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The implementation of a Smart Grid in the EU

A review of the contributions of the smart grid to achieving climate goals

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Milieu- en Natuurwetenschappen
Bachelorthesis
24.06.2015
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Index

Figures

Tables

1.1 Introduction

Both the European and North-American electrical grids (EG) are operating at near full capacity nowadays, and are struggling to keep up with the ever increasing demand for electricity. This growing demand due to ongoing growth in energy consumption is one of the key drivers to upgrade the existing EG. Other drivers are governmental preferences to become less dependant on foreign fossil fuels and the need to act against climate change, which can be partly attributed to the emission of greenhouse gasses into the atmosphere as a result of the burning of fossil fuels (Clastres, 2011). To achieve these goals, both the US and the EU have set targets for a more sustainable production of electricity and are changing legislation accordingly. The targets set by the EU for 2020 focus on competitiveness, security of supply and environmental sustainability:

- A reduction in CO_2 emissions of 20% compared to emissions in 1990,
- Renewable energy sources (RES) account for 20% of all electricity generation,
- A reduction of 20% in primary energy consumption (PEC) compared to the projected PEC in a business-as-usual (BAU) scenario (Europe, 2009).

RES will be one of the main contributors to a reduction in the emission of CO_2 (PNNL, 2010). However, with the integration of these power sources into the existing EG a number of new problems present themselves that previously did not need to be addressed. Furthermore, an upgrade in capacity of the EG will be realised through increases in efficiency as well as expansion (Tekiner-Mogulkoc et al., 2012).

This is why the development of an ‘intelligent’ grid is necessary, and research towards the required technologies, legislation and economic models is carried out on a global scale (JRC, 2011). The functions of a smart grid (SG) as defined by the US and the EU differ slightly and are displayed in **box 1.1** and **1.2** respectively (Ardito et al., 2013).

1.1 *The American list consists of a list of achievements, of which the most relevant are:*
- *the use of digital information to improve reliability, security and efficiency;*
- *integration of distributed resources and generation;*
- *“smart” technologies for metering, communication and automation;*
- *deployment of energy storage technologies (i.e., electric vehicles).*

1.2 *A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies. A smart grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies. Smart grids development must include not only technology, market and commercial considerations, environmental impact, regulatory framework, standardization usage, ICT and migration strategy, but also societal requirements and governmental edicts*

1.2 Research objectives and relevance

The main research question of this review is *"How much can the implementation of a SG contribute to achieving the environmental goals set by the EU for 2020?"*. In order to formulate a comprehensive answer to this question, it has been divided into four subquestions which correspond to the chapters of this review. The problems that a SG tries to solve will be discussed in chapter 2.1 in order to answer the first subquestion: *"What problems does a SG try to solve?"*. To answer the second subquestion, *"What technologies does a SG consist of?"* several of the technologies that can be used to implement a SG are discussed in chapter 2.2. In chapter 2.3 the monetary costs and benefits as well as the environmental benefits of the implementation of a SG are assessed, as a whole as well as for individual technologies, in order to answer the subquestion "*What are the costs and benefits of these SG technologies?*". In chapter 2.4 the obstacles for the implementation of a SG are discussed in order to answer the last subquestion: *"What are the obstacles for the implementation of a SG?"*. The conclusion and discussion will summarize the main findings and shortcomings of this review and address areas in which additional research is needed.

The goal of this review is to assess up to what level a SG can contribute to achieving the environmental goals set by the EU. In the process it will also make an attempt to identify the 'low-hanging fruits' for investments in order to achieve these goals, by creating a clear overview of the costs and benefits of the implementation of a SG. Additionally, it tries to make a contribution to the creation of a shared vision for the deployment of a SG, and identify areas where more research is (most) needed. The benefits of the implementation of a SG have been researched and estimated more thoroughly in the US than they have been in the EU. This review tries to assess up to what level these estimated costs and benefits are valid for the EU by identifying the variables that influence these estimates, and assessing whether their values differ between the US and the EU.

1.3 Methodology

The first two subquestions will be answered through literature analysis of various articles and reports. The costs and benefits of the SG will be obtained by review and comparison of several reports. In order to make this comparison, the possible individual and total gains of several technologies will be discussed. Large scale projections and estimations of annual monetary and environmental benefits seem to be based mostly on research carried out in the US. Several key performance indicators (KPI) have been defined to judge the benefits that can be achieved by implementing one or several technologies that together form a SG. A selection of these KPIs has been made that fits the scope of this review, including quantified reduction of CO_2 emissions, hosting capacity for distributed energy resources in distribution grids and level of losses in transmission and in distribution networks (JRC, 2012). The quantified reductions of CO_2 emissions will be expressed both in an absolute and relative value, as compared to the total CO_2 emissions as projected in a BAU scenario. Where possible, an effort has been made to convert numbers into universal units, and make a universal categorisation based on the technologies and segments presented in previous chapters. Inflation will be accounted for. All assumptions used for conversions can be found in the appendix. Subsequently, a range of variables that may influence the efficiency of these technologies will be defined. Finally, the differences in the values of those variables between the US and Europe will be discussed, together with their respective consequences for the applicability of these models. The obstacles for the implementation of a SG will be derived from this assessment as well as literature analysis.

2.1 Goals of the Smart Grid

The SG is meant to solve a number of problems threatening the security of the current and future EG and power supply, as well as enable progress towards environmental goals. These improvements can be subdivided into three segments: the enhancement of the capacity of the current EG, enhancement of capacity for RES integration and a better flow of information, all of which will now be discussed in this order.

Capacity enhancement

The current EG is aging and reaching the limits of its capacity while demand is constantly growing (Clastres, 2011). The need for extra capacity is addressed in three ways within the SG: through (1) efficiency enhancements, (2) conservation and (3) expansion (PNNL, 2010). This review will focus on efficiency enhancements and conservation exclusively, since the benefits from these areas can be contributed solely to the implementation of the technologies that make up the SG.

A great way to reduce strain on the existing grid is reducing peak demand (PD) by shifting power consumption to other moments during the day, since capacity has to match the largest peaks in demand and these will occur during these hours. The inequality of demand for electricity during the day poses great difficulties on the generation and distribution of all electricity, and electricity generated from RES in particular, since it cannot easily be ramped up on demand. A large part of the extra capacity that will be added to the EG in the future will be in the form of RES, which presents its own problems.

RES integration

One of the main problems that the SG tries to address is the integration of higher penetrations of RES, both through distributed generation (DG) and bulk generation. The production of these RES is not as constant or predictable as the generation from traditional fuel-powered power plants and therefore a more flexible grid is needed. This grid flexibility can be partly characterized as a "controllable multi-directional power flow" (Jarventausta et al., 2010), and enables customers to sell back electricity in times of abundant production. Since production is inconsistent, RES need to be installed in abundance to account for the period of reduced generation. A SG is capable of reducing the size of these required reserves, as will be explained in the next chapter. Furthermore, as the distance over which the SG operates increases, variables such as wind speed and solar power become less correlated for the grid as a whole, which enables more consistent generation.

Flow of information

The current EG is characterized by a lack of information for both customer and producer (Güngor et al, 2011). In the past decades, demand-forecasting and data processing have proven to fail at efficiently providing the right amount of energy at the right time, resulting in losses through overproduction and inefficient distribution (Ardito et al., 2013). An improved flow of information is also supposed to “make customers more aware of their electricity consumption and the means by which it is produced. On a further note, it empowers users with more choice and power in managing their own electricity consumption" (Verbong et al., 2013), which refers more to a conservation of energy than an improvement in efficiency.

The current lack of information doesn't just result in unnecessary losses but also complicates the identification and localization of electricity theft (Depuru et al., 2011). Another objective of the SG is to reduce costs due to outages and improve energy security, by reducing the length of the outages and even predicting them, which enables preventive measures (Clastres, 2011). Concludingly, a SG can be said to improve capacity, security of supply and possibilities for a higher penetration of RES by balancing supply and demand through the flow of information and several new technologies.

2.2 Concepts and technologies within the SG

In the following chapter the technologies and concepts that impact the different aspects of the grid will be discussed as we move down the energy supply chain. This chain has traditionally been divided into the segments generation, transmission, distribution and supply. The traditional segregation of these segments will become more dubious as the features of the SG become more perceptible. This is due to the technologies that impact and blend several stages of the energy supply chain, and the repositioning of suppliers and consumers within the energy market (Ferreira et al., 2011). A SG consists of several technologies that need to be developed, and several technologies that need to mature (Simoes et al., 2012).

Generation

A substantial fraction of the electricity in the SG will be generated using RES, both on an industrial scale and on a small scale through DG. Bulk RES generation is often located more distant from residential customers due to geographic and social restrictions, which introduces new challenges for the transmission of power over long distances (Breuer et al., 2011). On the other hand, several countries within the EU have reported an increase in small-to-medium sized generation installations, that are located more closely to the customer and are often called microgrids (MG) (Ferreira et al., 2011).

Microgrids (MG) can be defined as "an integrated energy system consisting of distributed energy resources and multiple electrical loads operating as a single autonomous grid either in parallel to or "islanded" from the existing utility power grid" (Asmus, 2010). These short distances usually result in smaller losses due to transmission and distribution, as well as improved security of supply, since the microgrid can isolate itself during blackouts of the main grid (Ferreira et al., 2011). Disconnected MGs (MGs that are not connected to the central electricity grid) with a substantial amount of RES do face great challenges for the security of energy supply, due to the fact that their production is dependant on many different variables. An advanced system for the integration of a forecast of these variables must therefore be put in place (Potter et al., 2009). As indicated by Lidula et al. (2011), most experimental research in microgrid technologies is focussed on energy generated by PV and wind.

In the foreseeable future fossil fueled power plants (FFPP) will still play a large role in the production of electricity, although this role is likely to diminish over time as both RES penetration and efficiency of electricity use rise. The different characteristics of FFPPs give them different roles within the energy supply chain. Nuclear emits little CO_2 but is rather static and cannot be turned on or off easily without reducing its lifetime significantly (PNNL, 2010). Gas powered plants emit more but can be fired up or cooled down quite easily which makes them a good fit to respond to peak demand periods, but this electricity is generally more expensive (Sims et al, 2003).

Transmission

After the electricity has been generated from a variety of sources, it needs to be transported towards distribution centers for customers. As RES penetration of the grid rises, electricity will have to be transported over greater distances to overcome the correlation of both solar and wind production within smaller areas, as well as in both directions (PNNL, 2010). Several new technologies for a more efficient transportation of electricity over long distances have been suggested, one of which is high voltage direct current (HVDC). HVDC typically has lower energetic losses over great distances, is able to connect separate AC grids with frequency differences and is more suitable for submarine electricity transport due to the reactive power limitations AC faces over distances longer than 120 kilometres. It is also capable of blocking fault-current which serves as protection against “cascading blackout events” (Breuer et al., 2011). Disadvantages of HVDC are costs, since the required converter stations are expensive, and the power losses that come with the conversion to AC, making the technology less applicable for smaller distances or smaller quantities of transmission (Rudervall et al., 2000).

The storage of energy is presenting itself as one of the bigger obstacles for a successful high level penetration of RES within a SG. On the level of transmission this manifests itself in the form of bulk storage. Various methods for large scale energy storage have been proposed, all of which have different qualities and characteristics that make them suitable for a specific type of task. Pumped-water, chemical and compressed air energy storage are suitable for the storage of large amounts of energy over a longer time, while flywheels, supercapacitors and certain types of batteries store smaller amounts but have a very short discharge time and are therefore more suitable for frequency- and quality control (Roberts & Sandberg, 2011). An illustrative summary of different methods of storage and their properties is given in figure 1.

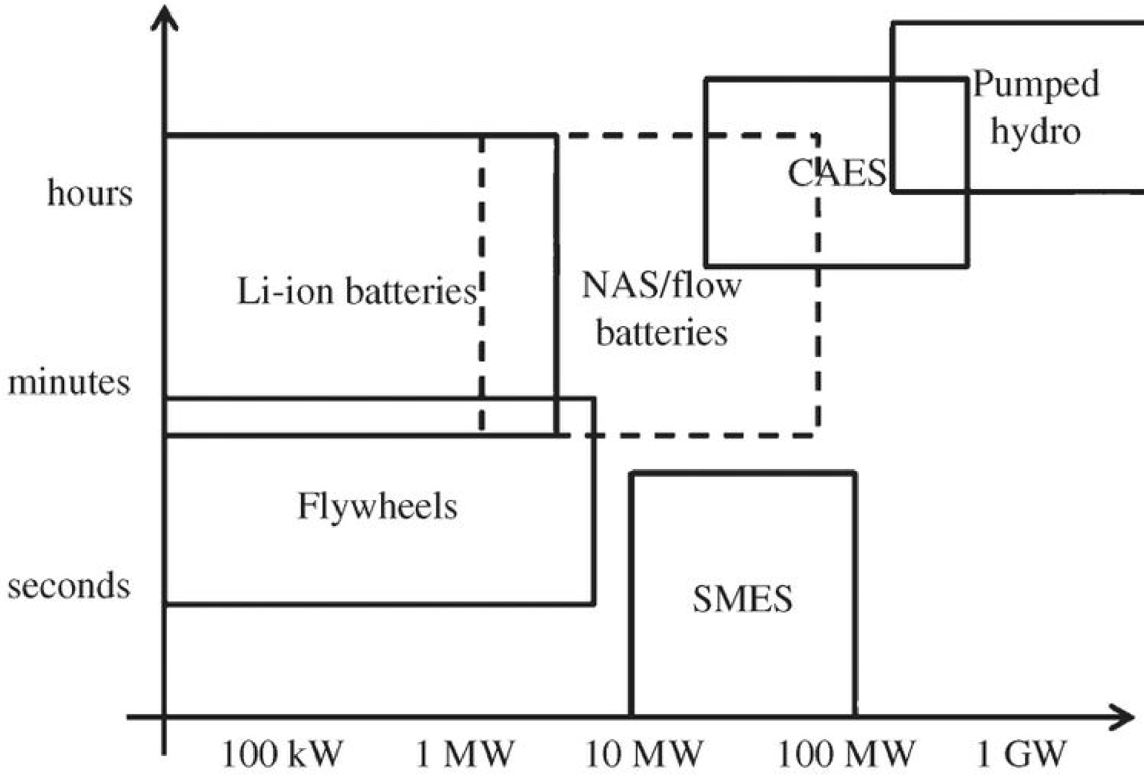


Figure 1: Discharge time and total capacity for a variety of storage methods (Simoes et al., 2012).

Distribution

Distribution refers to the transmission of electricity from high voltage transmission lines through distribution centers to the customer. The combined length of these low voltage distribution lines is much greater than transmission lines. Maintaining the optimal voltage within distribution systems is a continuous tradeoff that could be automated and optimized by advanced voltage control (AVC). Lowering the voltage within those systems tends to increase electrical losses since certain devices will respond by drawing more current, and line losses square with the current. On the other hand, several other electrical devices use less power when voltage is reduced, many of which are residential (PNNL, 2010). The point of AVC is maintaining the lowest possible voltage at the home of the customer. By measuring voltage at the end of the line, distribution operators can get rid of the excess 'safety' voltage that is maintained since voltages that are too low can damage the customers electronics (PNNL, 2010). Since AVC requires a simple measurement of voltage it is a relatively inexpensive efficiency measure (PNNL, 2010).

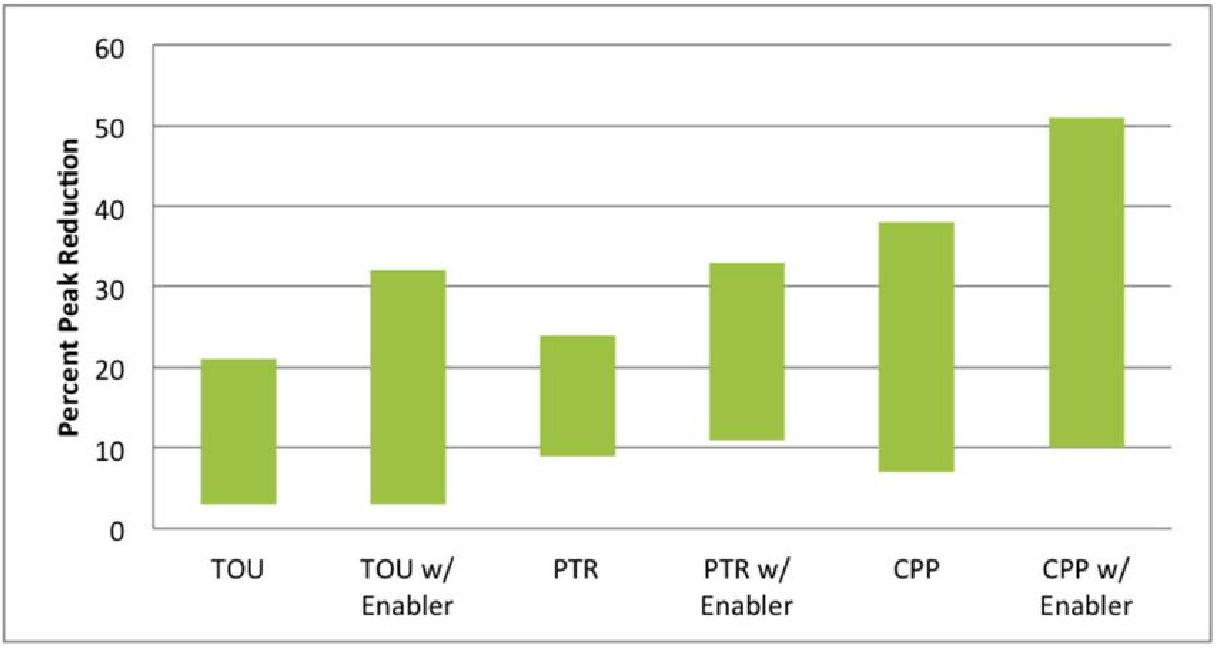
Within the segment of distribution, storage plays an important role as well. This technique takes the form of distributed storage (DS) and the use of PHEVs as a means to store electricity has been mentioned several times by researchers. A higher penetration of electric vehicles automatically means a larger supply of batteries. These could be deployed by vehicle-to-grid technology in order to store electricity. A vehicle connected to the grid with a full battery could be drained in times of high demand and vice versa (Guille & Gross, 2009). However, a distributed storage system doesn't necessarily have to depend on PHEVs for storage capacity, as other technologies could be installed as well. The main advantages of DS would be peak load reduction, off-peak storage and ancillary services for the regulation of frequency (Eyer & Corey, 2010).

Furthermore, automated distribution should also add self-healing capabilities to the electricity grid. Through the use of sensors inconsistencies in frequency and quality can easily be measured and the grid can respond accordingly. Through this technology, outages can be reduced and even forecasted (Simoes et al., 2012). As became clear from the concept of a microgrid, in some cases a surplus of energy could be produced and sold back into the grid. In order to feed electricity back into the grid, devices that are able to convert the DC power created by RES to AC and maintain a constant level of quality need to be developed and optimized. These devices are called power electronics, and should enable bidirectional power flow, synchronization capabilities, smart metering and fault tolerance/self healing (Simoes et al., 2012).

Supply

The implementation of an advanced metering infrastructure (AMI) is one of the most prominent features of a SG, and concerns the integration the data from consumers and the aforementioned automated distribution sensors and provides network operators with a multitude of the data previously available. The concept of an AMI could therefore be seen as somewhat transcending the traditional borders of the supply segment, but since many of its key features concern customer interaction it is listed in this section.

Demand-side management (DSM) is a key concept within the AMI, and refers to "the ability to change energy consumption patterns and characteristics via structured programs" (Simoes et al., 2012). This can be achieved through the installation of smart meters for consumers, of which the deployment has already started in many European countries. Smart meters replace old, analog electricity meters for customers with a more modern, digital version, and unlock new streams of information in the process. A range of strategies to accomplish behavioral change through demand-side management has been proposed, some of which are dynamic pricing models (of which several versions have been suggested) and automatic control schemes (Depuru et al., 2011).



TOU: Standard Time-Of-Use rate design; *n* = 37 studies.
TOU w/Enabler: TOU with enabling technology; *n* = 14 studies
PTR: Peak-Time Rebate rate design; *n* = 12 studies
PTR w/Enabler: PTR with enabling technology; *n* = 17 studies
CPP: Critical Peak Price rate design; *n* = 23 studies
CPP w/Enabler: CPP with enabling technology; *n* = 21 studies

Figure 2: Benefits from various dynamic pricing models (SGCC, 2013).

Dynamic pricing models aim to reflect the actual cost of energy by changing prices according to information provided by a central data station. Through this technology, behavioral change and increased awareness of consumers could be achieved by implementing time-of-use- (TOU), critical peak- (CPP), or real-time- (RTP) pricing schemes (Geelen et al., 2013). An overview of the benefits in terms of peak reduction is presented in figure 2. *"Smart meters can also be used to monitor and also to control all home appliances and devices at the customer's premises"* (Depuru et al., 2011). Through the use of home energy management systems (HEMS) smart meters could be enabled to control 'smart appliances', e.g. household appliances that can be controlled by the grid operator or through the use of an application (Geelen et al., 2013). HEMSs can be configured to switch smart appliances on/off, or adjust their settings. These services could manifest themselves to the end user through an in-home display (IHD) (Hledik, 2009). IHD are not necessarily bound to a dedicated display inside the residence. Experiments have been ongoing using websites or smartphone applications as a means to cut costs of implementation.

These variations in tariffs, the increased customer awareness and automated control of consumer appliances can stimulate load shifting, resulting in smaller peak demand and a less volatile load. Furthermore, they can provide an incentive for trading of energy, for example by selling energy produced by a MG when demand is high (Geelen et al., 2013). Automated monitoring could also reduce non-technical losses of energy (electricity theft for example) by reducing to time taken to identify the location of losses (Depuru et al., 2011). Other functions of the AMI consist of automatic billing and outage management systems which reduce outage times by sensing and predicting irregularities within the grid, such as faults and overloads (Hart, 2008).

Overarching

Some technologies that need to be developed affect all parts of the energy supply chain and are therefore listed in this section. The data generated by smart meters needs to be transmitted towards central data stations. There are a number of technologies that have been suggested to enable this communication, "which use the existing electricity grid, cellular/pager network, mesh network, combination of licensed and unlicensed radio, wireless modem, existing internet connection, powerline communication, RS-232/485, Wi-Fi, WiMAX, and Ethernet to upload data" (Depuru et al., 2011).

Since SGs rely more heavily on ICT then the current electricity grid, they are more vulnerable to cyber-attacks. The security of these information systems therefore needs to be severely enhanced (McDaniel & McLaughlin, 2009). The technicalities of these security measures are outside of the scope of this review and will not be discussed.

2.3 Costs and benefits of the SG

In the following chapter, estimations of the costs and benefits of the technologies discussed in the previous chapter are obtained through the review of several reports. These will be evaluated in terms of total monetary costs, annual benefits and annual reductions in CO_2 emission. Monetary costs and benefits will be expressed in €2014 (in most cases €B, or €billion), reduced CO_2 emissions in megatonnes (Mt), and added generation capacity in gigawatts (GW). In the last part of this chapter, the differences between the US and EU that could affect these estimations are discussed.

Monetary costs

There have been various estimations of the monetary costs of implementing a SG. Total implementation costs for the US have been estimated at €329 billion for a low RES penetration (BAU) scenario or €464 billion with a RES penetration of 20% (EPRI, 2011). For the low-cost scenario, these would translate to €80, €226 and €23 billion dollars for the segments 'transmission and substations', 'distribution' and 'consumer' respectively (see figure 3).

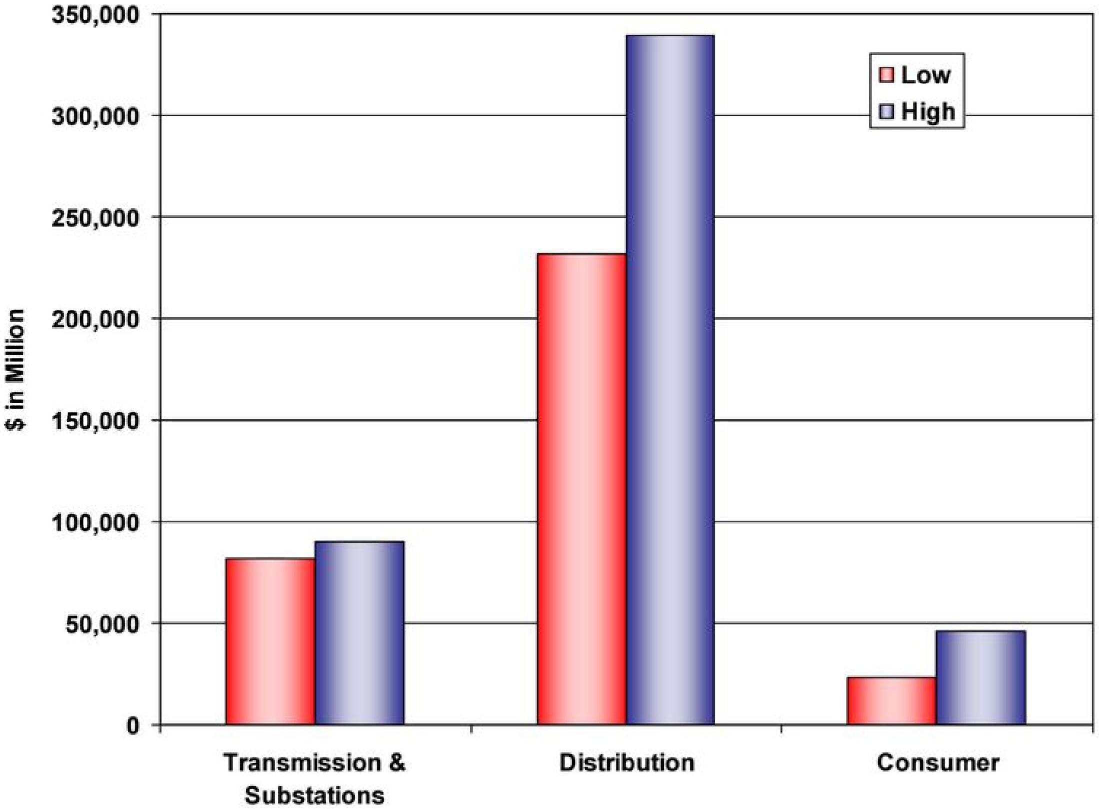


Figure 3: Costs for different segments of the supply chain as projected by EPRI (2011).

Other reports for the US have chosen to present the costs on a per-customer basis, in order to perform a costs-benefits analysis from the customer's point of view. The costs-per-customer (CPC) are estimated at €346, categorised into 'smart meter' (€284) and 'distributed automation' (€62) (SGCC, 2013). The CPC as estimated by other reports is presented in the same row. SGCC claims to review rather than forecast the estimated costs and benefits of the SG since more data is becoming available, and focusses on the segments of distribution and supply of the residential part of the grid only.

The costs for implementing a SG within the supply segments seems to be the only consistent estimation across all reports. SGCCs (2013) estimations of the costs for upgrading the distribution segment are much smaller than estimations by other reports, since a smaller variety of technologies is considered. However, the costs for implementing AVC seem to be estimated quite similar within both reports.

The IEA presents the 'New Policies Scenario' in its World Energy Outlook (WEO), in which official targets set by specific regions are taken into account. Investments in renewable generation are estimated to be much higher in Europe, mainly due to more progressive environmental goals, while investments in transmission and distribution technologies will be smaller (IEA, 2010). It is estimated that 3-4% of total costs made within the transmission and distribution segments are related to enabling integration of a higher penetration of RES (IEA, 2010).

	EPRI (2011)	SGCC (2013)	International Energy Agency (2010) (p. 199)	International Energy Agency (2010)
Region	United States	United States	Europe	United States
Period	2011-2031	Total	2010-2035	2010-2035
Total (€B)	€329-464	€44.4	€2126.5	€1743
Renewable generation (GW/€B)			630/€1351	357/€777.5
Transmission (€B)	€80-88		€153.5	€299
Distribution (€B)	€226-330	€7.9	€622	€667
Advanced Voltage Control (€B)	€3.7-16.2	€7.9		
Supply (€B)	€23-44	€36.5		
CPC (€)	€970 - 1366[1]	€346	€8179[1]	€13630[1]

Table 1: Estimated monetary costs of the implementation of a SG

Monetary benefits

There are several stakeholders involved in the implementation of a SG, segmented into consumers, utilities and society. Benefits for consumers and utilities are rarely mutually exclusive, since increases in efficiency translate into lower production costs, which in turn translates to lower electricity prices (EPRI, 2011). The categories of monetary and environmental benefits are not mutually exclusive, since some of these benefits are the direct result of a reduction in energy use and can therefore affect total CO_2 reduction as well. This can be recognized in the fact that a distinction is being made between direct and indirect benefits. Direct benefits are monetary benefits that find their way directly to the customers electricity bill. Indirect benefits are an attempt to translate increases in reliability and environmental gains into a monetary value.

The report by EPRI takes the benefits for all stakeholders into account, while the report released by SGCC focusses solely on the benefits for consumers. Total benefits in the period 2011-2035 are estimated at €1205-1889 billion accounting for all stakeholders, and including direct and indirect benefits (EPRI, 2011). The most consistent estimation seems to be the benefits from time-varying rates or dynamic pricing schemes, an extensively researched subject with multiple large-scale project already up and running (Geelen et al., 2013; SGCC, 2013; Depuru et al., 2011). Annual direct economic benefits

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[1] See assumptions (4.3) for number of connected customers to each grid. Note that these take all stakeholders into account and do not focus on customers specifically.

for customers have been estimated at €36-€93 due to lower energy losses. Indirect benefits have been estimated at €45-€49 (SGCC, 2013). It is likely that most differences between both reports can be attributed to the selection of stakeholders that are accounted for. The WEO does not provide an estimation of the benefits of a SG.

	SGCC (2013)	**EPRI (2011)**
Region	United States	United States
Period	Annual	Annual
Total (€B)	€4.51-11.3	€24.9-58.1
Generation (€B)		€13.5-44.5
Regulation capacity reduction (€B)		€9-17.5
EV/PHEV capacity (€B)		€4.5-27
Distribution (€B)	€1.29-3.67	€1
Advanced Voltage Control (€B)	€1.29-3.67	
Load shifting (€B)		€1
Supply (€B)	€3.22-7.63	€10.35-12.55
Time-varying rates (€B)	€0.23-2.09	€0.9
Pre-payment programs (€B)	€0.84-2.1	
Remote meter reading (€B)	€1.58-2.75	€4.75
IHD (€B)	€0.09-0.21	€1-3.2
Other factors (€B)	€0.48	€3.7

Table 2: Estimated monetary benefits from the implementation of a SG

Environmental benefits

The environmental benefits of the implementation of a SG are hard to estimate since a variety of technologies are still being considered. Some attempts have been made at quantifying them, and the results of these reports are expressed both in an absolute and relative (compared to projections) value in table 3. Total benefits are estimated to range from 3.1Mt (0.1%) up to 475Mt (15.8%).

Hledik (2009) presents a conservative and an expanded scenario that are both modelled for the US. Total reductions in CO_2 by 2030 are estimated at 5.1% and 15.7% respectively. The expanded scenario takes the implementation of a larger penetration of renewables (20%) and the mandatory automated distribution upgrades that accompanies these RES, and is therefore more closely related to the other scenarios presented here. 4% is attributed to overall conservation due to consumer awareness and peak demand is said to be reduced by 11.5% (which seems conservative compared to figure 2), resulting in a CO_2 reduction of 1.1% (Hledik, 2009). EPRI (2011) estimates that line losses will be reduced by 0.1-0.6%, which is in line with numbers provided by Hledik (2009).

Hledik (2009) observes that load shifting leads to a reduction in CO_2 emissions in some parts of the US, but also to an increase in other parts. This is due to the fact that loadshifting results in a decrease of natural gas peak load generation and an increase in coal-based baseload generation, and benefits in this area are thus highly dependant on fuel mix. Other reports make similarly small estimations. The reduction of emissions due to the implementation of load regulation cannot be contributed solely to the use of cleaner sources of energy, because it also means load regulation plants will have to ramp up or slow down production less often, resulting in more efficient fuel use. At the same time indirect benefits are gained, since emissions are reduced because the construction of extra generation capacity is avoided (PNNL, 2010). Supported penetration of RES offers very little direct benefits (<0.1%) but large indirect benefits (5%) (PNNL, 2010).

EV/PHEV capacity refers to the additional amount of EVs that can be charged using the SG in comparison to current EG technologies. These numbers will be higher since the SG will allow for better control of moments of charge, outside of peak hours (PNNL, 2010). EVs being charged through the grid are more efficient than vehicles burning fossil fuels directly, since these resources can be converted more efficiently in large scale electricity plants than in small combustion engines (EPRI, 2011). Smart charging allows for 18 million more EVs than the projected capacity using unmanaged charging, estimated at 140 million. These differences occur because many EVs arrive home during peak hours and commence charging immediately. The benefits shown in the table are derived solely from this increase in capacity. Additionally, a higher penetration of EVs enables the storage of electricity by DS. However, the monetary and environmental benefits of these processes are too uncertain to estimate at this point.

	SGCC (2013)	**Hledik (2009)**	**PNNL (2010)**	**EPRI (2011)**
Region	United States	United States	United Stated	United States
Period	Annual	2010 - 2030 (Annual)	2010 - 2030 (Annual)	2010-2030 (Annual)
Total	3.1-34.3 Mt (0.1-1.2%)	471 Mt (5.1-15.7%)	475 Mt (15.8%)	54-188 Mt (1.8-6.3%)
Generation		297 Mt (9.7%)	233 Mt (5.32%)	19-37 Mt (0.6-1.2%)
EV/PHEV capacity			82 Mt (3%)	10-60 Mt (0.3-2%)
Regulation capacity			1 Mt (0.02%)	

reduction				
Indirect benefits			150 Mt (5%)	
Transmission		21 Mt (0.7%)		3-18 Mt (0.1-0.6%)
Distribution	up to 21.5 Mt (<0.75%)	3 Mt (0.1%)	60 Mt (2%)	2-18 Mt (<0.6%)
Integrated Volt/vAR control	up to 21.5 Mt (<0.75%)		59 Mt (2%)	2-16 Mt (<0,5%)
Load shifting		3 Mt (0.1%)	1 Mt (0.03%)	0-2 Mt (<0.06%)
Supply	3.1-12.8 Mt (0.1-0.4%)	153 Mt (5%)	182 Mt (6%)	23-73 Mt (0.8-2.4%)
Time-varying rates	0.6-6.4 Mt (0.01-0.2%)	102 Mt (3.3%)		
Prepayment programs	1.7-4.4 Mt (0.1-0.2%)			
Mass deployment diagnostics			90 Mt (3%)	1-5 Mt (<0.2%)
IHD (customer awareness)	0.8-2 Mt (0.03-0.1%)	51 Mt (1.7%)	92 Mt (3%)	22-68 Mt (0.7-2.3%)

Table 3: Estimated environmental benefits from the implementation of a SG

Differences

A number of problems arise when trying to compare the estimations. The exact benefits of some technologies are (still) hard to quantify, allowing for very large ranges of predictions. Most reports classify their findings and estimations into a number of arbitrary categories that often differ between reports, and use a different definition or scope of the technologies that a SG consists of, or use different BAU- or hypothetical scenarios as a benchmark. Another problem is the different stakeholders that are accounted for within the various reports: some only focus on residential customers, while others also include commercial and industrial customers.

There are several factors that might influence the applicability of the models for environmental and monetary benefits within the US towards the EU. As noted by Hledik (2009) and others, the composition of the fuel mix for the generation of electricity determines whether peak load reduction results in net environmental benefits or costs. The relative share of coal within the fuel mix is smaller within the EU, which could indicate larger possible environmental benefits. However, “the estimation of energy and carbon benefits achievable by load shifting is challenging because of the highly dynamic nature of the power plant dispatch options that provide literally thousands of options for rearranging the generation mix, and the corresponding generating efficiency and carbon intensity of the input fuel" (PNNL, 2010).

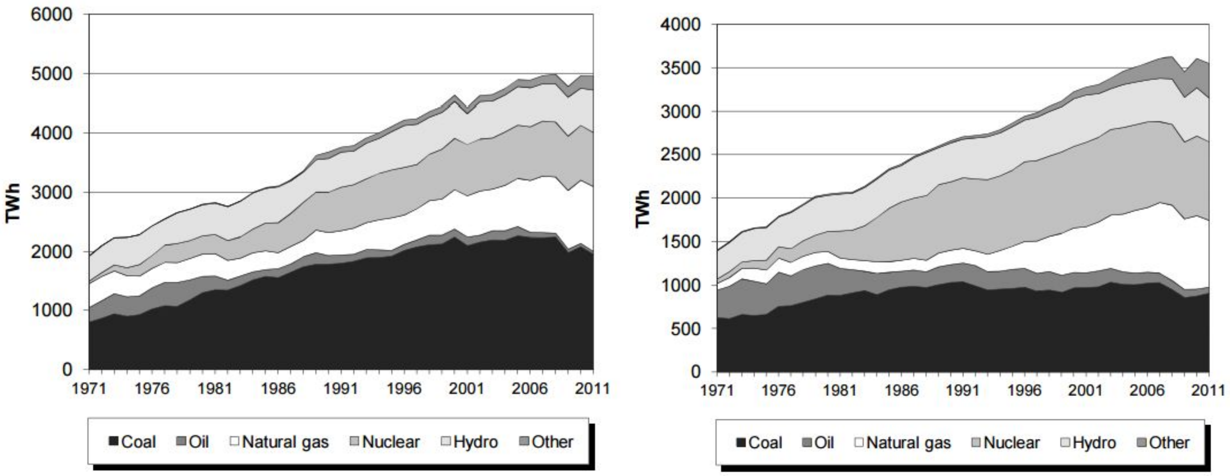

Figure 4: Comparison between US (left) and EU (right) electricity generation fuel mix (IEA, 2012).

A possible method for quantifying the benefits or losses of peak load reduction is the 'Renewable Energy Capacity Planning (E3 RECAP) model[2], which takes all these variables into account. Unfortunately, an application of the E3 RECAP model to estimate the effects of peak load reduction is outside of the scope of this review. Average electricity consumption per customer is also smaller in the EU than in the US (5633 vs.11280 kWh/year), which could reduce benefits from DSM compared to the US (IEA, 2012).

Another variable that could influence the applicability of several models is the reduction in outage times and security of supply, which are already relatively high in the EU compared to the US (Campbell, 2012), which drastically reduces benefits in this category.

2.4 Obstacles for the implementation of the SG

The implementation of a SG within Europe in order to progress towards environmental goals still faces a number of challenges from a technological, economical and social perspective. These will be discussed in the following chapter.

Shared vision

First and foremost, the biggest obstacles for the estimation of the costs and benefits of a SG is the absence of a shared vision for both the components that make up the grid and for the methodology of assessment. The absence of a shared vision for the components that make up the SG is logical, because as research into new technologies continues, certain possibilities will present themselves as being more fruitful than others and will thus be incorporated or disintegrated from the concept of a SG.

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[2] Model available from https://ethree.com/public_projects/recap.php.

However, several methodologies for assessing the costs and benefits of the SG have been proposed, but few have been conducted on a larger scale and even less methodologies have been used more than once, which makes a direct comparison of several reports hard to achieve and poses problems when trying to identify the low-hanging fruits for investments and benefits.

Technical

By creating a shared vision, the industry would also be enabled to establish standards for the production of SG components. "By allowing components to interact with each other, and ultimately to reduce costs, standards will enable true interoperability between assets produced by various companies." (Simoes et al., 2012). A conclusion that can be drawn from the comparison in the previous chapter is the fact that not a single business case or quantifiable benefit has been given for bulk storage of electricity (EPRI, 2011). While the need for storage as an effect of RES generation can be reduced by connecting grids over longer distances, it would greatly enhance the maximum capacity for RES penetration.

Economic

Some economical obstacles to making progress towards environmental goals through the implementation of a SG can be recognized from the comparison made in the previous chapter. One of these obstacles is the relatively small reductions in CO_2 emissions that can be accomplished by shifting peak demand. Even though these monetary and environmental benefits are small, shifting peak demand is necessary to allow for a higher penetration of RES. These discrepancies between direct and indirect benefits could be problematic.

It should be noted that most reports and research into the development of SGs is several years old, which could be partly attributed to the economic crisis that has hit many countries worldwide. This means that "as more and more governments are taking austerity measures, this funding [for SG projects] is expected to decrease, or not be renewed, and will need to be either replaced or supplemented by private funding sources" (Simoes et al., 2012). Another challenge is the changes to present business models that accompany the unbundling of the segments of the energy supply chain. Is has been observed that EU countries with less concentrated markets show higher penetrations of DG, while more concentrated markets are generally slower to pick up on the trend (Ferreira et al., 2011).

Social

In many EU countries and US states, concerns have been expressed about privacy issues regarding the installation of an AMI and smart meters. These concerns definitely need to be addressed, and are "fundamentally an issue about the choice of parameters to be transmitted and administrator authentication to access that information" (Bennett & Highfill, 2008).

3.1 Conclusion

As can be observed from the reports discussed in this paper, the reductions in consumption and emission that can be achieved through the implementation of a SG suggest that while the implementation of a SG alone is not enough for achieving long-term climate goals in the EU, it is capable of delivering a substantial contribution to some of them. Additionally, the SG is a major tool in achieving RES penetrations higher than 20% (PNNL, 2010), which in turn is a key factor in achieving long-term environmental goals after 2020. Transmission and distribution investments will be lower in the EU than in the US while generation investments will be higher due to more aggressive environmental goals.

The need for the formulation of a shared vision has to be stressed, as it is probably the largest obstacle for further research. The term SG is used in different ways and categories for judging the benefits differ across reports making direct comparisons hard to achieve. Furthermore, a shared vision will enhance the establishment of standards within the industry, which would in turn increase the speed of implementation. Especially in Europe, where differences in legislation concerning the electricity grid and market may cause significant hiccups in the implementation of the SG, the need for a shared vision and clear definition in order to enable standardization efforts is dire.

A few components of the SG with little monetary or direct benefits but greater environmental benefits have been identified, such as the increase of customer awareness or an increased capacity for RES integration.

3.2 Discussion

It has to be noted that extensive estimates of the large-scale costs and benefits of a SG are more prevalent in US research. EU research could be done by applying the methodologies described in the various reports discussed in this paper. Some examples of EU research exist, such as the cost-benefit analysis "*A Smart Grid for the City of Rome*" by Vitiello et al. (2015), but they do not cover large-scale estimates for all segments of the supply chain. Differences in stakeholders, timelines, technologies and scenarios accounted for make it difficult to compare estimations and reports to one another.

A possible strategy for improving the level up to which future research can be compared to other reports, is a segmentation for the different stakeholders involved (consumers, utilities and society). An improved estimation could also be made when more data about a feasible business case for energy storage becomes available. This would likely reduce the need for FFPPs during peak demand, and have an positive impact on the emission of CO_2. The limits for RES penetration within the SG should be researched, especially photovoltaics and wind generation. In this review, the implications and difficulties of securing the grid from cyber-attacks have not been accounted for. These should be discussed more thoroughly in future research.

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4.2 Terminology

€B: billions of euros
AMI: advanced metering infrastructure
AVC: advanced voltage control
BAU: business-as-usual
CPC: cost per customer
DG: distributed generation
DSM: demand side management
EV: electric vehicle
EG: electrical grid
FFPP: fossil fueled power plant
GW: gigawatt
HVDC: high voltage direct current
KPI: key performance indicator
Mt: megatonnes
MWh: mega watt hour
NTL: non-technical loss
PEC: primary energy consumption
PD: peak demand
RES: renewable energy sources
SG: smart grid
SM: smart meter

4.3 Assumptions

Average American residential electricity consumption	11280 kWh	SGCC, 2013
Average EU residential power electricity	5633 kWh	IEA, 2012
Number of residential customers connected to the US grid	127,882,249	http://www.eia.gov/electricity/annual/html/epa_01_02.html
Number of residential	260,000,000	http://www.eurelectric.org/me

customers connected to the EU grid		dia/113155/dso_report-web_final-2013-030-0764-01-e.pdf
Euro-dollar conversion	€1 = $1.14	07.08.2015