscape. This thesis examines the vulnerabilities present in devices and cyber assets, as well as possible threats of the network.

Another aspect which is of considerable interest in the electric sector is the evolution of electricity tariffs in smart grids. The document describes the current electricity tariff structure in Europe and how it can change due to the integration of new technology in the distribution network.

Smart grid project should be assessed quantitatively and qualitatively to determine the impact on current power systems. For this purpose, it is performed a cost-benefit analysis (CBA) on future projects. The European commission through the Joint research center elaborated a CBA methodology to evaluate smart grid projects. The asset-functionalities-benefits mapping is at the core of the methodology, and with this, projects show the economic value proposition for the customers.

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1. Introduction

The entire electricity sector is facing a digital transformation, but the electric utilities will change dramatically its operation, organization and business. Smart grids are expected to bring this digital transformation to the power system. It is planned that the implementation of smart grids will improve the efficiency, resiliency of the networks, as well as integrate more renewable energy sources and distributed generation. The following sections provide an overview of Smart Grids and their development over the years.

1.1. Background

The electric sector has change in different areas in the last 20 years. The first major change was the restructuration of the market: In the past, the supply chain of electricity in every country was handled by one utility company, from bulk electricity generation through transmission to the distribution and retailing of electricity. After 1990 the power sector in several countries, was restructured from the traditional vertically integration to a deregulated market. Now, the participants of the market own generation units and transmission infrastructure and they sell the electricity into the market. The second major change is operational with the smart grids: In 2003 took place a major black out in the north east of United States and Canada. This blackout was a systemic failure on a large scale. This event showed the need of more investment in digital technology to monitor and control the power network. In the same year Michael T. Burr coined the concept of smart grid for the first time, in reference to the implementation on a large scale of the digital technology in the power grid. Since then the concept was applied in several modernization initiatives worldwide.

Nowadays, the concept of smart grids covers not only reliability and resilience solution (as it was originally conceived), but also renewable sources integration, efficiency improvement and network efficiency, among others.

Governments and organizations started large programs and initiatives to research, developed, demonstrate and deploy smart grid in their electrical infrastructure and the results of many projects are finishing currently and now the results are being analyzed by the stakeholder worldwide and the compiled information will help decision makers to reproduced in a large scale smart grids.

According to the International Trade administration of the U.S. department of commerce, the estimated disbursement in modernization of electricity assets and smart grid technologies would be between USD 15 and USD 500 billion annually worldwide (depending on which technology is applied in the forecasting). Energy research market groups estimate that spending in this area will increase from 5-18 percent each year over the next decade (ITA, 2016).

1.2. Motivation

It is important for managers in the electric sector to understand how smart grid technologies will impact their organizations and the effects of such systems in the overall performance of the network. The implementation of smart grids will affect not only the operators and the major actors of the energy sector, but also small consumers.

Once the smart grid technologies are fully implemented, the cost of such system will be transferred to the final users (industrial and household consumer). For this reason, it is essential that smart grid technologies bring the optimal benefits for society at large.

Based on the above, the present thesis should answer the following questions:

- What kinds of smart grid technologies have been deployed in the last years?
- What are the risks and opportunities of implementing such technologies in the electric infrastructure?
- Which economic tool exist to assess the implementation of smart grid projects?
- What are the key feature to be evaluated in a smart grid project?

1.3. Thesis Outline

This thesis is divided into 5 chapters, which are divided into several sub-chapters. After this introduction, chapter 2, Smart electricity grid, gives a definition of smart grids, and explain in which areas these technologies are integrated. Also, this chapter introduce the European Smart Grid Architecture Model (SGAM), the technical standards and cybersecurity applied in smart grids, as well as the network tariff structure of electricity distribution and the future development of this tariffs in the context of smart grids.

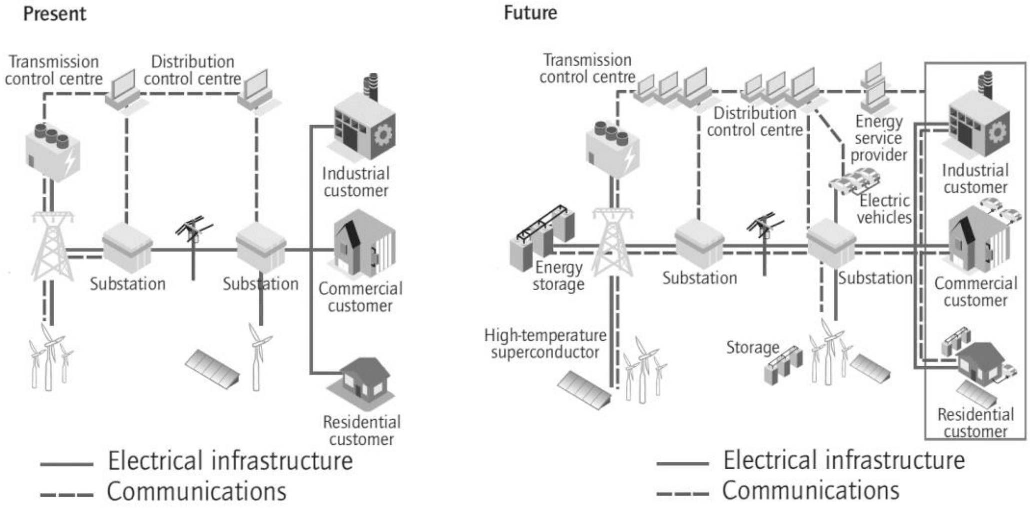
Chapter three deals with smart grids initiatives and projects. This chapter gives an overview of the motivation of these initiatives worldwide. In addition, chapter 3 shows an overview of smart grid projects in U.S. and the European Union.

Chapter four describes the assessment of smart grid projects, which is divided in two parts: Quantitative and Qualitative assessment. The quantitative assessment is performed by using cost-benefit analysis. The cost benefit analysis for Smart Grids was developed by the European Commission Joint Research Center, which is an adaptation of EPRI CBI methodology. Chapter four shows several key performance indicators that can be evaluated in the qualitative assessment. Also, this chapter gives a research plan for demonstration project. The outcomes of the research plan can be used in the quantitative assessment.

The conclusions, in chapter five, gives a summary of the findings and opportunities of smart grids are highlighted.

2. Smart Electricity Grid

The International Energy Agency (IEA) defines a smart electricity grid as: “an electricity network system that uses digital technology to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. Such grids are able to co-ordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders in such a way that they can optimise asset utilization and operation and, in the process, minimize both costs and environmental impacts while maintaining system reliability, resilience and stability.” (IEA, 2015). Additionally, the European Smart Grid Task Force defines smart electricity grids as “electricity networks that can efficiently integrate the behavior and actions of all users connected to it – generators, consumers, and those that do both – in order to ensure an economically efficient, sustainable power system with low losses and high quality and security of supply and safety” (EC-TFSG, 2011).



(a) (b)

Figure 1. Evolution of “smartness” in power systems: (a) present status of electrical networks (b) future of electric networks: smart grid (IEA, 2011).

Based on above, Smart Grids is a major transformation on how distribution system operators, transmission system operators, power plants, renewable energy sources and final users interact. As shown in Figure 1(a), the current power system has a certain level of “smartness”, especially between generation, transportation and distribution infrastructure, but overall there is a lack of “smartness” between the distribution and the final users. In smart grid, stakeholders make full use of the advantages of information and communication technologies in order to optimize the distribution of power and energy in electrical networks, without losing the quality and reliability of the services, as shown in Figure 1(b). It is important to emphasize that smart grids allow in the distribution area a stronger integration of distributed renewable resources, electric cars and storage units.

2.1. Smart grid technologies

The IEA defines at least 8 smart grid technology areas, which will deploy from power generation, through transmission and distribution grid to industrial, commercial and residential consumer. In the following section briefly summarize these technologies based on the technology roadmap for smart grid elaborated by IEA (IEA, 2011).

2.1.1 Wide area monitoring and control

Provides a real-time assessment of the power system stability and performance, particularly to supervise important interconnections, over large geographic areas. With these systems, the electric utilities can better understand the behavior and constraints of the electrical network (dos Santos, et al., 2015, p. 4). The type of hardware to be used includes: phasor measurement units (PMU), phasor data concentrators (PDC), global positioning System GPS, and sensor devices. The type of systems and software to implement implemented are: Supervisory control and data acquisition (SCADA) and WAMS-related technologies.

2.1.2 Information and technology Integration

This technology area integrates the fundamental communication technology to be adopted through the whole power system infrastructure, which uses the private utility communication networks (radio networks, meter mesh networks) and also provided by telecommunications companies (Internet, cellular, cable or telephone) in order to support data transmission and real-time operation. This area also includes the computing and control system software, as well as enterprise resource planning software (EPR). this kind of technology allows the two-way communication between stakeholders. Hardware to be used: Communication devices, routers, relays, switches, gateways and servers. Type of systems and software to be implemented: enterprise resource planning (ERP) and customer information system (CIS).

2.1.3 Renewable and distributed generation integration

Smart grid technology can help to integrate the distributed and renewable energy sources in the low (DER and RES), medium and high voltage network. Transmission system operators and distribution system operators can use automation and control of these sources in order to balance the electric network. The hardware used in this area can be: communication and control equipment for generation and storage units. Software and System to be implemented: Energy Management System (EMS); Distribution Management System (DMS), SCADA, geographic information system (GIS).

2.1.4 Transmission enhancement application

By using these technologies, the transmission system can enhance the controllability, maximize power transfer capability, decrease losses and optimise the utilization of transmission assets. Hardware to be used: flexible AC transmission systems (FACTS), high voltage DC (HVDC) equipment, sensors for Dynamic line rating, High temperature superconductors. Software and System to be used: Network stability analysis, automatic recovery system.

2.1.5 Distribution grid management

The advance distribution grid management includes automation process in real-time from sensors and meters. This equipment detects fault locations, reconfigures feeders automatically, optimizes reactive power and voltage levels and controls distributed generation in the distribution network. Hardware to be used: Automated re-closers, switches and capacitors, remote controlled distributed generation and storage, transformer sensors, wire and cable sensors. Software and systems to be used: GIS, DMS, outage management system (OMS), workforce management system (WMS).

2.1.6 Advanced metering infrastructure

It involves the application of several technologies that permit two-way data transfer, allowing final users and electric utilities information of electric energy prices and consumption. Hardware to be used: smart electric meter, in-home control panels, servers, relays. Software and systems to be used: meter data management system.

2.1.7 Electric vehicle charging infrastructure

In this area, smart grid technologies allow customers to handle billing, scheduling and other aspects for grid-to-vehicle charging. The charging station infrastructure are expected to provide ancillary services and capacity reserve to the grid. Hardware to be used: charging infrastructure, batteries and inverters. Software and systems to be used: energy billing, grid to vehicle charging and discharging methodologies.

2.1.8 Customer-side systems

These systems are designed to manage energy consumption at industrial facilities, commercial and residential users. Using these technologies, peak electric demand can be reduced, as well as improvement in energy efficiency and application of demand response in different voltage levels. Hardware to be used: Internet of thigs home products (IoT), routers, in-home displays, building automation systems, thermal accumulators, smart thermostats. Software and systems to be used: industry, commercial and home energy management systems, energy dashboards, energy apps for mobile devices.

2.2. Smart grid architecture model

The deployment of Smart Grid demands that several and different organizations and entities are involved. These entities have different roles and vision on the realization of Smart Grid e.g. regulator, manufacturer, service provider. Due to all this, it is important to have a common guidance and framework for organizations for comparability of different activities, and with this show capabilities and possible optimization potential.

In order to create a reference model for the analysis and visualization of smart grid requirement (use cases) in a technology-neutral way, the CEN-CENELEC-ETSI Smart Grid Coordination Group, with the mandate of the European Commission, creates the Smart Grid Architecture Model (SGAM). The model can be used to analyze potential implementations, to stablish a consensus between stakeholders, to anticipate the sphere of Smart Grid projects, and also to handle smart grids complexity. A

Use case describe a goal which is set by a player with a system of interest. The way on how a player reach the goal is determined in several steps, and that include information about the other players and the communication between them (Trefke, et al., 2013, p. 1)

It is important to clarify that SGAM does not try to model the power system in the process zone and does not try to change specifications on safety rules or operational requirements (CEN-CENELEC-ETSI, 2014).

2.2.1 SGAM plane: domains and zones

The basis of SGAM is the Smart Grid Plane, as shown in Figure 2. This plane has two dimensions: physical domain and the hierarchical zones. The domain axis represents the physical part of the power system and the zone axis the vertical levels of the power system management. A detailed description of domains and zones, follows bellow (CEN-CENELEC-ETSI, 2014).

- **Generation domain:** represents the conventional electric generation usually connected in high voltage, such as combustion engine for power generation, nuclear power plants, hydro power plants, off shore wind farms, photovoltaic power plants.
- **Transmission domain:** This domain represents the whole infrastructure, which is used to transport the energy over long distance.

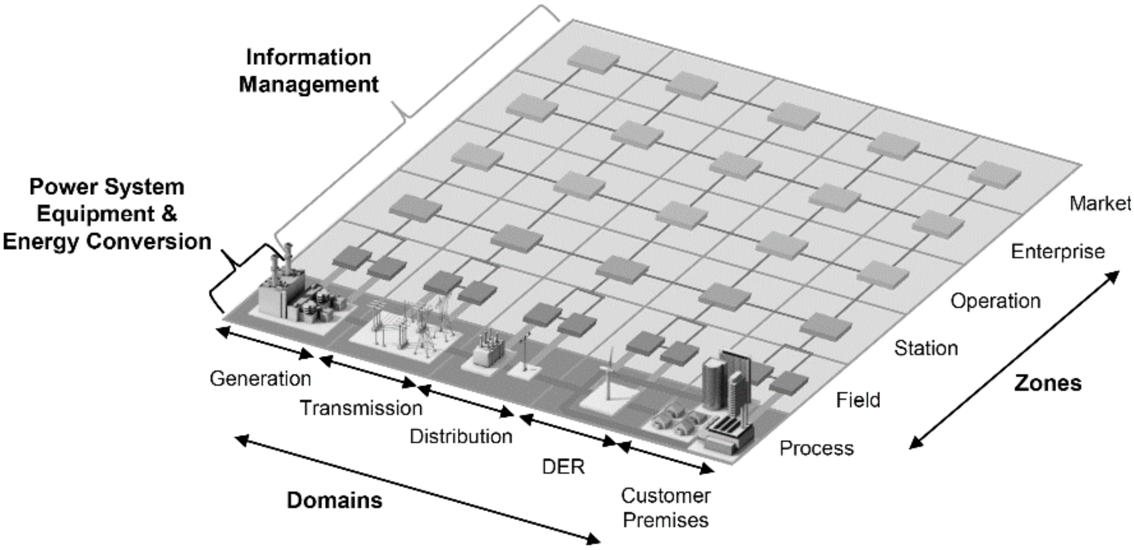


Figure 2. Smart Grid Plane (CEN-CENELEC-ETSI, 2014)

- **Distribution domain:** represents the equipment, that is to distribute electricity to end users.
- **DER domain:** stands for Distributed Energy Resource. This domain includes all the power plants connected directly to the distribution grid the main purpose of this entities is to generate electricity.
- **Customer premises domain:** includes end users and local producers (home, industrial and commercial users/producers) connected to the distribution grid. The main business objective of this kind of producers are not to inject electricity to the grid.
- **Process zone:** includes the physical transformation (kinetic, thermal, chemical transformation) and the equipment connected directly to the power grid (power units, transformers, transformers, power lines, and other electric equipment)
- **Field zone:** the equipment used to protect, control and monitor the process of power system is included in this zone.
- **Station zone:** data aggregation and spatial aggregation for field level is considered in this zone.
- **Operation zone:** This zone includes the control operation of the power system (e.g. DMS, EMS, microgrid management systems, VPP management systems, EV fleet charging management system).

- **Enterprise zone:** commercial and organizational process, as well as services and infrastructure for entities are included in this zone.
- **Market zone:** shows the market operation allowed by the regulation in the power gird. Energy trading and retail market are examples of the market zone.

2.2.2 SGAM interoperability layers

SGAM is also composed of 5 layers, as shown in Figure 3. These layers represent interoperability between: business objectives, functions and services, information exchange and models, communication protocols and components.

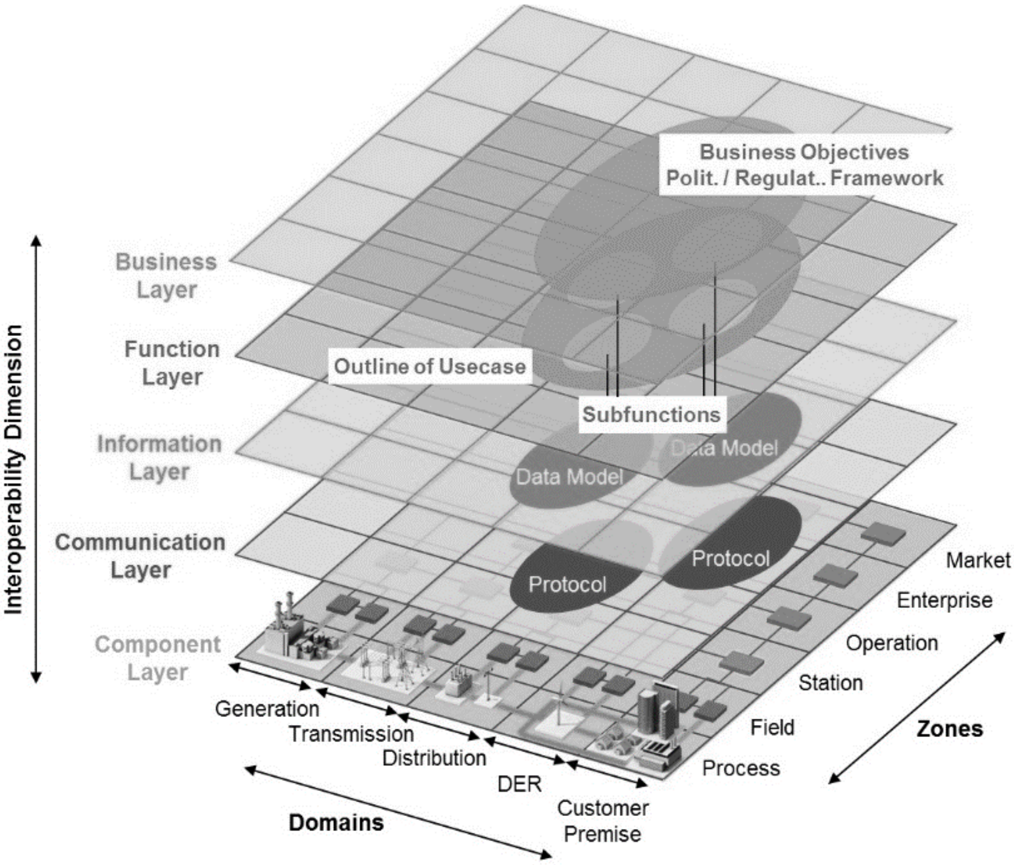


Figure 3. Three-dimensional Smart Grid Architecture: domains/zones/interoperability layers (CEN-CENELEC-ETSI, 2014).

These layers include the whole SGAM plane. The interoperability layers are (CEN-CENELEC-ETSI, 2014):

- **Component layer:** represents the physical components of the smart grid system. This includes computers, network infrastructure, protection and control equipment, electric power equipment, and any kind of system and device actors.
- **Communication layer:** describes the protocols to exchange information between the smart grid components.
- **Information layer:** defines the information used between functions, services and components. It contains information objects and canonical data models.
- **Function layer:** this layer describes system use cases, functions and services from the point of view of the architecture.
- **Business layer:** represents the business aspects of information exchange in smart grids.

2.3. Technical standards of smart grids

The International Electrotechnical Commission has developed a large number of standards in the field of smart grid. In this collection of standards, there is a set which is considered be the backbone of the smart grids. These set of standards are described in the following sections (CENELEC-ETSI-CEN, 2014).

2.3.1 IEC 61850 Communication network and systems in substations

The standard contains the communication requirements for a power substation, and it is structured as follows (IEC, 2010):

- Object oriented data model.
- The model contains the representation of equipment and functions in a power substation.
- Different methods of communication e.g. reporting, logging, control of switches, control of functions, polling.
- Generic Object Oriented Substation Event (GOOSE) messages,
- Communication of sampled value.

- Communication of disturbance reports.
- Communication services for sensors to relay.
- Decoupling of data model and communication services.
- De-linkage of communication service and data model from a certain communication technology.
- A common formal description code (Substation configuration Description Language).
- Interoperability between substation electrical assets.
- The standard contains a list of specifications, which includes all communication issues that may occurred inside a substation.

2.3.2 IEC 61970 & 61968 - EMS/DMS app. interface and Integration

The IEC 61970 includes classes, semantic information, services and data exchange for energy management system applications. This standard also has two important parts (IEC, 2010):

- IEC 61970-401 Component interface specification network: This part defines a interface that can be used by electrical equipment and its applications.
- IEC 61970-402 Common services. This part of the standard includes common services like: Resource identification and description, as well as classification.

The main applications of the IEC 61968 can be found in following smart grid components: Distribution management System, Distribution Energy Resources, Advance Metering Infrastructure and Demand Response. In this context, the applicable sections are: Part 1 – Interface architecture and general requirements, Part 3 – Interface for network operations, Part 4 – Interfaces for records and asset management, Part 8 - Interface Standard for Customer Support. Part 9 Interfaces for meter reading and control, Part 11 – Information extensions for distribution, Part 13 Common Information Model RDF Model exchange format for distribution.

The IEC 61968 has the objective to achieve inter-application integration of distributed software application systems, which support the management of electricity grids.

2.3.3 IEC 62325 & 62056 - Energy market communication and metering

The guidelines of the IEC 62325 are applicable for e-business in energy markets, which provide (IEC, 2010):

- An explanation of the electric energy market scenery.
- Description of electric energy market specifications for electronic business.
- One case of the electric energy market composition.
- An overview of modelling methodology.
- Examples of network configuration.
- A general evaluation of communication security.

On the other hand, the IEC 62056 describes electricity meter data communication, which includes data models, messaging and protocols. IEC 62056 is based on communication standards such as: Open systems Interconnection model, Abstract Syntax Notation One, High Level Data Link Control, Internet RFC, NIST's Federal Information Processing Standards.

2.3.4 IEC 62351 & 61508 - communication security and Functional Safety

The main application of the IEC 62351 can be found in the following smart grid components: Energy Management Systems, Distribution Management System, DA, SA, Distributed energy resources, Advance Metering Infrastructure, Demand Response, Smart Home, Storage, and Electric Vehicle (IEC, 2010). The objective of the IEC 62351 is to specify security standards for communication protocol in power system operations, and the enhancement of communications networks in the electric power systems.

By contrast, The IEC 61508 describes the requirement for securing that electrical systems are designed, implemented, operated and maintained to give the necessary safety integrity level. This standard is useful for equipment under control and control system and It includes the whole safety life cycle. The origin of this standard comes from the process control industry (Sato, et al., 2015).

The main difference between safety and security is that safety is protection against casual events that are undesirable. On the other hand, Security is protection against planned incidents by a person or group.

2.4. Smart grid cybersecurity

In smart grids, ICT will become the backbone of the power network, and for this reason the electrical grid infrastructure will be more vulnerable to cyberattacks. Attacks against the electric grid can impact seriously the daily lives of people, for this reason it is important to take action that will help to secure the proper operation of the distribution and transmission of electricity.

2.4.1 Incidents on Smart Grids

There are several technological vulnerabilities and human factors that external forces can exploit. A list of possible cyberattacks on electrical grid is shown in Table 1.

There are several documented incidents on power grids were the security of the network has been compromised. In 2009, the US public authorities declared that cyber spies from foreign countries hacked the US power grid and installed software that could use to disturb the power supply.

Also, in 2009, an electric utility in Puerto Rico and the federal bureau of Investigation (FBI) found that smart meters were altered by former employees of the meter manufacturer and employees of the electric utility to steal electricity.

There are malicious programs that are specifically designed to attack the electric control systems like, for example: Stuxnet, Night Dragon (combination of several techniques, tools and vulnerabilities) and Duqu. (ENISA, 2012).

Targets of cyberattacks	Domains Affected*				
	GE	TR	DI	DER	CP
Delay, block or alteration of the generation process of an electric generation facility.	X				
Delay, block or alter information related to a process of bulk energy provider from obtaining production metrics.	X	X	X		
Energy market manipulation by changing smart grid information about the power demand or supply.	X	X	X	X	X
Fraudulent information about demand or supply causing automatic operations of the power system.	X	X	X	X	X
A physical and or cyber attack on a single-point-of failure smart grid component(s).	X	X	X	X	X
Technology related anger of smart grids technologies of a person or organized group of people	X	X	X	X	X
Organized crime manipulating larger sets of consumer premises smart grid components or data concentrators			X		X
The AMI being an entrance point to the smart grid network for hackers and criminals			X		X
Privacy related information in smart grid component network link used by hackers to create reputation loss of stakeholders	X	X	X	X	X

*Table 1. Target of cyberattacks. *GE: Generation; *TR: Transmission; *DI: Distribution; *CP: Customer Premise (ENISA, 2012).*

2.4.2 Smart grid vulnerability

Cyber security in smart grid must be present in the 5 domains of the SGAM, and it must be considered at all phases of the system life cycle. The vulnerabilities can be identified in any cyber asset or process, and more important now as smart grids have more entry points than traditional electricity network. Table 2 shows the list of ICT components that need to be noted as source of vulnerabilities/weakness (ENISA, 2012):

In the past, cyberattacks were more difficult to perform due to multiple layers of control or lack of interoperability among systems. With smart grids, cybercriminals may exploit a single vulnerability and harm the power network.

ICT Components	Devices and cyber assets
Operational Systems	Generators, transformers, SCADA, EMS, DMS, PLC, Substations, smart meters, as well as intelligent electrical devices (IED)
Classic IT systems	PCs, servers, mainframes, applications, databases, web sites, web services, it also includes the components of corporate infrastructure.
Communications networks and protocols	Ethernet, Wi-Fi, PRIME, DLMS/COSEM, Zigbee, 4G, DNP3, among others.
End Points	Smart meters, electric vehicles, smart phones, and other mobile devices. Taking into account both physical an logical components.

Table 2. List of vulnerable ICT components: devices and cyber assets (ENISA, 2012).

The human aspect is also a vulnerability to be evaluated. Examples of social engineering attacks can include (ENISA, 2012):

- Supplant contractors to obtain important information or sabotage systems.
- Dropping USB keys that contain malicious software
- Using phishing scams which target sensitive information.

2.4.3 Threat in smart grids

Security expert are still learning on cyber security threats due to very few experience with cyberattacks on smart grids and industrial control systems. Despite this situation, experts are developing rapidly tools and finding new vulnerabilities at all levels. A possible list of threats in smart grids are shown in Table 3.

2.4.4 Managing risks in smart grids

In the first stage of smart grids, it is expected that the whole system will be less reliable, and for this reason, it is important to analyze and manage risk. Cyber risks management is a program and supporting processes which help the company's operations to mitigate cybersecurity risks. This management should be a continuous reassessing process that includes identification of threats, management of vulnerabilities and implementation of countermeasures (ENISA, 2012).

Type	Threat
Technical	Malware, Non optimized processes, weak innovation, manipulation of device's internal electronics, physical manipulation of devices subcomponents, removable component replacement, manipulation of home devices, unauthorized firmware replacement, compromised firmware update, escalation of privileges, sensible information interception, alteration of information in transit, traffic injection, sensible information theft, credential discovery, partial denial of service, general denial of service, breakdown, propaganda, disclosure of information, disinformation
Corporate image and information management	Low quality info for decision making, damage to brand image/reputation, rumor, bad patenting policies and procedures, weak knowledge of regulations, lack of comprehensive insurance coverage, unfavorable contractual agreements
Legal, social aspects, and human ethics	Non compliance with national and international regulations, strike, sabotage, retention, faked sickness, incompetence, bribery, dishonest behavior, employee unreliability, error, illicit action, panic, epidemics, penuries
Organizational	Weak relations between management staff, weak internal controls, not respected management, procedures are not followed, Illness, Badly controlled outsourcing, low morals, labor accidents.
International relations, Politics	War, terrorism, regional conflict, ornised crime, kidnapping, government corruption, mass psychoses, group anarchy, riots
Marketing, Economical & Financial	Volatile market, Product/service boycott, unsuccessful merger/acquisition, bad product/service performance, non adapted product, unsatisfied client, bad strategic decisions, client dependence, high competition, interrupted production, negative return on investment (ROI), debt, low capital, demands of shareholders, untrustworthy financial sources, slowdown in economic growth Fraud, Insufficient resources.
Environment	Natural catastrophe, pollution, nuclear catastrophe, biological disaster, chemical disaster, radioelectric incident.

Table 3. Threat classification (ENISA, 2012).

The first step of risk assessment is the identification and classification of the most important infrastructure in the 5 dimension of the smart grids. This critical electrical infrastructure can be classified as follows:

- Assets that could trigger national or international outage and harm infrastructure.
- Assets that could affect market participants.
- Assets that could impact O&M processes of electricity grids.
- Assets that represent major risk to data privacy.
- Assets that might cause major safety issues.

2.5. Electricity distribution network tariff

Electric distribution utilities are natural monopolies, and because of that, their business activities are regulated. Regulatory authorities set the tariff levels in a specific period of time, and with this tariffs, utilities cover their costs and derive their revenues.

2.5.1 Distribution network cost

The direct cost of an electric utility company can be divided as follow (EURELECTRIC, 2013):

- **Capital Costs**: Investment in assets, depreciation and interest are included in this type of expenses.
- **O&M:** The operation and maintenance costs needed to manage the distribution grid.
- **Network losses:** it can be divided in technical and commercial losses. Just a part of these losses can be considered as cost.
- **Customer service:** electric utilities can include in this cost; metering services, invoicing, operation and maintenance, as well as administrative and commercial cost related with the customer service management.
- **Overhead costs:** Includes the corporate cost not related to the O&M of the electrical network, but related with the network service delivery.

2.5.2 Network Pricing

The grid tariff includes (EURELECTRIC, 2013):

- The regulator set up the permitted level of revenue of the DSO (grid tariff level). This comprises the operating expenditures (OPEX), depreciation, interest, as well as other costs. The revenue rate should be objective settled, to provide an adequate remuneration to utilities.

- The regulator set up the initial grid connection charge and network tariff structure. This setting determines the amount of charge to be covered by the customers who are connected and the amount to be socialized through the network tariff structure.

On one side the level of revenue affects DSO investment behavior, on the other hand network tariffs affect customer behavior (see Figure 4).

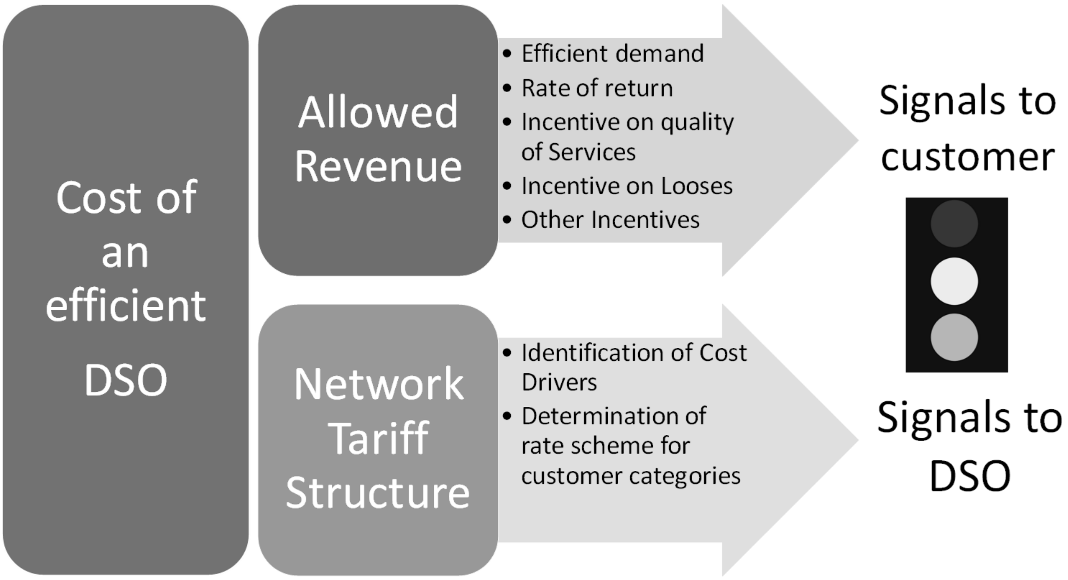


Figure 4. cost signals for DSO and customers (EURELECTRIC, 2013)

In order to have a sustainability of the electric distribution business, optimal network operation, development of the grid, as well as the protection of the consumers, the electricity regulatory authority should set the tariff based on three principles: System sustainability, Economic Efficiency and Protection (EC, 2015). The principles are:

System sustainability principles:

- **Sufficiency:** this principle states that grid tariffs should allow the grid operator to recover the efficient network costs and a reasonable return on capital.
- **Achievability and adequacy of the regulated rate of return:** the regulator should set a rate of return that guarantee a return equivalent with the relative risk of investments and financing conditions.

- **Achievability of the incentive components:** tariff network should pursue achievable goals.
- **Additivity of components:** the components of the tariff must add up to give the total expected revenue to be recovered.

Economic Efficiency Principles:

- **Productive efficiency:** the grid services should be provided at the lowest possible cost.
- **Allocative efficiency:** in the other hand, tariff should drive users to use the network in an efficient way.
- **Cost reflectiveness:** users should be charged, depending on the network services they received.

Protection Principles:

- **Transparency:** The rules and result of tariff allocations should be available for all the participants. The bills should state exactly which charge correspond to which component.
- **Nondiscrimination:** Users that belong to the same tariff level, should be charge the same.
- **Equity:** Users with lower income and located in remote areas, have lower tariff than the rest of users, which receive same network services.
- **Simplicity:** tariff allocation and rules should be easy to understand and implement.
- **Predictability:** Tariff variables should be easy to forecast.
- **Stability:** Tariff regulation should be stable, as well the tariff methodology.
- **Consistency:** regulation should comply with all the applicable law.

2.5.3 Tariff structures for Smart Grids

The capital expenditure (CAPEX) in smart grid will be higher mainly due to more DER connected in the distribution electricity network, the need of more efficient operation of the grid, as well as the new requirements of network users. DSOs should change their current tariff structure to represent properly the different nature of fixed and variable costs of the smart grid. Table 4 shows the different approach of network tariff structure:

Type of Tariff	Options
Volumetric Tariffs	• Flat (fixed price for affixed amount of energy) • Fixed (fixed price per unit of energy) • Time of Use (ToU) (price per kWh depends on time of consumption) • Event Driven (higher prices if peak occurs) • Dynamic (dynamic prices e.g. depending on wholesale prices)
Capacity Tariffs	• Flat (fixed price for a predefined capacity) • Variable (different capacity levels) • ToU (price per kW depends on time of consumption)
Two part Tariffs	• Merging of Volumetric and Capacity Tariff (e.g. ToU event driven, dynamic options possible within the energy component)
Tariff + Auxiliary service contracts	• Interruptible load tariff options (for example lower network tariffs for giving the option to control a predefined amount of load) • Others

Table 4. Tariff options in smart grid (EURELECTRIC, 2013).

Consumers will be able to supply electricity and auxiliary services to the grid. Due to this, DSOs should change the business model from traditional volume based model (revenues depends on how much electricity flows in their grids) to service business model, but this new business model needs the full support of current regulation, which is currently not in place (EURELECTRIC, 2013).

3. Smart electrical grids initiatives and projects

There are several initiatives to demonstrate and deploy smart electrical grids in different parts of the world. Each country or region is implementing smart gird projects in different ways, due to local requirements and conditions. Therefore, it is anticipated that different priorities, technologies and approaches will be applied for each territory (Gianinoni, et al., 2014).

3.1. Drivers and technologies for smart grid implementation

In 2014, the International Smart Grid Action Network (ISGAN) conducted a survey in 22 countries regarding the main drivers that push the countries to invest in smart grid solutions. The key findings are shown in *Figure 5*.

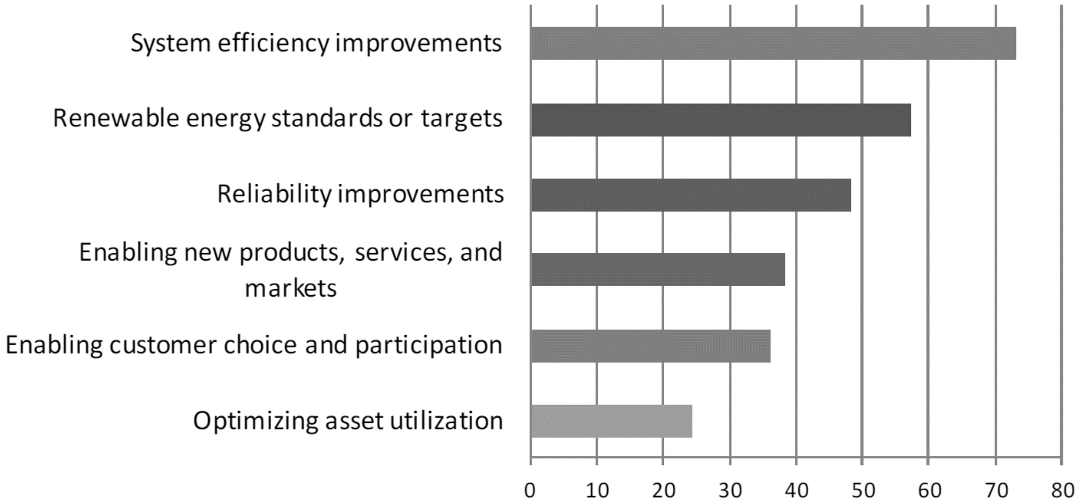
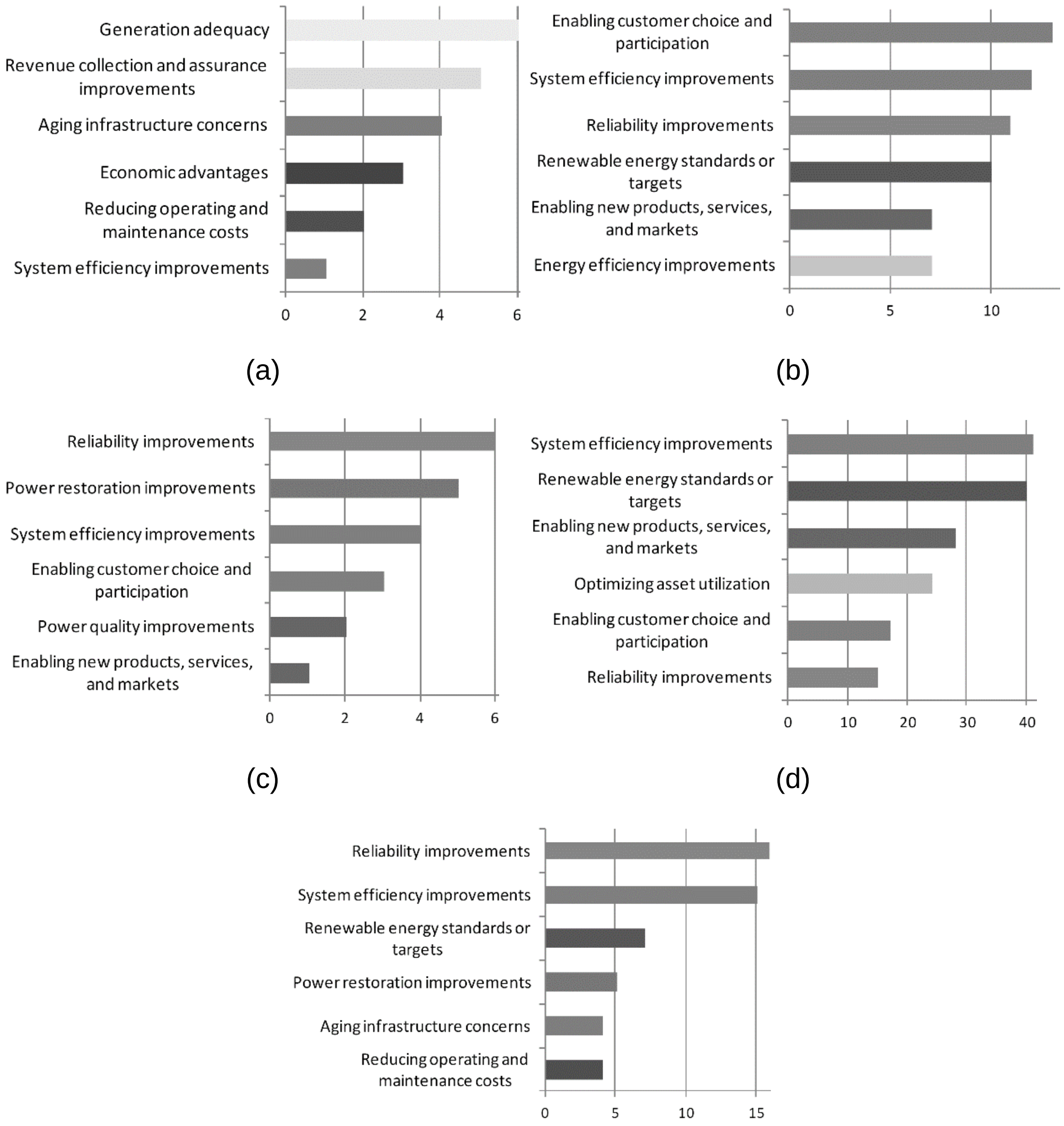


Figure 5. Smart grid motivation drivers worldwide. (ISGAN, 2014)

Overall, the 3 most important drivers of smart grid implementation are: 1) Network efficiency improvements 2) Renewable energy targets 3) Grid reliability improvements. However, in a regional context, the motivation deploys smart grid solution change. Figure 6 shows the results by region. It can clearly be seen that the priorities to deploy smart grids in Europe are completely different than in Africa (see Figure 6 (a) and (d)).



(a) (b)

(c) (d)

(e)

Figure 6. Smart grid motivation drivers – by region. (a) Africa. (b) Asia. (c) Australia (d) Europe (e) North America (ISGAN, 2014).

In Europe, the participants of the survey considered that smart electrical grid is an important tool to improve efficiency in the electrical grid, integrate renewable energy sources and enable markets, products, and services. This is primarily due to the European Union 2020 energy strategy: 20% reduction in greenhouse gas (GHG) emissions, 20% of EU energy from renewable energy sources and 20% improvement in energy efficiency.

On the other hand, in Africa the participants expressed that smart electrical grids could help on generation adequacy problems, revenue collection and assurance, as well as monitor the aging infrastructure. The reason for this can be that electrical infrastructure in Africa is not so robust, high losses in the commercial side and issues in the maintenance management of the electric utilities in that region.

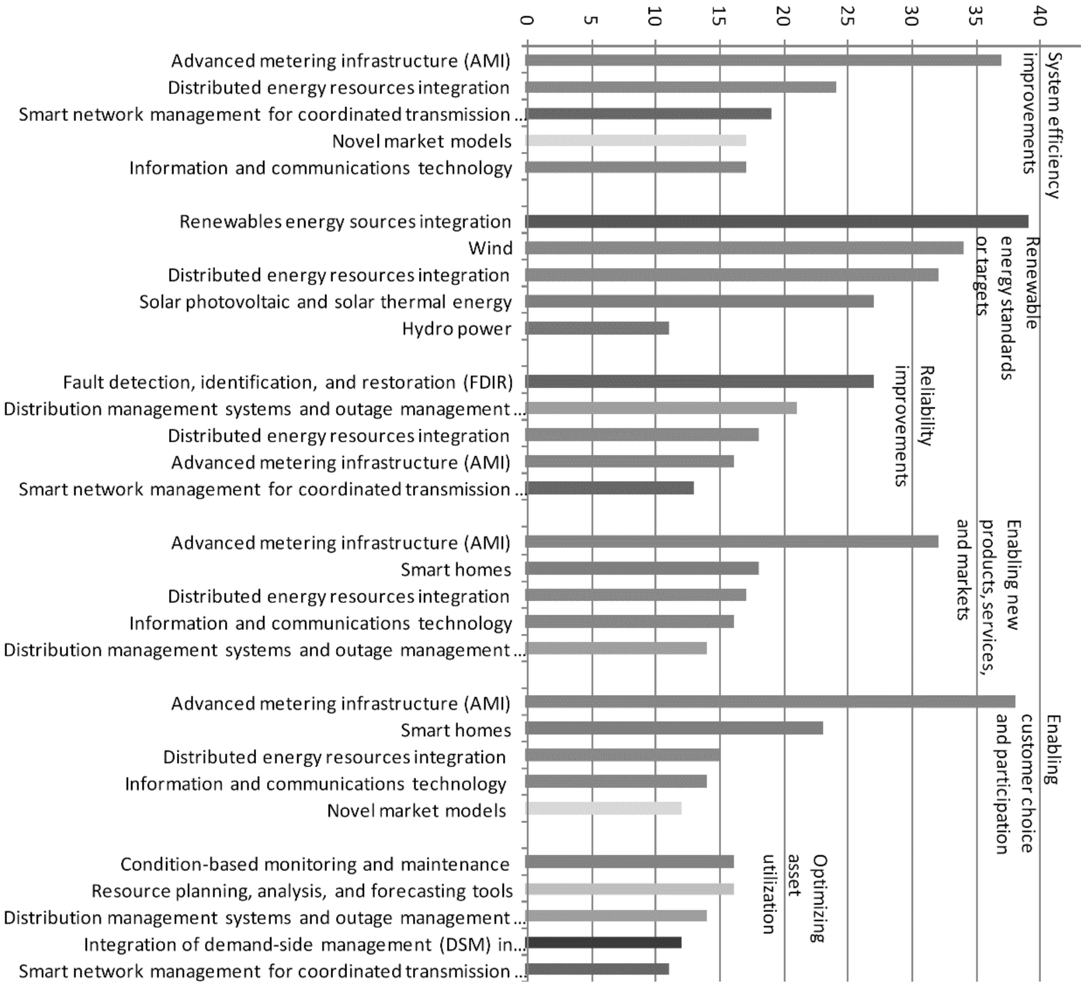


Figure 7. Smart grid technologies for each 6 ranked drivers (ISGAN, 2014).

The Figure 7 shows the top 5 most ranked technologies to support each 6 ranked drivers. As can be seen from this figure, the Advanced Metering Infrastructure (AMI) is the most highly valued technology to be deploy in the smart grid infrastructure, followed by DER, RES integration, smart network management.

3.2. Smart grid projects in the U.S.A.

The institution responsible for leading the electric network transformation is the Office of Electricity Delivery and Energy Reliability which is part of the Department of Energy (DOE-OE). The Smart Grid Investment Grant (SGIG) program was the implementation scheme to deploy the smart grid technology in the power system of the U.S. This program concluded in the 4th quarter of 2015 and their conclusions and major findings were reported in December 2016. The SGIG was applied in the infrastructure in the following way (Gianinoni, et al., 2014):

- Direct investment in projects that apply smart grid technologies and systems.
- Direct benefit from smart grid projects through operation of these technologies and systems.
- Reduced uncertainty from analysis of the costs and benefit of SGIG projects

The main characteristic of the U.S. electricity system, regarding the ownership of the infrastructure, is that most part of the electric system is owned by for-profit, investor-owned utilities (Gianinoni, et al., 2014).

3.2.1 SGIG Program objectives

The Smart Grid investment grant program had the following objectives (Gianinoni, et al., 2014):

- Accelerate the application of smart grid technologies and systems over the electricity network and enable customers to get information and better administer their electricity consumption.
- Attract more investments for this type of technology due to reduction of uncertainty.
- Accelerate the application of cybersecurity for the smart electrical grid.

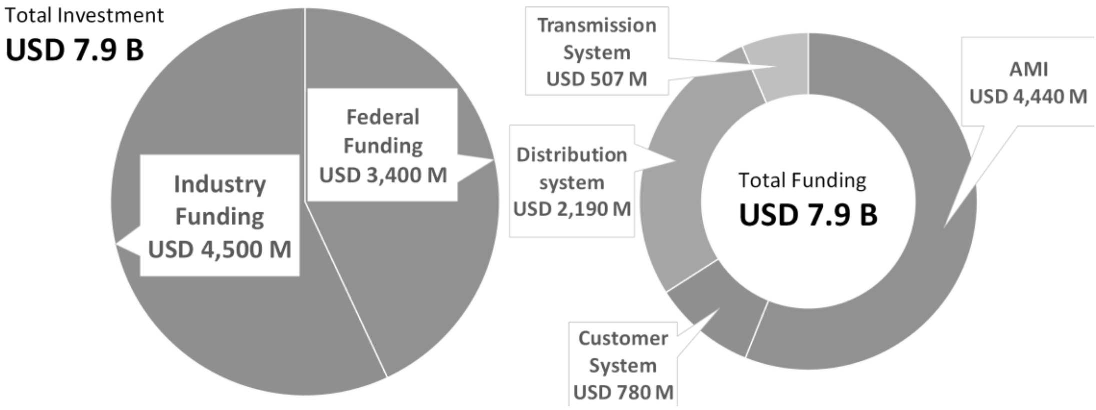
The SGIG program pursued the following improvements in the electricity network:

- power system reliability.
- reduce the peak demands, and with this improve asset utilization.
- informed final users with energy consumption.
- system operation efficiencies.
- reduce harmful environmental impact.
- Create economic opportunities for enterprises and job creation.

To achieve these objectives, DOE-OE sought that agencies, private industry and other stake holders worked together and built strong coordination and collaboration.

3.2.2 SGIG program funding

The SGIG program funded 99 selected smart grid projects with USD 3.4 billion. Also, attracted USD 4.5 billion of private investment, making a total of USD 7.9 billion investment in smart grid infrastructure. 228 utilities and organizations participated in this program in a 6-year period (USDOE-OEDER, 2016). The breakdown of the SGIG program by technology areas can be seen in Figure 8.



(a) (b)

Figure 8. SGIG funding distribution. (a) by source (b) technology area. (USDOE-OEDER, 2016)

3.2.3 SGIG Technology Areas

The main technology areas demonstrated in the program were (USDOE-OEDER, 2016):

- **Synchrophasor technologies:** 1380 PMU installed in the U.S: transmission network to improve observability of the transmission network, also 226 phasor data concentrators. Also, by using the phasor measurement unit, grid operators improve state estimator models, dynamic planning models of the grid for better understanding of the network condition (see Figure 9)

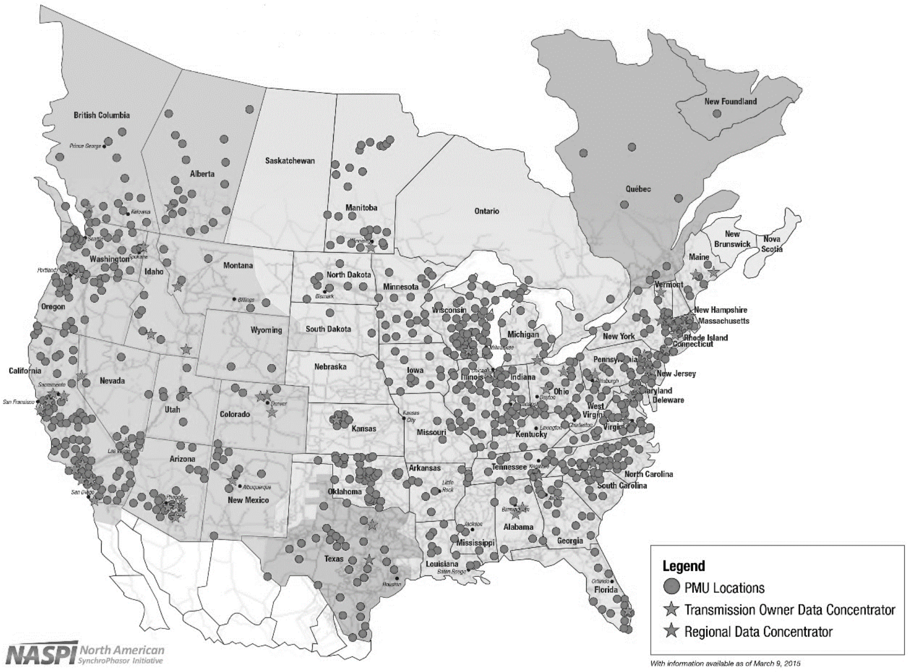
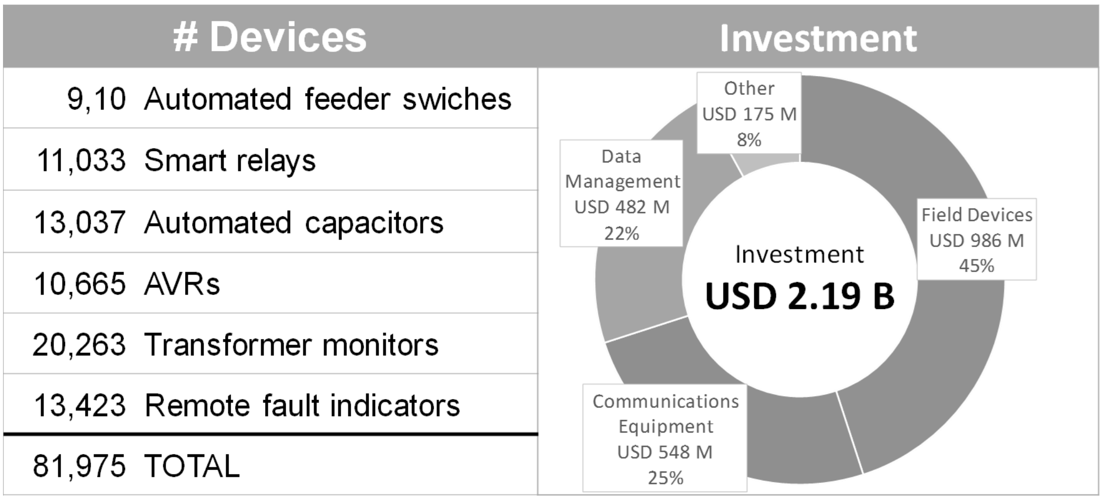


Figure 9. Location of PMUs deployed in 2015. (USDOE-OEDER, 2016)

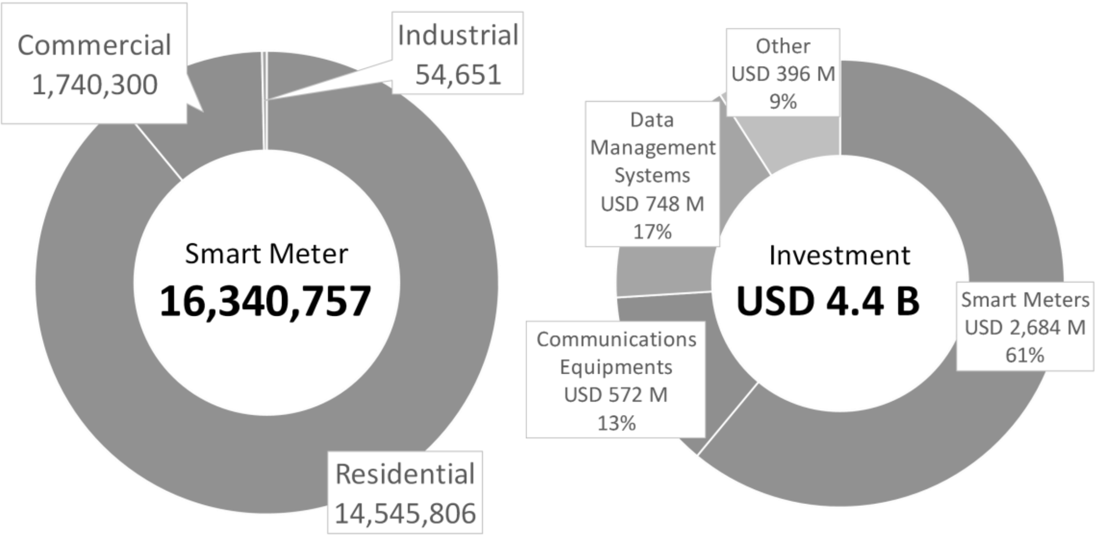
- **Distribution Automation:** during the program, near 82,000 intelligent and automated devices were installed. Due to smart gird deployment, more utilities in the U.S: are using conservation voltage reduction modules (CVR) to improve the efficiency of distribution networks, and Automated Volt/VAR controls to improve power factors. Also, by installing sensors health sensors on important equipment, the Operation and Maintenance cost were reduced. Using these sensors, the control centers can send field crews to the relevant places based on diagnostic data (See Figure 10).



# Devices	
9,10	Automated feeder swiches
11,033	Smart relays
13,037	Automated capacitors
10,665	AVRs
20,263	Transformer monitors
13,423	Remote fault indicators
81,975	TOTAL

Figure 10. SGIG distribution devices deployed and Investment breakdown (USDOE-OEDER, 2016).

- **Advanced metering infrastructure (AMI):** 16 Million Smart meters were deployed, which is 33% of the total smart meters installed in the U.S. the DSO improved billing precision, reduce users complains and inform of strange energy usage pattern to customers. Pre-pay billing plans were implemented by utilities, also remote service connection and disconnection orders. (See Figure 11)



(a) (b)

Figure 11. SGIG AMI installed (a) distribution of smart meter installed (b) Investment breakdown (USDOE-OEDER, 2016).

- **Customer systems:** nearly 700,000 customer devices were installed in homes, which includes: direct load control devices, in-home displays, and programable communicating thermostats. The AMI and the customer systems enable the consumer behavior studies, which evaluated final user acceptance, permanence and reaction, as well different recruitment methods, and tariff structure. The type of tariff evaluated through the AMI were: critical peak and variable peak pricing (CPP and VPP), TOU and critical peak rebates (CPR). (See Figure 12)

# Devices & Systems	
413,734	Direct load control devices
262,183	Programmable communicating Thermostats
21,228	In-home display
2,379	Energy management systems
368	Smart appliances
49	Customer web portals
699,941	TOTAL

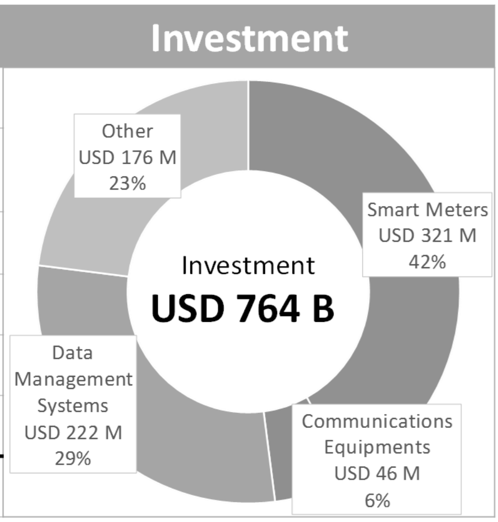


Figure 12.SGIG customer system installed (a) number devices and systems installed (b) Investment breakdown (USDOE-OEDER, 2016)

3.3. Smart grid projects in EU

The European Commission through the Joint Research Centre (JRC) classifies Smart grid projects in two main categories (maturity levels):

- **Research and experimental development (R&D) projects** are creative works which are elaborated in a systematic way. The main task of these projects is to acquire new knowledge. R&D projects can be classified in three categories: basic research, applied research and experimental development projects (EC-JRC, 2014).

Basic research project is a theoretical or experimental project that seeks to acquire new knowledge of a phenomena and observable facts. This new knowledge has no practical application in the industry (OECD, 2002).

Applied research is an original project that seeks to acquire new knowledge, but the main goal of this research is to be practical in the electricity industry (OECD, 2002).

Experimental development projects apply the knowledge gained from research and practical experiment to produce new materials, products, devices, process, system and services (OECD, 2002).

- **Demonstration / Deployment (D&D)**. Demonstration projects are designed to test the performance of technologies in different operational environments, which are used to refine the commercial offering of support systems and new products. (Brown & Hendry, 2009). Deployment Project are specific implementation of technologies, support system or application in a specific region or nationwide.

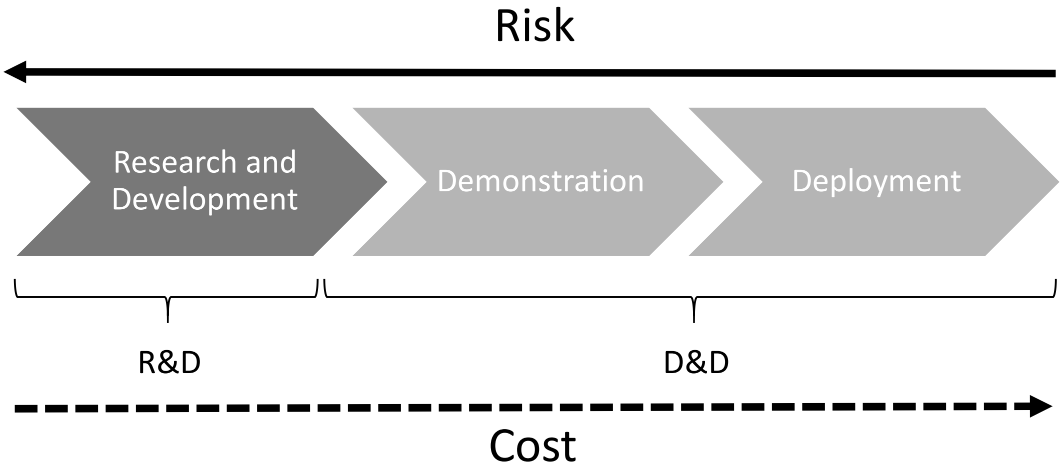


Figure 13. Risk and Cost related to the different project stages of smart grid (EC-JRC, 2014)

Figure 13 shows the relationship between risk and cost levels in different stages of the smart grid. It is possible that one smart grid project has R&D and demonstration level at the same time. Due to this, limits between project phases can be blurred.

The Smart grid projects outlook 2014 shows that Germany has the highest number of smart grid projects, followed by Denmark (Figure 14). The ratio of R&D and demonstration/deployment projects in the EU countries is in general balanced, with the exception of Denmark.

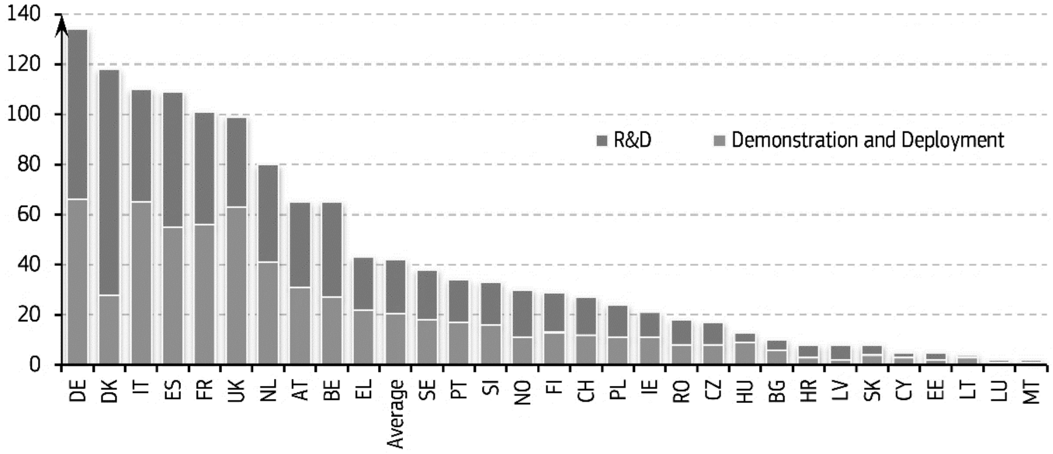


Figure 14. Number of Smart grid projects in 2014: R&D and D&D projects (EC-JRC, 2014).

3.3.1 Source of funding for smart grids in the E.U.

The main sources of funding for smart grid in the European Union are classified into five types as follows:

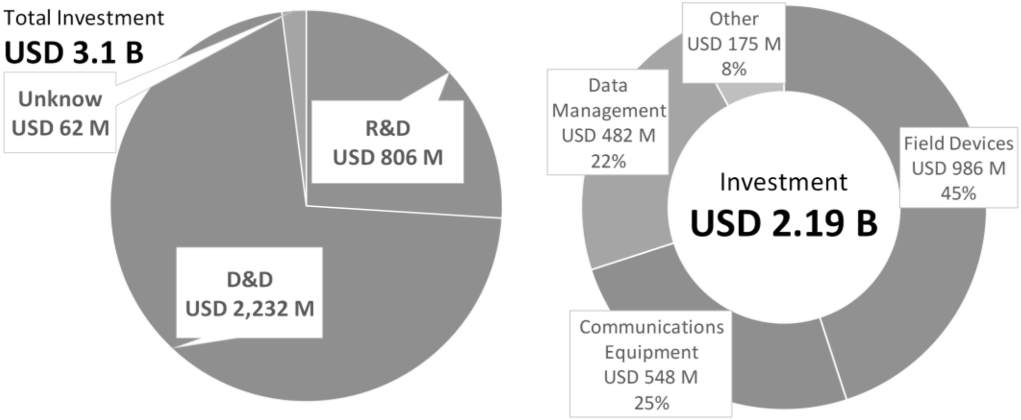
- **Private Funding**: This type of funding typically is part of the private capital of organizations, investors and/or private capital groups. Private organizations provide non-repayable funds and resources in support of R&D and D&D projects.

- **European funding:** there are different European funding and financing programs to support R&D and D&D smart grids projects, one of this programs is the European Regional Development Plan.

- **National funding:** at national level, there are several governmental Agencies that support in smart grid projects, and this support is growing every year (e.g. (climate and energy funds in Austria)

- **Regulatory funding:** This type of support is managed by regulators, which is financed from specific tariff schemes.

In 2014, the total amount of investment in smart grid projects was circa EUR 3,150 M. The source of the funding was the following: 49% was provided by private capital, 22% from European funding, 18% from national funding and 9% was provided by regulators (the rest had unclassified source). Figure 15 shows the amounts for each source of funding.



(a) (b)

Figure 15. (a) distribution of funding (b) Source of funding for smart grid projects (EC-JRC, 2014).

The EU countries with the highest total budget for smart grid projects were France and United Kingdom. In other hand Denmark, Finland and Slovakia had more money assigned to R&D projects than demo and deployment projects (See Figure 16).

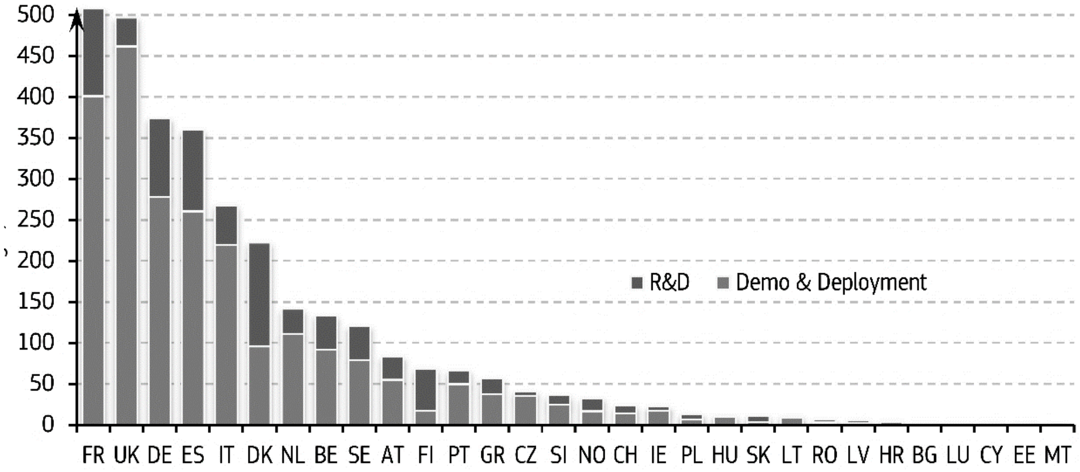


Figure 16. Budget distribution of smart grid projects in 2014: R&D and D&D projects (EC-JRC, 2014)

3.3.2 Smart grid applications in the E.U.

in the E.U., the Smart grid application technologies are divided in 7 categories, which are (EC-JRC, 2014):

- Smart network management: technologies that allow the operational flexibility of the network, like substation automation, network control and monitoring are considered in this type of technologies. The goal of smart network management systems is to improve the observability and controllability of the grids.

  The observability of the power grid can be improved with: 1) implementation of smart meters to collect and store data from customers. 2) i distribution grid monitoring. 3) asset monitoring 4) fault identification and localization.

  On the other hand, the controllability of the network can be improved with: 1) implementation of new capacities for frequency, reactive and power flow control 2) controllable substation in the distribution level, as well as inverters, smart relays, DER and load intelligent controllers. 3) auto reconfigurable networks, on line tap changer 4) dynamic line rating 5) installation of modern transformers in the distribution grid and substation, Capacitors and VAR control devices and electronic boosters to reduced losses from the network.

- Integration of large scale RES: the most important technologies considered in this area are: 1) tools for planning, control and operate RES to allow their market integration. 2) new services provided by DSOs to support TSO operation like: demand side management and ancillary services. 3) Tools to forecast RES power generation. 4) Off-shore grids for wind power plants integration.

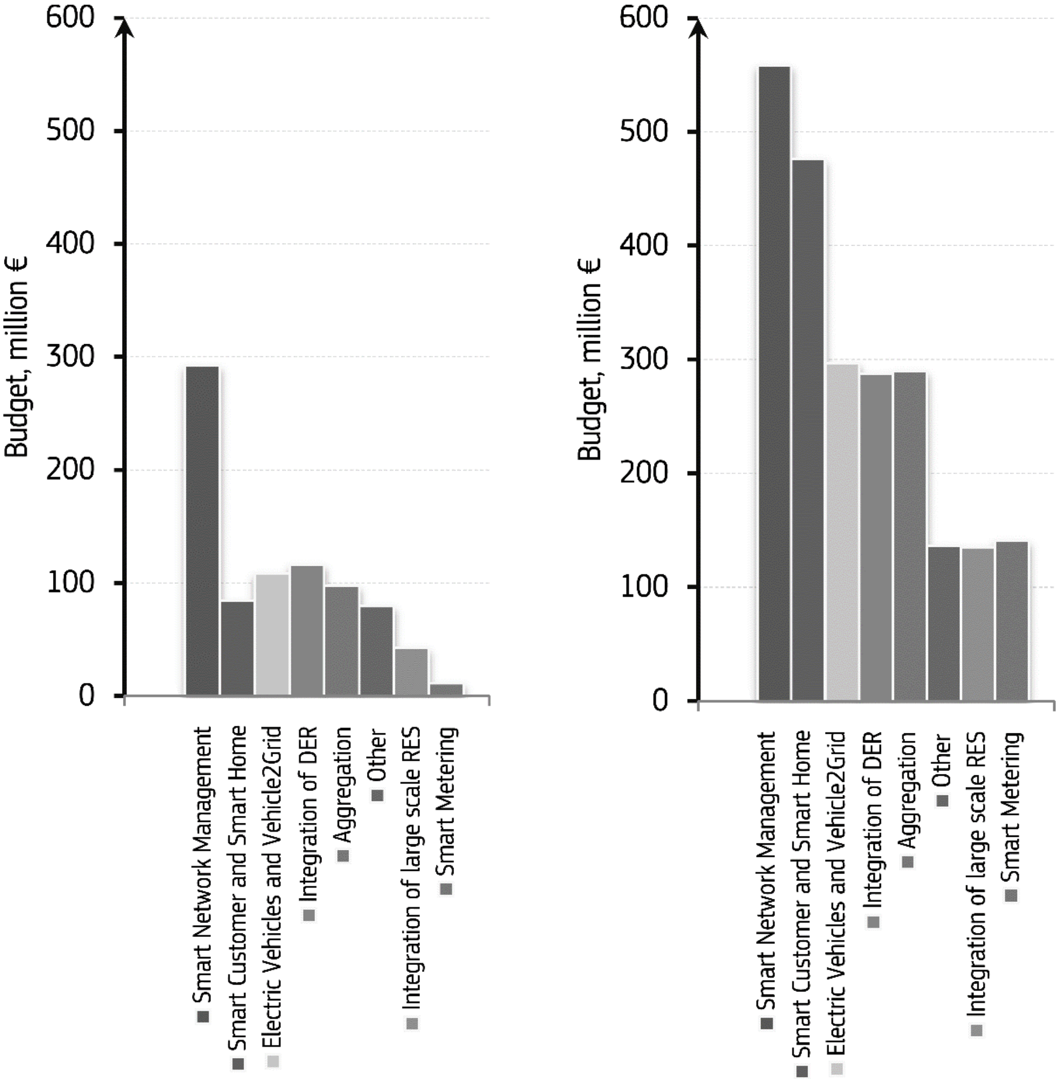
- Integration of DERs: this category includes projects with new algorithms and hardware/software that allows the integration of DERs without sacrificing the reliability and security of the power system. For example: 1) Voltage control and Reactive power control of DERs for the supply of ancillary services; 2) Forecast of DER power generation and active/reactive measurements. 3) anti-islanding protection for DER 4) Storage operation with DER for voltage and power flow control, balancing, among other operations. 5) smart grid architectures 6) Aggregation of DERs in VPPs and microgrids.

- Aggregation: The integration of DER in VPP and demand response considering constraints of the system and market signals are considered in this category of projects.

- Smart customers and Smart homes: The technologies implemented in projects that test IoT and home automation with new tariff schemes are considered in the category of smart customers and smart homes.

- Electric vehicle and Vehicle2Grid implementations: examples of this technologies includes projects that integrate electric vehicles (EV) and Plug-in Hybrid Vehicles in the grid.

- Smart metering: specifically projects with the application in smart metering with 1 or 2 extra application are included in this category.



(a) (b)

Figure 17. Investment in Smart grid per technology in the E.U. (a) R&D Projects (b) D&D Projects (EC-JRC, 2014)

The investment for each application technology is shown in Figure 17. The data was collected from smart grid projects, conducted between 2004 and 2013. It can be seen from Figure 17 that, Smart network management applications was the largest application invested by stakeholders in the E.U. The second largest investment in R&D projects was Integration of DER technology. On the other hand, Stakeholders deployed smart customer and smart home technologies as the second largest investment in D&D projects.

4. Assessment of smart grid projects

DSOs commonly invest in equipment and systems which comply the requirement of the electricity regulatory framework, and usually it is no necessary to list the economic benefits of each investment. The decision of investment is based on the cost minimization analysis.

Smart Grid projects may not comply with the utility cost-minimization argument, because can improve standards beyond currently acceptable levels, but also, smart grid applications could offer benefits beyond levels stablished by regulation. Furthermore, Smart grid technologies are the only technical solution, for example, integration of DER and electric vehicle charging stations (EPRI, 2012).

The assessment of smart grid projects through the cost-benefit analysis (CBA) is a tool for electric utilities to evaluate investment decision over a certain period of time. The cost-benefit analysis includes not only monetary considerations, but social and environmental impacts (ECommission-REGIO, 2014).

These non-monetary impacts (Qualitative analysis) are evaluated in chapter 4.4 as key performance indicators of policy goals (performance assessment), but the overall assessment can also include other type of elements, like impact on jobs along the value chain, hazard exposure, privacy and security, among others.

The CBA of smart grid projects consists in three main parts (see Figure 18):

i) Delineation of boundary conditions and set parameters.
ii) Calculation of costs and benefits
iii) Sensitivity analysis of the outcomes to judge the riskiness of the smart grid project and to assess preventive actions.

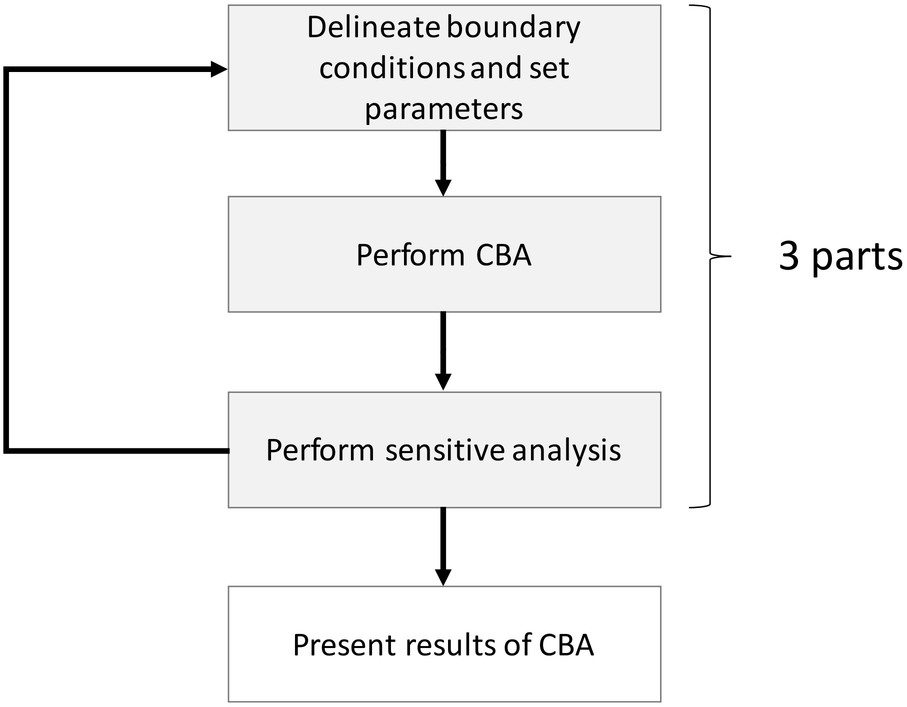


Figure 18. CBA flow chart (EC-JRC, 2012)

The main goal of the CBA is to obtain the range of parameter values for a positive outcome of the economic analysis and define actions to maintain the parameters in the correct range.

Output indicators of the CBA are: Net present Value (NPV), Internal rate of return and discounted economic benefits and costs. These indicators are defined as follows (EC-JRC, 2012):

- NPV is the sum of induvial cash flows of the smart grid project. The project needs to:
    - (-) subtract estimated costs from annual benefits
    - (-) subtract annual net benefits
    - (∑) sum up the discounted values.
- IRR of a smart grid project is a discount rate at which the NPV of cash flows equal to zero.
- B/C is the relationship between discounted benefits and costs

IRR and NPV are calculated using economic values instead of financial values.

4.1. Delineate boundary conditions and set parameters of the project

The main variables and assumption of a smart grid project depend on regional or geographical conditions, which determine the level of impact on benefit calculations. In this stage, the data sources should be reliable for making assumptions, and the level of uncertainty must be specified. The table below shows the most important parameters to be tailored:

Variables/data to be set/collected	Unit
Projected variation of energy consumption	%
Projected variation of energy prices	%
Peak load transfer	%
Electricity losses at transmission and distribution level	%
Estimated non-supplied minutes	# of minutes
Value of lost load, value of supply	€/kWh
Discount rate	%
Hardware costs	€
Life expectancy of installed systems	# of years
Installation costs	€
Carbon costs	€/ton
Inflation rate	%
Cost reduction associated with technology maturity	%
Implementation schedule	% asset deployment/year
Percentage of asset deployment in rural vs urban areas	%

Table 5. list of parameters to define in a smart grid project (EC-JRC, 2012).

The values of the parameters shown in Table 5 are estimated as follows (EC-JRC, 2012):

- **Discount rate** considers the time value of money and the risk of anticipated future cash flows. The discount rate gives the relative risks of projects. Considering this, smart grid projects have a higher risk level than conventional projects. On the other hand, smart grid benefits can appear after a long period of time.

The smart grid project may be publicly funded, due to societal value of Smart Grid investments, the impacts of this type of projects can affect several stakeholders and the society. Because of this, then public policy discount rate may be used. In Europe, the societal discount rates range from 3.5% to 5.5%, but in any case, this parameter should be always tested for sensitivity.

- **Time period of the CBA** varies according to the nature of the investment. Typically, energy infrastructure projects are appraised over a period of 20 to 30 years. The time horizon may be specified conforming to the lifetime of the most important asset. The asset with the shorter lifetime should be included as an additional cost in the economic analysis.

- **The implementation schedule** of a smart grid project has a great influence on parameter estimation of Cost Benefit Analysis. If a fast installation rate is applied, then higher net benefits are obtained. The following rule applies: when total benefits of each installation per asset exceed its costs, the sooner the installation occurs, and the NPV of the installation increase. The implementation schedule can be divided into two groups: urban and rural installation, this is because, each installation can have different installation cost (EUR or USD/asset/day).

- **The impact of the regulatory framework** affects the distribution of costs and benefits among stakeholders. Each country has its own regulatory instruments to incentive innovative projects, for this reason, it is important to specify the impact of regulation on the assumptions.

- **The macroeconomic factors** need to be considered, in order to make reliable estimates. Some of the macroeconomic factors to take into consideration are: inflation rate and carbon costs.

- **Implemented technologies**. The outcome of the CBA is directly affected by design parameters, smart grid architecture and technology. It is also important to consider in this part, the cost reduction derived from technology maturity.

- **Peak load transfer and consumption reduction**. Peak load can be shifted from high demand period to low demand period, and with this reduce up to 30% of peak load. This parameter is important to consider in the electricity demand.

- **Electricity demand** depends on the development of population growth, rate of domestic and non-domestic consumption, network losses, as well as electricity prices. These parameters have a large impact on the CBA results, because of this it is recommended to perform a sensitivity analysis on electricity demand and electricity prices.

4.2. Cost-benefit analysis

The Joint Research Center of the European Commission (JRC-EC) proposes 7 steps to perform the cost benefit analysis for smart grids projects (see Figure 19). After obtaining the results of the CBA methodology, a sensitivity analysis is performed.

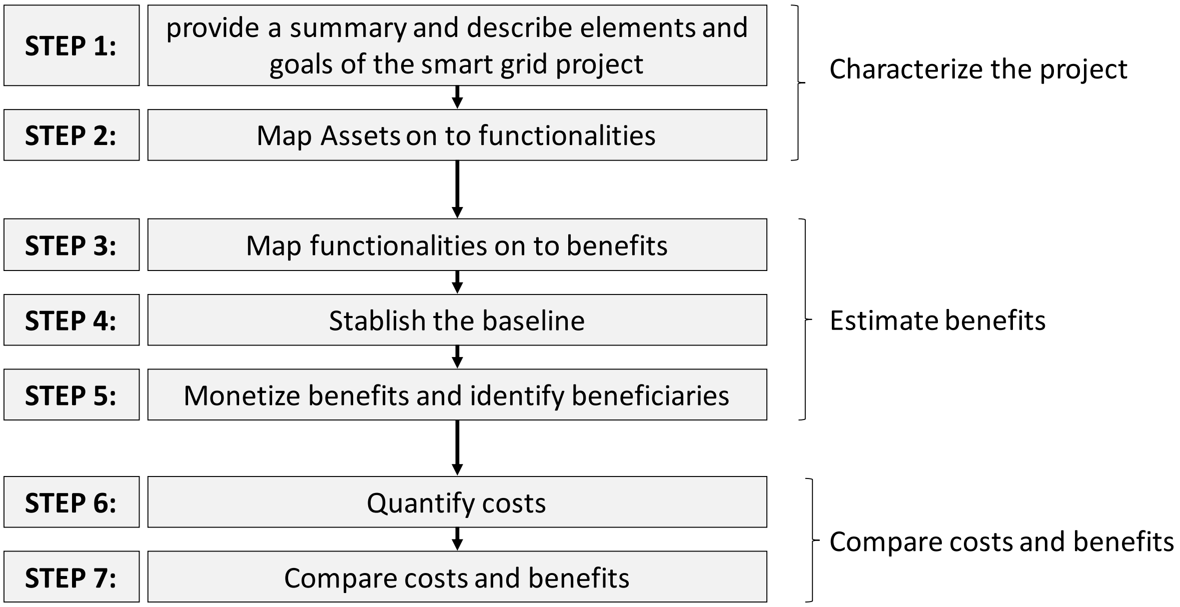


Figure 19. Cost benefit methodology for Smart Grid projects (EC-JRC, 2012)

The CBA methodology propose to estimate the benefits from assets functionalities. These functionalities are general capabilities of the Smart Grid and not the strong technical dimension of the asset itself (e.g. overcurrent protection, thermal overload protection) (EC-JRC, 2012). The mapping method from Asset to benefits is depicted in Figure 20.

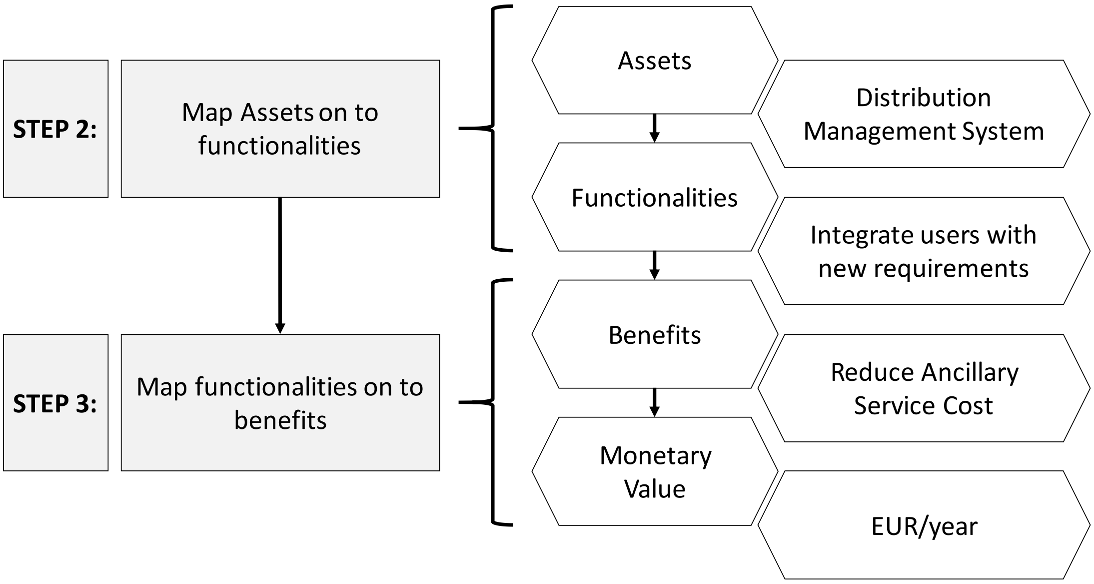


Figure 20. Mapping applied in the CBA (EC-JRC, 2012)

The smart grid project impacts should consider the value chain and society at large. Therefore, the project should show the social surplus and the fair distribution of costs and benefits among the stakeholders (EC-JRC, 2012, p. 18). The 7 steps of the cost benefit analysis are described in the following sections.

4.2.1 Summary of technologies, elements and goals of the project.

The smart grid project must provide the following information (EC-JRC, 2012):

- The scale and dimension of the project.
- The engineering features.
- The characteristics of the network
- The stakeholders

- A statement of the objectives including its anticipated socio-economic effect.
- The regulatory framework and its effect on the smart grid project.

4.2.2 Map assets on to functionalities

The assets used in a smart grid project offer different functionalities that enable benefits. The functionalities for each asset can be selected from Table 6.

Service	Provider	Beneficiaries	Functionalities
Enabling the grid to integrate users with new requirements	DSOs	Generators, Consumers, Storage owners	1. Facilitate connections at all voltage and locations for all type of devices 2. Facilitate the use of the grid at all voltage and location 3. Use of the grid control systems for network purposes 4. Update grid performance data on continuity of supply and volt. quality
Enhancing efficiency in day-to-day grid operation	DSOs, Metering operators	Consumers, Generators, Suppliers, DSOs	5. Automated fault identification and reconfiguration, reducing outage times 6. Enhance monitoring and control of power flows and voltages 7. Enhance monitoring and observability of grids down to low voltage levels 8. Improve monitoring of network assets 9. Identification of technical and non-technical losses by power flow analysis 10. Frequent info. exchange on actual active-reactive generation consumption
Ensuring network security, system control an quality of supply	DSOs, aggregators, suppliers	Generators, Consumers, Aggregators, DSOs, TSOs	11. Allow grid users and aggregators to participate in ancillary services market. 12. Operation schemes for volt/current control 13. Intermittent sources of generation to contribute to system security 14. System security assessment and management of remedies 15. Monitoring of safety, particularly in public areas 16. Solutions for demand response for system security in the required time
Better investment network plans	DSOs, metering operators	Consumers, Generators, Storage owners	17.Better models of Distributed Gen., storage flex. loads and ancillary services 18. Improve assets management and replacement strategies 19. Additional info. on grid quality and consumption by metering planning
Improving market functioning and customer Service	Suppliers, Power exc. Platform providers, DSOs, metering operators	Consumers, Suppliers, Application and service providers	20. Participation of all connected generators in electricity market 21. Participation of VPP and aggregators in the electricity market 22. Facilitate consumer participation in the electricity market 23. Open platform (grid infrastructure) for EV recharge purposes 24. Improvement to industry systems 25. Support adoption of smart homes/facilities automation and IoT 26. Provide grid users with individual advance notice of planned interruption 27. Improve customer level reporting in the case of interruptions
Enabling stronger involvement of consumers in their energy usage and management	Suppliers + Metering Op. + DSOs, Energy Service Companies	Consumers, Generators	28. Sufficient frequency of meter readings 29. Remote management of meters 30. Consumption/injection data and price signals by different means 31. Improve energy usage information 32. Improve information on energy sources 33. Availability of individual continuity of supply and volt. quality indicators

Table 6. List of assets services and functionalities in a smart grid project (EC-JRC, 2012).

Once standardized functionalities are selected, the project developer can create a map of the main asset on to functionalities, as shown in Table 7 (a).

	FUNCTIONALITIES					
		1	2	…	32	33
ASSETS	Asset 1	X	X			X
	Asset 2)		X		X	
	⋮					
	Asset n			X		X

(a)

	FUNCTIONALITIES					
		1	2	…	32	33
BENEFITS	Benefit 1	X	X			X
	Benefit 2		X		X	
	⋮					
	Benefit 3			X		X

(b)

Table 7. Cost-benefit methodology: (a) step 2 - map assets on to standardized functionalities. (b) map functionalities on to standardized benefits.

4.2.3 Map functionalities on to benefits

The third step of the cost benefit methodology is to map functionalities provided by assets on to benefits of the smart grid project. For this purpose, benefits are selected from Table 8 and then map in Table 7 (b).

This analysis should continue until all functionalities have been designed. The mapping of step 2 and 3 depends on various factor, such as:

- Characteristics, dimension as well as scope of the project.
- Measurability or applicability of some category of benefits on type the type of stakeholder involved.
- Monetization of benefits.
- And regulation.

Category	Benefits
Economic	1. Optimized Generator Operation 2. Deferred Generation Capacity Investments 3. Reduced Ancillary Service Cost 4. Reduced Congestion Cost 5. Deferred Transmission Capacity Investments 6. Deferred Distribution Capacity Investments 7. Reduced Equipment Failures 8. Reduced Distribution Equipment Maintenance Cost 9. Reduced Distribution Operation Cost 10. Reduced Meter Reading Cost 11. Reduced Electricity Theft 12. Reduced Electricity Losses 13. Detection of Anomalies relating to Contracted Power 14. Reduced Electricity Cost
Reliability	15. Reduced Sustained Outages 16. Reduced Major Outages 17. Reduced Restoration Cost 18. Reduced Momentary Outages 19. Reduced Sags and Swells
Environmental	20. Reduced CO2 Emissions 21. Reduced SOx, Nox, and PM-10 Emissions
Security	22. Reduce Oil Usage 23. Reduced Wide-Scale Blackouts

Table 8. List of benefit provided by asset functionalities in a smart grid project. (EC-JRC, 2012)

4.2.4 Stablish the baseline

In this step of the CBA methodology, the Business as Usual (BaU scenario or Scenario A) and Smart Grid scenario (SG scenario or Scenario B) are defined. The cost benefit analysis evaluates the benefit metrics between those two scenarios. The Table 9 shows examples of cost metrics and benefit metrics (EC-JRC, 2012, pp. 22-24)

the assessment should consider these two scenarios:

- Business as Usual scenario (BaU scenario), this means that scenario represent the status of grid without the deployment of Smart Grid. This scenario includes just the planned maintenance.

- Smart Grid project implementation scenario (SG scenario). This scenario includes the Smart Grid project in place.

There are two sources used to calculate Business as Usual scenario:

1. Control Groups: the main goal is to test smart grid technologies/devices in a segment of the grid to evaluate their impact on the overall grid behavior.

2. Historical data: the information extracted from historical data gives a good indication of the Business as Usual Scenario, but because some factors are likely to vary over time, it is therefore required to extract information from control groups.

BaU Scenario	Metric	Type	SG Scenario - Benefit	Metric	Type
Maintenance cost of trafos and substations	• Direct costs of maintenance	H	8. Reduced Distribution Equipment Maintenance Cost	• Reduce maintenance cost through remotely monitor control and monitor of asset conditions.	F
Cost of local meter readings	• Meter reading cost: [EUR/client/year]	H	10. Reduced Meter Reading Cost	• Communication success rate	H
	• No. of LV users	H		• % of customers unable to use an smart meter	F
	• Inflation rate	F		• Cost of disperse local readings	
Looses relating to power outages	• Annual revenue LV	H	15. Reduced Sustained Outages	• Reduced outage through smart grid devices [time]	F
	• min/year	H			
	• Min non-suppl./year	H		• Reduce outage through telecommunication Infrastructure	F
	• Cost per kWh of load not served	F			

Table 9. Example of baseline conditions for Smart Grid benefits (based on InovGrid project). (H): Historical metrics (F): Forecasted metrics (EC-JRC, 2012).

4.2.5 Monetize the benefits and identify the beneficiaries

In this step of the CBA methodology, the data for quantification and monetization of the benefits is collected and reported (EC-JRC, 2012). The value of a benefit is calculated as follows:

$$Benefit[EUR] = Cost_{BaU}[EUR] - Cost_{SG}[EUR] \tag{4.1}$$

Table 10 shows an example on how to monetize the benefits. A guide on how to calculate the monetization of the 23 benefits (see Table 8) is described in *Guidelines for conducting a cost-benefit analysis of smart grid projects-Annex II* (EC-JRC, 2012).

Benefit	Calculation
8. Reduced Operational and maintenance cost	$B_8 = B_{8.1} + B_{8.2}$
8.1. Reduced maintenance cost of assets	$B_{8.1} = [Maintenance\ cost\ of\ assets]_{BaU} - [Maintenance\ cost\ of\ assets]_{SG}$
8.2 Reduced cost of equipment breakdowns	$B_{8.2} = [Equipment\ breakdowns\ cost]_{BaU} - [Equipment\ breakdowns\ cost]_{SG}$

Table 10. Example of calculation of Benefit No. 8: Reduced operational and maintenance cost (EC-JRC, 2012).

After calculating the monetary value of the benefits, it is important to identify the beneficiaries of the smart grid project and how the benefits are distributed through the whole value chain. Also, it is important to indicate the level of uncertainty of the calculations to characterize the relative level of precision.

4.2.6 Identify and quantify the costs

There are two ways to quantify the cost: a) measured directly by the investing company or b) estimated via current prices of products and services provided by suppliers. This step is expected to be relatively easy to perform, because it requires just the itemization of all important costs.

The capital costs of the project are amortized over time. The activity-based cost should be applied in the smart grid project. Energy taxes and Value added Tax should not be incorporated into this analysis. (EC-JRC, 2012)

4.2.7 Compare costs and benefits

There are several methods to assess the cost-effectiveness of a project. Most important among these are: annual comparison, cumulative comparison, net present value and benefit cost ratio. The net present value is described below (EC-JRC, 2012).

- **Net Present Value:** consist of calculating the sum of net present values of each cash flows of the project for the time horizon (outlined in chapter 4.1) of the CBA. The following steps are taken: 1) Costs are subtracted from benefits each year. 2) These net benefits are discounted and 3) the discounted values are added up. The NPV is calculated as follows:

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \qquad (4.2)$$

where:

t is the period (year) of the cash flow;

i is the discount rate;

R_t is the result between cash inflow minus cash outflow at time t.

n is the number of periods considered in the project

4.3. Sensitivity Analysis

The last step in the CBA (see Figure 18) is the sensitivity analysis. This step is necessary because of: 1) different economic, demographic, regional, commercial and industry factors determine the amount of benefits expected for the country. And, 2) CBA is based on forecasted and estimated variables. These variables cover a long period of time and it is likely that these values will be very different from forecasts (EC-JRC, 2012).

The sensitivity analysis seeks to clarify to what extent the profitability change by variations in key parameters. The key parameter to test is the internal rate of return

(IRR) or NPV. The goal is to find the range of values that makes positive results of the CBA. These range of values are known as “switching values” of key parameters. The switching values suggest the level of riskiness of the project, and considering these risks, the project developer can assess preventive actions (EC-JRC, 2012). The key parameters that affect and smart grid project are: 1) Energy consumption rate and energy efficiency potential, 2) Peak load transfer, 3) transmission and distribution electricity losses, 4) number of non-supplied minutes, 5) value of lost load, 6) discount rate 7) implementation schedule

4.3.1 Energy consumption rate and energy potential

The estimation of benefits is very sensitive to the estimation of energy consumption rate. The InovGrid project is the smart grid case study that JRC-EC selected for testing the CBA methodology. In this project, it was found that 1% increase of the energy consumption rate would result in an increase of 16% of the NPV. Also, there is a clear connection between the energy efficiency benefits due to energy consumption. The benefits affected due to a variation of energy consumption rate are: (12) reduced electricity technical losses and (14) reduced electricity costs (see Table 8) (EC-JRC, 2012).

4.3.2 Peak Load transfer

The portion of energy shifted from peak periods to off-peak periods is known as peak load transfer. A smart grid project can reach up to 30% peak load transfer and up to 11% in the residential sectors. A change of 1% in this parameter can lead to 4.7% of variation in the NPV. The benefits affected because of a variation of the peak load transfer are: (14) reduced electricity costs and (6) deferred distribution capacity investments (see Table 8) (EC-JRC, 2012).

4.3.3 Transmission and Distribution electricity losses

The percentage of losses in transmission and distribution network depends on the grid configuration, the consumption mix and the percentage of cables and overhead lines of the network. The InovGrid project shows that 1% increase in distribution losses leads to 0.4% increase of benefit. The benefit affected due to a variation of transmission and distribution electricity losses are: (12) reduced electricity technical losses (see Table 8) (EC-JRC, 2012).

4.3.4. Number of non-supplied minutes

The reduction of power outages can be realized with two different actions: 1) increasing the observability of the network and 2) improving the distribution automation. In the case study described above, 5% variation in non-supplied time leads to 0.2% variation in the NPV. The benefits affected due to a variation of number of non-supplied minutes are: (15) reduced sustained outage and (17) restoration costs (see Table 8) (EC-JRC, 2012)

4.3.5 Value of lost load

The cost per kWh of load not served is known as Value of lost load (VOLL). The VOLL depends on the type of customer base in different regions. Higher VOLL means higher share of industrial customers or high activity business. The InovGrid project used 1.5 EUR/kWh as VOLL. An increase of EUR 1 in the VOLL leads to a 3% increase in the NPV. The benefits affected due to a variation of VOLL are: (15) reduced sustained outage and (17) restoration costs (see Table 8) (EC-JRC, 2012)

4.3.6 Discount rate

One of the important variable to test in the sensitivity analysis of a project is the discount rate. The discount rate sensitivity analysis is described in the following example (see Figure 21): The discount rate varies from 0% to 20%, and the two X’s over the curve represent a discount rate of 3% and the IRR, the curve shows that the higher values of discount rate, the lower the NPV figures (EC-JRC, 2012).

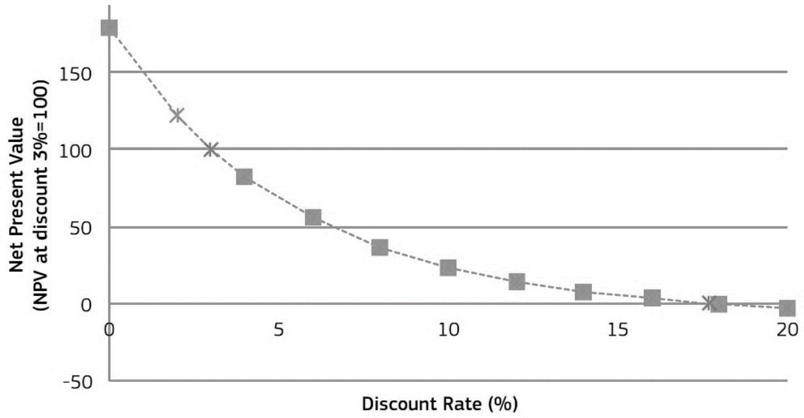


Figure 21. Example of discount rate sensitivity analysis (EC-JRC, 2012)

4.3.7. Implementation schedule

An important factor for the viability of the project is the implementation schedule of the project. The Figure 22 shows three different types of implementation schedules of smart grid project. In this example, the fast roll-out results with the lowest NPV and roll-out by 2022 with the highest NPV. An optimal implementation schedule should consider the following factors:

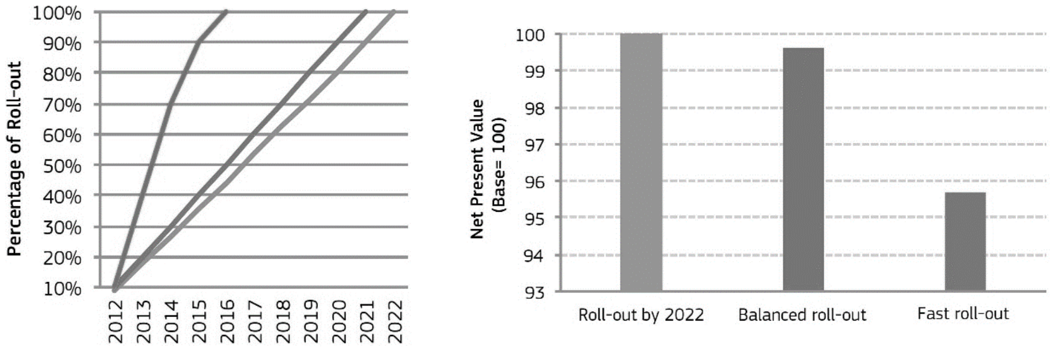
- **Discount rate:** already discussed in chapter 4.3.6.

- **Installation time frame and installation rate:** The project should prevent installations peaks of asset for a better supply chain management.

- **Rural vs. urban roll out**: Due to different installation costs, urban and rural roll-out should have different implementation schedules.

- **Dispersed vs. concentrated:** Wheatear the deployment of smart grid infrastructure is concentrated or scattered can impact the smartness of the grid functionalities and change the cost benefit outcome.

- **Technology Maturity:** If the technology has a reduction of cost over the year (economy of scale), it is desirable to take advantage of the cost reduction and slow the implementation schedule.



(a) (b)

Figure 22. Sensitivity analysis of implementation schedule: a) percentage of roll-out vs. time horizon of the project. b) Net present value of different of roll-out (EC-JRC, 2012) .

4.4. Qualitative Analysis

An overall smart grid project evaluation should also consider the non-quantifiable benefits. Some benefits like policy and social impact are difficult to calculate its monetary value in the CBA. Also, the cost-benefit analysis does not estimate future applications and functionalities that enable smart grid project (EC-JRC, 2012).

When performing the qualitative evaluation of the smart grid project, it is important to considerer the following aspects:

1. Contribution of the smart grid project to the policy objectives. The outcome should be a KPI based score (see Chapter 4.5).

2. Identification and evaluation of non-monetary effects on society. In this case the outcome should be a qualitative evaluation of projected externalities.

The outcome of the qualitative analysis should be a vector that includes the aspect discussed above, as shown in Figure 23.

Once the outcome vector is constructed, a set of criteria should asses the overall impact. The outcome of the qualitative analysis should be combined with the economic analysis to perform a weighting to make complete project evaluation. This analysis should be treated carefully, because rely on subjective descriptive assessment.

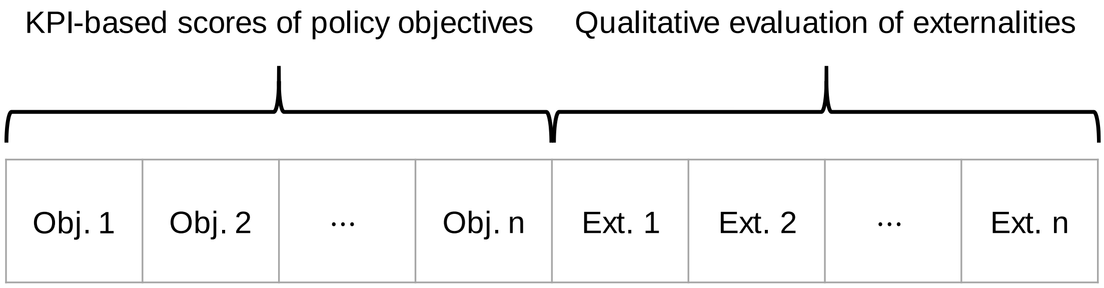


Figure 23. Outcome vector of the qualitative analysis (EC-JRC, 2012).

4.4.1 Performance Assessment

The KPI defined in chapter 4.5 can be difficult to monetized, but provide qualitative indication of the effect of the smart grid project, specially to measure the achievement of the project and policy goals that support it (EC-JRC, 2012).

The qualitative assessment of the indicators resides in the link between KPI and functionalities. For this purpose, a merit deployment matrix should be constructed. This matrix is constructed in the following way:

- KPIs and benefits are given in the rows.
- functionalities are given in the columns.
- locate cell with the corresponding link between benefits/KPI and functionality.
- Explain how the project achieve the link between benefits/KPI and functionalities. Then, assign a weight to quantify this link (a value between 0 and 1).

The quantification of the project impact in terms of functionalities is given by summing up the cells along the columns. In the same way, the quantification of the project impact in terms of benefits is given by summing up the cells along the rows (see Table 11) .

		Services and Functionalities				
		Functionality 1	Functionality 2	···	Functionality 33	Total Sum
Benefits / Policy Goals	KPI_1^1					Sum Row 1
	KPI_1^2					Sum Row 2
	⋮					⋮
	KPI_n^m					Sum Row p
	Total Sum	Sum Column 1	Sum Column 2	···	Sum Column 33	

Table 11. Merit deployment matrix (EC-JRC, 2012).

4.4.2 Externalities and social impact assessment.

The qualitative analysis should also identify the costs and benefits from the project into society that cannot be monetized (externalities). These externalities should be expressed in physical terms, where the calculation of externalities is not possible, it should estimate the impact with the whole range of elements for the evaluation. Possible externalities of the smart grid projects are listed below:

1. Jobs
2. Safety
3. Environmental impact
4. Social acceptance
5. Time lost/saved by users
6. Enabling new services and applications and market entry for third parties
7. Ageing workforce – gap in skills and personnel
8. Privacy and cybersecurity

4.5. Key performance Indicators and EU policy criteria

The KPIs required to perform qualitative analysis are listed in Table 12 below. These KPIs are linked with its respective benefit. The list is elaborated for the European context.

Benefits	KPIs
Increased Sustainability	1. Quantified reduction of carbon emissions 2. Environmental impact of electricity grid infrastructure 3. Quantified reduction of accidents and risk associated with generation technologies
Adequate capacity of T&D grids for collecting and bringing electricity to the users	4. Hosting capacity for distributed energy resources in distribution grids 5. Allowable maximum injection of power without congestion risks in transmission networks 6. Energy not withdrawn from renewable sources due to congestion and/or security risks 7. An optimized use of capital and assets
Adequate grid connection and access for all kinds of grid users	8. First connection charges for generators, consumers and prosumers. 9. Grid tariffs for generators, consumers and prosumers. 10. Methods adopted to calculate charges and tariffs 11. Time to connect a new user 12. Optimization of new equipment design resulting in best cost benefit 13. Faster speed of successful innovation against clear standards
Satisfactory levels of security and quality of supply	14. Ratio of reliably available generation capacity to peak demand 15. Share of electrical energy produced by renewable sources 16. Measured satisfaction of grid users with the grid services they receive 17. Power system stability 18. Duration and frequency of interruptions per customer 19. Voltage quality performance of electricity grids.
Enhanced efficiency and better service in electricity supply and grid operation	20. Level of losses in T&D grids. 21. Ratio between minimum and maximum electricity demand within a defined time period 22. Percentage utilization of grid elements 23. Demand-side participation in electricity markets and in energy efficienca measures 24. Availability of grid components and its impact on network performances 25. Actual availability of network capacity with respect to its standard value
Effective support of transnational electricity markets	26. Ratio between interconnection capacity of one country region and its electricity demand 27. Exploitation of interconnection capacities. 28. Congestion rents across interconnections.
Coordinated grid development through common European, regional and local grid planning to optimise transmission grid infrastructure	29. Impact of congestion on outcomes and prices of national/regional markets 30. Societal benefit-cost ratio of a proposed infrastructure investment 31. Overall welfare increase 32. Time for licensing/authorization of a new electricity transmission infrastructure 33. Time for construction of a new electricity transmission infrastructure
Enhanced consumer awareness and participation in the market by new players	34. Demand side participation in electricity markets and in energy efficiency measures. 35. Percentage of consumers on ToU/critical peak/real-time dynamic pricing. 36. Measured modifications of electricity consumption patterns after new pricing schemes. 37. Percentage of users available to behave as interruptible load. 38. Percentage of load demand participating in market-like schemes for demand flexibility. 39. Percentage participation of users connected to LV levels to ancillary services.
Enable consumers to make informed decisions related to their energy to meet the EU Energy efficiency targets	40. Base-to-peak load ratio. 41. Relation between power demand and market price for electricity. 42. Users can comprehend their energy consumption and act based on free info. 43. Consumers are able to access their historic energy consumption information. 44. Ability to participate in relevant energy market to purchase and/or sell electricity. 45. Coherent link is establish between the energy prices and consumer behavior.
Create a market mechanism for new energy services such as energy efficiency or energy consulting for customers	46. Enable Automatic changes to users energy consumption in reply to demand response. 47. Clearly definition of data ownership and data process. 48. Physical grid-related data available in an accessible form. 49. Transparency of physical connection authorization, requirements and charges. 50. Effective consumer complaint handling and redress.
Consumer bills are either reduced or upward pressure on them in mitigated	51. Transparent, robust process to evaluate the positive cost-benefit ratio. 52. Regulatory mechanism that ensure benefits are reflected in the bills. 53. New smart tariffs that deliver tangible benefits to consumers or society. 54. Market design is compatible with the way consumers use the grid.

Table 12. List of KPIs and benefits (Vasiljevska & Gras, 2017).

In Addition to the KPIs defined above, the smart grid projects could evaluate a set of key performance indicators (KPI), which should comply with the six policy criteria of the European Commission. These criteria are described in article 4.2.c of “guidelines for trans-European energy infrastructure and repealing Decision” (EC, 2011). The following sections describe each KPIs in more detail (Vasiljevska & Gras, 2017).

4.5.1 Level of sustainability

This KPI is calculated as follows: the variation of Greenhouse gases emissions normalized divided to total energy demand in the portion of the network where the project will be implemented (see Table 13):

a) The KPI$_1$ should reflect the reduction of greenhouse gases (GHG) in the smart grid project, such as:
   - Reduction of GHG as result of reduction of energy losses,
   - Decrease in GHG as result of energy savings,
   - Decline of GHG as result of reduction of peak load and displacement of base load generated by fossil fuel.
   - Reduction of GHG because of integration of RES and DER.

b) The KPI$_2$ evaluate the impact of smart grid projects against the BaU scenario, should be considered the following aspects:
   - Impact on soil, air, water, climate, among others.
   - Impact on land, landscape.
   - Visual impact.
   - Other type of pollution

1. Level of Sustainability	**calculation method**
a. Reduction of greenhouse gas emissions (GHG)	$KPI_1 = \frac{GHG_{BaU} - GHG_{SG}}{Total\ Energy\ Demand}$
b. Environmental impact of network Infrastructure.	$KPI_2 =$Quantitative/qualitative analysis

Table 13. Level of sustainability metrics (Vasiljevska & Gras, 2017).

4.5.2 Distribution and Transmission grid capacity

a) The KPI$_3$ calculate the additional generation capacity of DER the can be integrated without risk in the Network.

b) KPI_4 is defined as the transfer capacity from a hypothetical power plant to the rest of the power system. This transfer capacity should comply with operational security rules (without congestion risks).

c) The KPI_5 evaluates the capability of the grid to integrate renewable energy generation.

2. Environmental Impact	calculation method
a. Installed Capacity of RES.	$KPI_3 = \frac{EI_{SG} - EI_{BaU}}{E_{Total}}$
b. Max. injection of electricity without congestion risk in transmission network.	$KPI_4 = \frac{Pi_{max-SG} - Pi_{max-BaU}}{P_{ref}} \times 100$
c. Energy not withdrawn from RES due to congestion or security risks.	$KPI_5 = \frac{E_{RES\_Q-BaU} - E_{RES\_Q-SG}}{E_{RES\_TOT}}$

Table 14. Environmental impact metrics (Vasiljevska & Gras, 2017).

4.5.3 Network connectivity and access

a) KPI_6 shows how the information captured with smart grid project technologies can be useful for regulators to allocate cost as accurately as possible.

b) KPI_7 evaluates the operational flexibility of the grid due to dynamic balancing of electricity provided by the smart grid project.

3. Network connectivity and access of users	calculation method
a. Methods to calculate charges, tariffs, and tariff structure for generator, consumers and prosumers.	KPI_6 =qualitative appraisal
b. Operational flexibility for dynamic balancing of electricity in the network.	$KPI_7 = \frac{P_{disp-SG} - P_{disp-BaU}}{P_{peak}} \times 100$

Table 15. Network connectivity metrics (Vasiljevska & Gras, 2017).

4.5.4 Security and quality of supply

a) KPI_8 evaluates the system adequacy of the smart grid project and is evaluated as the percentage variation of the ratio between reliably available capacity (RAC) and the peak load in the BaU scenario and smart grid scenario.

b) KPI_9 quantifies the proportion of RES that can be integrated in the system accordingly with the security rules of the grid.

c) KPI_{10} evaluates the ability of the smart grid project to remove system instabilities in the part of the network under study.

d) KPI_{11} evaluate the system average interruption duration index (SAIDI) and the System average interruption frequency Index (SAIFI) indexes in the smart grid and BaU Scenario.

e) KPI_{12} assess the impact of the smart grid project on power quality parameters such as short interruptions, voltage sags, flicker, variation in voltage and Total harmonic distortion (THD).

4. Security and quality of supply	calculation Method
a. Ratio of reliably available generation capacity to peak demand.	$KPI_8 = \frac{\left(\frac{RAC}{P_{peak}}\right)_{SG} - \left(\frac{RAC}{P_{peak}}\right)_{BaU}}{\left(\frac{RAC}{P_{peak}}\right)_{BaU}} \times 100$
b. Share of generation from RES.	$KPI_9 = \frac{E_{RES\_SG} - E_{RES\_BaU}}{E_{Total}}$
c. Stability of the power system.	KPI_{10} = Via dynamic simulation analysis
d. Duration and frequency of interruptions per customer including climate related disruptions.	$KPI_{11a} = \frac{SAIDI_{BaU} - SAIDI_{SG}}{SAIDI_{BaU}}$ $KPI_{11\text{b}} = \frac{SAIFI_{BaU} - SAIFI_{SG}}{SAIFI_{BaU}}$
e. Voltage quality performance.	$KPI_{12\text{a}} = \frac{V_{violations\_BaU} - V_{violations\_SG}}{V_{Violations\_BaU}}$ $KPI_{12\text{b}} = \frac{THD_{BaU} - THD_{SG}}{THD_{BaU}}$

Table 16. Security and quality of supply metrics (Vasiljevska & Gras, 2017).

4.5.5 Efficiency and service quality

5. Efficiency and service quality	calculation method
a. Losses in transmission and distribution grid.	$KPI_{13} = \frac{EL_{BaU} - EL_{SG}}{E_{total}} \times 100$
b. Ratio of minimum to maximum electricity demand within a time period.	$KPI_{14} = \frac{\left(\frac{P_{min}}{P_{max}}\right)_{SG} - \left(\frac{P_{min}}{P_{max}}\right)_{BaU}}{\left(\frac{P_{min}}{P_{peak}}\right)_{BaU}} \times 100$
c. Demand side participation in electricity markets and in energy efficiency measures.	$KPI_{15} = \frac{P_{DSM\_SG} - P_{DSM\_BaU}}{P_{peak}} \times 100$
d. Utilization rate of electricity network components.	KPI_{16} =Via DSO/TSO estimation method
e. Availability of network components and its impact of network performances.	$KPI_{17} = \frac{Availability_{SG} - Availability_{BaU}}{Availability_{BaU}} \times 100$ where: $Availability = \frac{MTBF}{MTBF - MTTR}$
f. Actual availability of network capacity with respect to its standard value.	$KPI_{18} = \frac{P_{SG} - P_{BaU}}{E_N}$

Table 17. efficiency and service quality metrics (Vasiljevska & Gras, 2017)

a) KPI_{13} quantifies the energy of losses comparing the smart grid scenario and the BaU scenario. The energy consumption in the part under study is used as basis for the KPI calculation.

b) KPI_{14} calculates the variation between minimum and maximum demand in the demand considering the smart grid scenario and the BaU scenario.

a) KPI_{15} estimates the variation of demand side participation in the smart grid and BaU scenarios. The result of this calculation divided by the maximum electricity demand.

b) KPI_{16} estimates the capability of a smart grid project to make better use of the network's assets.

c) KPI_{17} calculates the variation of network components availability in the smart grid and BaU scenarios. The availability is a function of the mean time between failures (MTBF) and the mean time to repair (MTTR).

d) KPI_{18} quantifies the availability of grid capacity in the smart grid scenario and de BaU scenario. this KPI is compared to a reference value at regional levels.

4.5.6 cross border electricity markets

a) KPI_{19} calculates the variation of the minimum connection capacity ratio in smart grid and BaU scenario.

b) KPI_{20} calculates the variation of cross-border transmission capacity per border with the average yearly load flow on the same transnational electricity link in the smart and BaU scenarios.

c) KPI_{21} estimates the alleviation price differential between two price zones/country.

6. Cross border electricity markets	calculation method
a. Ratio of interconnection capacity to a member state to its electricity demand.	$KPI_{19} = \frac{r_{BaU} - r_{SG}}{r_{BaU}} \times 100$ where: $r_j = \frac{r \sum_i \mu_i(NTC_i)}{E_{tot_j}} \times 100$
b. Exploitation of interconnection capacities.	$KPI_{20} = \frac{ER_{BaU} - ER_{SG}}{ER_{BaU}} \times 100$ Where: $ER_i = \frac{\mu_i(load\_flow)}{NTC_i} \times 100$
c. Congestion rents across interconnections.	KPI_{21} = via congestion rent estimation

Table 18. Cross border electricity markets metrics (Vasiljevska & Gras, 2017).

4.6. Research plan for Smart Grid demonstration project

The CBA elaborated by the Electric Power Research institute (EPRI) includes a research plan for smart grid project, which allows DSOs/TSOs to produce reliable and reproducible results from smart grid demonstration projects (EPRI, 2012). EPRI encourage the implementation of the scientific method to measure the impact of projects. This impact is considered also an input to the CBA. The research plan should answer two important question: To what extent does the application of the smart grid perform? and does that implementation justify the cost?

4.6.1 Layering of smart grid project steps

The project, can be broken down into sub-projects, which must be considered separately. Therefore, the CBA may be subdivided into a series of questions above described. Figure 24 shows an example of the methodology over the baseline scenario (BaU scenario).

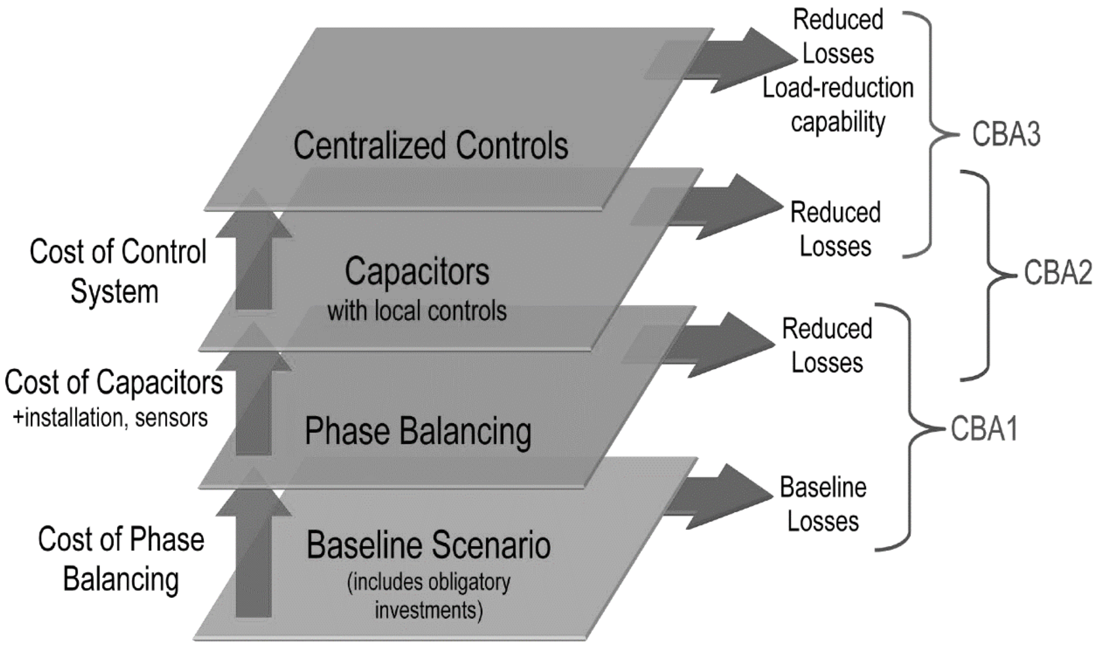


Figure 24. Smart grid sub-projects, impacts and outcomes (EPRI, 2012).

The final goal of the project depicted in Figure 24 is to implement a centralized control system of capacitor on a distribution feeder, but is important to evaluate single steps to determine how much loss reduction is assigned to each sub-project.

The CBA can be divide into a series of questions, such as: *Physical question:* Is there a first step (second step, third step, and so on) that delivers impact? How much of the impact/benefits come with this step? *Economic Question:* How much does this step cost to implement? (EPRI, 2012)

The CBA framework evaluates the physical impacts of the project, and with the outcomes of this evaluation, project developers can form the economic value proposition.

4.6.2 Baseline quantities

The description on how to obtain the Information of baseline quantities can be found in chapter 4.2.4 of this thesis.

4.6.3 State hypotheses in demonstration projects

The Hypotheses in smart grid projects are statements used to design experiments, which isolate and measure quantities that demonstrate the impacts of the project. These Hypotheses are tested by experiment, which can be true or false. If a Hypothesis is proved false, a corresponding “null” hypothesis should explain the outcome. A hypothesis statement should not contain an estimate measurement unless the figure assume something specific to verify/falsify the hypothesis (EPRI, 2012).

4.6.4 Hypothesis testing

When results from experiments are obtained, it is important to differentiate the measured quantities from random variation. Random variations can be small or big relative to the quantities being measured. Therefore, it is important to perform two measurements of the impact of the smart grid project that are subject to the same kind of chance variation. When behaviors of population samples are compared, it is expected that first and second samples would not be the same, but statistics inference indicate what can be expected from one sample relative to the other (EPRI, 2012).

Hypotheses in a smart grid demonstration projects should be (EPRI, 2012):

- True/false statement on smart grid applications and their physical impacts.
- Testable by experiment
- Concluded by measurements taken within the boundaries of a smart grid demonstration project.

4.6.5 Experiment Design

The smart grid demonstration (or experiment) project is designed to test the hypothesis. The process of the research plan (described in this section) is depicted in Figure 25 (EPRI, 2012).

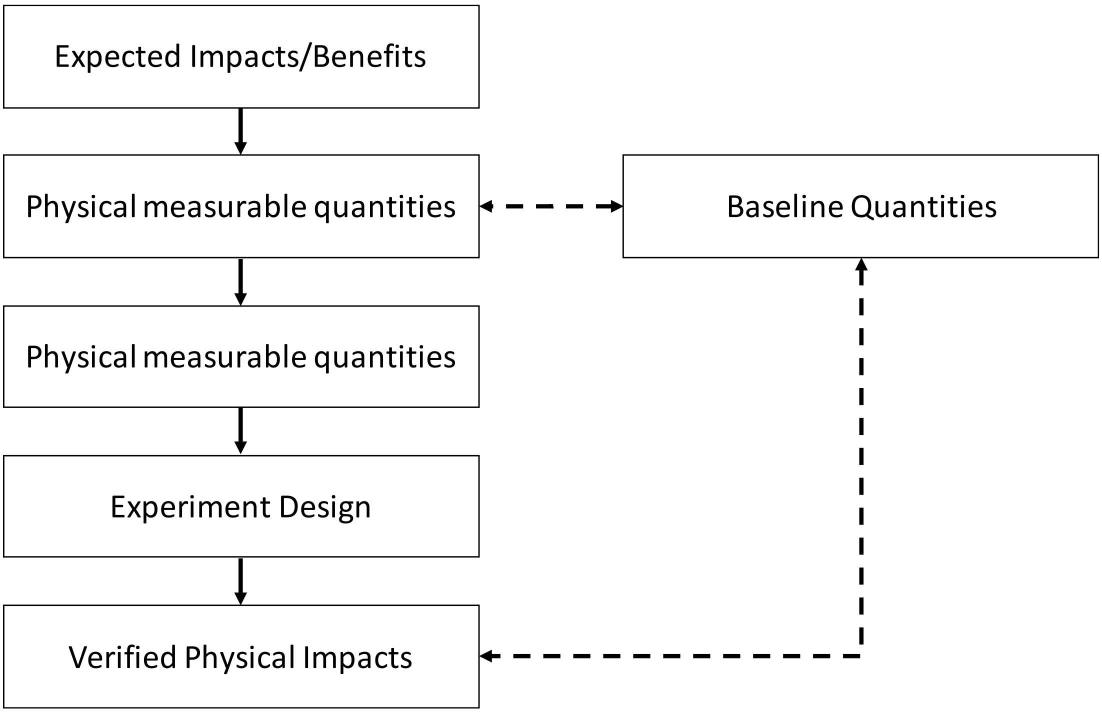


Figure 25. Process to experiment design in a smart grid project demonstration.

5. Summary and Outlook

The smart electricity grids are changing the traditional technology management in the electricity sector by merging operational technology of the grid and information technology. I think that this new state of the grid is leading to enhance the efficiency, reliability, resiliency and flexibility of the electric networks worldwide.

Also, I think that in order to have a smooth integration of both technologies (operational and information technology) it is important to have standards to allow interoperability between them. SGAM is a standard model that helps to analyze smart grid systems (information and communication) in a technology neutral approach. SGAM is organized in 5 layers, which are: component, communication, information, function and business layer, as well as each layer has two components: physical component and hierarchical component.

I presented, in this thesis, that this technology integration brings to the electricity grids high risk of cyberattacks. Cyberattacks can affect a portion of a grid, as well as whole country, therefore it is of great importance to identify any vulnerability and weakness in smart grid systems.

Another point of crucial importance in smart grid implementation is the application of electricity distribution tariffs and its impact in the customer billing. The cost of smart grid technologies integrated in the power system is fully transferred to the customers. I think, special care must be taken in deploy this type of technologies in the grid in order to not adversely affect customer rates. The implementation of Smart Meter will change the customer behavior, and this requires a change in the type of electricity tariffs.

The smart grid technology implemented in one specific power network, highly depends on the policy targets, current regulation and specific characteristics of the country or region where the grid operates. However, As I show in this thesis, there are 3 types of smart grid technologies that are being broadly integrated in the electricity networks: Advance Metering Infrastructure, DER/RES Integration and network management.

This thesis also overviewed the investments of smart energy technologies in two regions, U.S. and the European Union, and it is observed that the level of investments is high in both region: USD 7.9 Billion and EUR 3;1 Billion, respectively. The investments in the U.S. are clearly focused in power system reliability and Advance Metering Infrastructure. In the other hand Europe investments are more focused in smart network management and customer and smart home technologies. It should be noted that Integration of DER was the second most invested technology in the R&D area. France, United Kingdom and Germany are the countries with the highest level of investment in the European Union. As was explained before, these differences between regions are result of policy decisions.

Finally, I believe that the cost-benefit analysis is an indispensable tool to assess smart grid implementation projects. The CBA analysis identifies the benefits of the project, and these provide the economic value proposition for the customers. The JRC-EC methodology includes not only an economic evaluation but also a qualitative assessment. This qualitative assessment is carried out thorough the evaluation of the KPI and externalities vector, which includes jobs, safety and environmental impacts, among others.

The “smartness” of the grids will increase in the following years worldwide. I think, this brings commercial opportunities for equipment manufacturers and service providers of smart grid technologies, especially on those regions where there are no smart grid initiatives or projects in place, like for example: developing nations.

In several national initiatives, smart grids are the principal components of smart cities. In this respect, it is expected more synergies between both areas. The principle obstacles in smart grids demonstration and deployment projects are the social and regulatory aspects rather than technical problems. Because of this regulator should review the results of smart grid projects and ensure the necessary changes in the power industry laws. I believe that human resources in electric utilities should be reinforced in the application and the optimum use of these technologies. New skills are required for professional development especially in areas, such as: Information technology, communication, signals and systems, electricity market, customer relationship management, among others.

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List of Abbreviations.

AMI	Advanced metering infrastructure
App	Application or mobile application
BaU	Business as Usual
CAPEX	Capital expenditures
CBA	Cost-benefit analysis
CEN	European committee for Standardization
CENELEC	European committee for Electro Technical Standardization
CPP	Critical Peak Pricing
CPR	Critical Peak Rebates
CVR	Conservation Voltage Reduction
D&D	Demonstration and deployment
DER(S)	Distributed energy resources(sources)
EC	European Commission
EMS	Energy management System
EPR	Enterprise resource planning
EPRI	Electric power research institute
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
FACTS	Flexible AC transmission Systems
FBI	Federal Bureau of Investigation
GHG	Green House Gas Emissions
GIS	Geographic Information Systems
GPS	Global positioning system
HVDC	High voltage DC power transmission system
IEA	International energy agency
IoT	Internet of Things
IoT	Internet of Things

IRR	Internal rate of return
JRC	Joint Research Center
JRC-EC	Joint Research Centre of the European Commission
KPI	Key performance indicator
LV	Low Voltage
MTBF	Mean time between failures
MTTR	Mean time to repair
NPV	Net present value
OMS	Outage management system
OPEX	Operating expenditures
PDC	Phasor data concentrators
PMU	Phasor measurement units
R&D	Research and Development
RAC	Reliably available capacity
RES	Renewable energy sources
SAIDI	System average interruption duration index
SAIFI	system average interruption frequency index
SCADA	Supervisory control and data acquisition
SGAM	Smart Grid Architecture Model
SGIG	Smart grid investment grant program
T&D	Transmission and distribution
THD	Total harmonic distortion.
USA	United States of America
VOLL	Value of Lost Load
VPP	Virtual Power Plant
VPP	Variable Peak Pricing
WAMS	Wide-area monitoring systems
WMS	Workforce management system

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