A systematic review of environmental and economic impacts of smart grids

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Abstract

Smart grids (SGs) have a central role in the development of the global power sector. Cost-benefit analyses and environmental impact assessments are used to support policy on the deployment of SG systems and technologies. However, the conflicting and widely varying estimates of costs, benefits, greenhouse gas (GHG) emission reduction, and energy savings in literature leave policy makers struggling with how to advise regarding SG deployment. Identifying the causes for the wide variation of individual estimates in the literature is crucial if evaluations are to be used in decision-making. This paper (i) summarizes and compares the methodologies used for economic and environmental evaluation of SGs (ii) identifies the sources of variation in estimates across studies, and (iii) point to gap in research on economic and environmental analyses of SG systems.. Seventeen studies (nine articles and eight reports published between 2000 and 2015) addressing the economic costs versus benefits, energy efficiency, and GHG emissions of SGs were systematically searched, located, selected, and reviewed. Their methods and data were subsequently extracted and analyzed. The results show that no standardized method currently exists for assessing the economic and environmental impacts of SG systems. The costs varied between 0.03 and 1,143 M€/yr, while the benefits ranged from 0.04 to 804 M€/yr., suggesting that SG systems do not result in cost savings The primary energy savings ranged from 0.03 to 0.95 MJ/kWh, whereas the GHG emission reduction ranged from 10 to 180 gCO_2/kWh, depending on the country grid mix and the system boundary of the SG system considered. The findings demonstrate that although SG systems are energy efficient and reduce GHG emissions, investments in SG systems may not yield any benefits. Standardizing some methodologies and assumptions such as discount rates, time horizon and scrutinizing some key input data will result in more consistent estimates of costs and benefits, GHG emission reduction, and energy savings.

Keywords: smart grid, ICT, electricity grid, cost/benefits, energy efficiency, GHG emissions

1. Introduction

The electricity network (i.e., electricity grid) is a physical infrastructure for the production, transmission, and distribution of electric power. It also represents an important carrier of economic and social development, mainly because of its relevant role in the spatial allocation of energy resources [1]. The current electric power system in many developed countries and regions strongly relies on fossil fuels such as coal, oil, and natural gases, which conflict with the needs to reduce GHG emissions and to increase the share of renewable energy sources in the power supply mix. Moreover, the present electric grid in many industrialized countries was built at the beginning of the twentieth century [2]. In Europe, for instance, the integration of electricity networks was achieved with the creation of the European Economic Community

(EEC). The European electricity grid is a radial energy flow [3] characterized by four main links: generation, transmission, distribution, and off-take. In this power generation and supply system, generators are power plants that produce electricity from different energy resources. These power plants are connected to high-voltage transmission networks that in turn, by means of a series of step-down transformers, are connected to low-voltage networks closer to the electricity users. At the end of the supply chain, consumers are connected to the low-voltage network by means of a second series of transformers.

These infrastructures were designed to produce reliable electricity at a reasonable cost [4], but the suitability and sustainability of this aging infrastructure to meet today's increasing electricity demand and to perform reliably in a situation of high volatility in fossil fuel prices has been heavily criticized by several authors [2,4,5]. Network congestion often occurs because current grid systems are unable to cope with such issues in a timely fashion. Such imbalances can lead to blackouts, which are costly for utility companies since they can spread rapidly due to the lack of communication between the grid and its monitoring center. These imbalances, combined with the needs to reduce GHG emissions, increase the share of renewable energy sources in the power generation mix, increase energy efficiency, and stabilize the volatility of fuels and electricity prices [5], have encouraged the modernization of conventional electricity supply chains, which are, at present, inadequate to meet these needs [2,4–6]. Among the potential solutions to these problems, smart grids (SGs) have been identified as the best tool to help reach energy and climate goals, with numerous benefits for both the supply and demand sides of the electricity market [7].

Smart grids are the result of the application of advanced communication devices to various segments of the actual electricity grid [4]. More specifically, a SG 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" [8]. This technologically advanced network is expected to facilitate the integration of renewable generation technologies such as, photovoltaic and wind, and innovative user applications (e.g., electric vehicles, heat pumps, distributed storage) into the electric grid, and thus to facilitate a transition to a low-carbon energy generation system [9,10]. The advantages of implementing a SG include: (i) reliability and security of energy distribution, (ii) shift of the peak load, (iii) enhanced efficiency, (iv) enable high shares of renewables in power system, (v) decreased GHG intensity of power system, and (vi) active participation of consumers [6,11–15]. Despite its potential benefits, initiatives and investments for the transition to a smarter energy system in the EU and in other developed countries have been low and have only started in the two last decades [2,16]. One reason for low investment in SGs may be the lack of information about the possible costs and benefits, as well as the environmental impacts of SG systems. Appropriate information on costs, benefits, GHG emissions, energy use, and other indicators is needed before decisions about considerable investment and large-scale deployment and diffusion of SG technologies in the EU and elsewhere can be made.

Earlier review studies on SGs have focused on more qualitative aspects of SGs, such as network protection [17], the role of Information and Communication Technologies devices on SGs [18–20], SG simulation tools and business models [10], definition of the benefits of SGs [21], and regulatory barriers for implementing SG technology [22–24]. Inevitably, the specific scope of each of these studies varies, but they all broadly suggest that the evolution toward a SG is worthwhile from economic and climate standpoints as an SG can reduce maintenance and congestion costs, and help to easily integrate renewable energy sources and distributed generation in the power supply mix [25,26]. However, these early analyses provide neither quantitative estimates nor convincing evidence of the net economic and environmental benefits of SGs. Identifying and understanding the reasons for variation in the estimates of costs, benefits, energy use, and GHG reduction is imperative for decision making at both regional and national levels. Except for a few qualitative syntheses [10,21,27], no quantitative review addressing simultaneously the economic and environmental impacts of SG systems has been undertaken until now. To fill this gap in research, the current paper (i) summarises and compares the methodologies used for economic and environmental evaluation of SGS, (ii) identifies the sources of variation in estimates across studies, and (iii) points to gaps in research and provides recommendations for future research on economic and environmental analyses of SG systems.

2. Database construction

Web of Science, Science Direct, and Google Scholar databases were searched for original studies published between 2000 and 2015 on economic costs and benefits, energy efficiency, and GHG emissions. The concept of SGs is new and appeared in scientific literature only since 2000. The keywords *smart grid*, *cost-benefit analysis*, *environmental impacts*, and *energy efficiency* were used in different combinations to identify relevant studies. Because of the limited number of peer-reviewed articles, the search was extended to include technical reports. One hundred and ninety-two articles and reports that met the terms used for the search were collected. A study was included in the analysis if it contained quantitative estimates of economic costs, energy efficiency, or GHG emissions and if it presented the methodology used to estimate the costs and benefits, energy use, or GHG emissions of SG systems. Studies related to only a segment of the grid were also included, whereas those addressing more broad topics such as “smart buildings” or “smart cities” were excluded from the analysis. Review articles, commentary letters, viewpoints, and editorial abstracts were excluded as this review focused on full-length, original studies. Studies not written in English were also excluded from this analysis. As a result, 17 studies (nine papers and eight reports containing quantitative estimates on cost-benefit analyses, energy use, and GHG emissions of SG systems) were selected for further analysis and evaluation. Data relating to the methodologies used, the system boundaries (generation, transmission, distribution, and consumption), and the technological devices included, as well as the SG definition, were extracted and entered into an Excel spreadsheet. Data reporting on the economic costs and benefits, GHG emissions, and energy savings, as well as the main assumptions made (for example, time scale, market penetration of renewable energy source, consumers' responses) for the analysis were elicited and further analyzed. Moreover, the reported data on energy savings, GHG emissions, and economic costs and benefits were elicited in order to obtain comparable results among the different studies (Table 1). The US dollar, Canadian dollar, Australian dollar, Danish Krone, Chinese Yuan, Japanese Yen, and Korean Won–to-Euro were converted to euros based on the exchange rates reported by the European Central Bank[1]. All the monetary values were adjusted for inflation using the data reported by the OECD[2] Descriptive statistics were used to evaluate the reported outcomes once they were converted to the same measurement units.

[1] https://www.ecb.europa.eu/stats/eurofxref/eurofxref-hist.xml?08acf7445df8cd19a51f0f885edfe310.
[2] https://data.oecd.org/price/inflation-cpi.htm#indicator-chart

Table 1: List and main characteristics of the examined publications (*N* = 17).

Country	SG definition	Technology included	Assumptions	Reference
Czech Republic		*Not specified*	*Not specified*	[28]
Hungary		Renewable energy resource and electric vehicle	Energy savings from 9 kWh to 150 kWh and CO_2 emissions based on country statistical data	[29]
New Jersey (USA)	An intelligent system that consists of an autonomous digital system capable of identifying surges, downed lines, and outages; resilient or "self-healing," which provide instantaneous damage control; flexible, which is capable of accommodating new off-grid alternative energy sources; reliable, which provide dynamic load balancing; and secure, minimizing vulnerability to terrorist or other attacks	Oil steam, coal steam, combined cycle gas turbines, wind, and nuclear power plant	Different combinations according to the level of penetration of SG devices into the current grid and according to different possible nondominated functions of smart technologies used (Pareto set)	[15]
Japan		Advanced Impedance Monitoring (AIM) and system performances monitoring	All consumers will change their behavior. Energy-use reduction of 6 percent. Electricity price 0.21 dollar/kWh. Energy savings of 100 dollars per barrel	[30]
European Union		Reduction in demand due to smart meter adoption (AMI)	AMI costs: mean value 120 to 450 euros from household and nonhousehold meters	[16]
United States		Several ICT utilities used as prototypical "examples" at different stages of deployment of the smart grid	One million customers within the service area; AMI is phased in gradually over a five-year time horizon	[31]
United States		Electric vehicles 16 kWh per one electric battery pack	Perfect market information: the value includes the degradation costs of the battery pack (4.2 dollar/kWh). Battery replacement $5,000	[32]

United States	"Smart Grid" refers to a modernization of the electricity delivery system so that it monitors, protects, and automatically optimizes the operation of its interconnected elements—from the central and distributed generator through the high-voltage transmission network and the distribution system, to industrial users and building automation systems, to energy storage installations, and to end-user consumers and their thermostats, electric vehicles, appliances, and other household devices	*Not specified*	The costs include the infrastructure to integrate distributed energy resources (DER) and to achieve full customer connectivity but exclude the cost of generation, the cost of transmission expansion to add renewables and to meet load growth, and a category of customer costs for smart-grid-ready appliances and devices. NPV for benefits estimated based on 2010 prices level	[33]
United States	A unified communications and control system on the existing power delivery infrastructure to provide the right information to the right entity (for example, end-user devices, T&D system controls, customers) at the right time to take the right action. It is a system that optimizes power supply and delivery, minimizes losses, is self-healing, and enables next-generation energy efficiency and demand response applications	Considering only the most direct-benefit mechanisms (improve operational efficiency, transform consumers' user behavior, introduce new hi-tech devices, Plug-in Hybrid Electric Vehicle penetration, etc.)	SGs resolve the wind energy intermittency by 25–50 percent; will save fuel costs since they run on the equivalent of 75 cents per gallon; 10–20 percent of reduction share due to PHEV penetration	[34]
Canada		Forty-one-bus radial system with one substation feeding per rural area (peak load 16,8 MW). The system includes: one substation (peak load 16,8 MW), seven wind power plants (power rated 1.1MW), and two diesel generators (power factor 1-0.9)	*Not specified*	[35]
Netherlands		Excluding smart meters and PCs	The router, PC, and smart meter were not included in the system boundaries. The economic profit is calculated as a 10 percent energy savings	[36]

Denmark	A smart grid is an "electricity network that can intelligently integrate the behaviour and 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."	Wind generation, electric vehicle, and heat pumps	Prediction on future electricity generation and consumption that brings about a high degree of uncertainty. Wind generation = 50 percent of annual consumption, electric vehicles = 600,000, and heat pumps = 300,000	[37]
China		Virtual power plant[a]	*Not specified*	[38]
United Kingdom	A smart grid is an electricity power system 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[b].	Renewable generation, home appliances, electric heating, electric vehicles, and distributed generation	Predictions based on past distribution price controls appropriately adjusted for savings that the deployment of a smart grid would generate. Deployment of smart technologies before 2020 and the majority of EV and heat deployment will occur after 2020	[39]
United Kingdom		Smart metering infrastructure, EVs, and HPs	Replacement of network assets was not accounted for. Different level of penetration of EV and HP (10-25-50-75-100%) Diversified household load profiles and average national driving patterns applied to all local networks	[40]
Australia	A smart grid is the application of information and communications technology to improve the efficiency and effectiveness of the generation, transmission and distribution, and usage of power.	Power management and information technologies, grid voltage control, energy storage, EVs, substation and network monitoring, and distributed generation	• \$21 million of societal value per minute of System Average Interruption Duration Index. • \$40/tCO2-e	[41]
South Korea		*Not specified*	Only direct benefits have been covered. The 32-year aggregate penetration of smart grid technologies will be 80 percent; the average generation capacity factor will increase to 80 percent in 2030; the 80% reduction in transmission	[42]

outage frequency is assumed; the discount rate is 6 percent and the exchange rate is ₩[c]1,200/$

[a] Defined as a set of devices or equipment that allow users to save power consumption [38]
[b] UK's Department of Energy and Climate Change (DECC)
[c] The won (₩) is the currency of Korea

Table 2: Data extracted from the examined publications for analysing the environmental and economic impact assessments of SG (n= 17).

Country	Economic impacts	Environmental impacts	Methodology	System boundary	Energy saved[a]	GHG emissions[b]	Other air emissions[c]	Baseline GHG emissions[b]	Costs[d]	Benefits[d]	Discount rate (%)	Time scale[e]	Reference
Czech Republic	√		CBA	Whole power industry					0.65	0.40	8	20	[28]
Hungary		√	Estimation based on energy savings forecasting	Transportation and distribution		168.85		337.69				1	[29]
New Jersey (USA)	√	√	CBA using Stochastic optimization method	Whole power industry (electricity generation expansion planning)		195.97[f]	21.04[f]		2.30[f]			15	[15]
Japan	√	√	CBA	Yokohama-wide energy system		275.04	2.05	285.37	1.17	1.01		1	[30]
European Union	√		CBA	Whole power industry					2.31	2.22[g]	8	20	[16]
United States	√		CBA	*Not specified*						2.48		20	[31]
United States	√		Transaction costs analysis	*Not specified*						0.04		6	[32]

United States	√		CBA	Fully functioning smart grid					0.03	0.15		20	[33]
United States		√	Estimation based on energy savings and SG penetration	The whole power generation system	0.95	551.4		640			5	22	[34]
Canada	√	√	CBA using multi-objective mathematical programming	Grid to consumers for demand response participation		169.03[c]		248.43	25.79[h]			*Not specified*	[35]
Netherlands	√	√	LCA and economic costs estimation	Home energy management system (production, use, and disposal)	0.031[i]					0.071[i]		5	[36]
Denmark	√		CBA	Whole power industry					96.37	80.64	5	15	[37]
China		√	Estimation based on historical data and future scenarios	Whole power industry		520		700				20	[38]

United Kingdom	√	CBA	Distribution network		1,143.14	804.41 [j]	3.5	38	[39]
United Kingdom	√	CBA	Distribution network			176.54[k]	3.5	20	[40]
Australia	√	Estimation	National whole power industry			4,121.21 [m]		1	[41]
South Korea	√	CBA	National whole power industry			235.86	6	22	[42]

[a] MJ/kWh
[b] gCO_2/kWh
[c] gSO_2/kWh
[d] Ml€/year
[e] Years
[f] Average value considering scenarios with: 0 percent, 5 percent, and 10 percent of demand shift from peak hours to off-peak hours
[g] Average value considering: high (10 percent) and low (2 percent) smart meter adoption scenarios
[h] Average value considering: baseline, cost minimization, costs, and emission minimization scenarios
[i] Average value considering scenarios with: energy monitoring and multifunctional and energy management
[j] The benefits were linked to the cost savings compared to investments costs in conventional grid technologies [39]
[k] Average value related to ten different rates of uptake (from 10 percent to 100 percent) of electric vehicles and heat pumps over the next 20 years.
[m] The benefits were estimated in terms of gross social benefit

3. Results

3.1. General characteristics of the reviewed studies

The United States and the EU are the leading nations/regions in SG research (6 studies each), followed by Japan, Canada, China, Australia, and South Korea with one study each (Table 1). Fifty three percent of the reviewed studies solely focused on economic costs and benefits of SGs, 23.5% assessed both the GHG emissions and energy savings, and the remaining studies (23.5%) investigated both the economic and environmental impacts.. One study on economic impacts reported only the costs [15], whereas another estimated only the benefits of SGs [32]. A striking feature of the reviewed studies is the lack of a standardized definition of SGs (Table 1). Of all the analysed studies, only four clearly defined SGs, discussed why SGs are important, and provided the goals of SG infrastructure development. In these studies, SGs have been defined by referring to their principal characteristics such as (i) optimizing power supply and delivery, (ii) automatically minimizing losses through transmission and distribution, (iii) providing instantaneous damage control, and (iv) accommodating new off-grid alternative energy sources [15,34,43].

The methodologies used to assess the costs and benefits, GHG emissions reduction, and energy savings differ across studies. Four methods were used to estimate the costs and benefits of SG systems. These methods include: , (i) transaction cost methods [32], and (ii) cost-benefit analysis (CBA) [15,16,30,31,35,37,39,40,42]. Moreover, the latter were also used in combination with stochastic or multi-objective optimization models (OP models) [15,35]. With regard to the assessment of environmental impacts, the methods used include: (i) life-cycle assessment [36] and (ii) carbon footprinting methods [29,34,38] (table 2). Each of these methods has its own advantages and disadvantages, as summarized in the following section. The time frame for the economic evaluation varies from one day to 38 years, with most studies choosing 20 years, which correspond to the average lifetime of a power grid. The share of renewable energy into the mix ranges from 20 to 50% and have been indicated in only four studies (Table 2).

3.2. Evaluation of the outcomes of the economic and environmental impact assessment of SGs

3.2.1. Economic impacts

The distribution of costs and benefits reported by the examined studies is shown in Figure 1. The system boundary includes the electricity production, transmission, and distribution network. The reported economic costs of SG systems range from 0.03 to 1,143.14 M€/yr, whereas the estimated benefits varied from 0.04 to 804.41 M€/yr (figure 2). The minimum cost estimate appeared in USA study, whereas the higher cost was related to the United Kingdom (e.g. Canadian) study. The potential benefits of SGs varied from 0.04 to 804.41 M€/yr (Figure 1). Here the minimum benefits originate from the study of USA while the maximum potential benefits of SG investment was from United Kingdom Study On average, the costs exceeded the benefits by 59.1 M€/yr. Figure 2 corroborates this latest result as it shows that cost-benefit ratios are higher than the unit, as reported by the six studies that present both economic indicators. But one study [33] reported higher potential benefits of SGs relative to costs (Figure 2). Consequently, SG systems are not economically viable despite their positive effect (that is, reduction) on GHG emissions and on other environmental impacts. Differences in estimates of costs and benefits are mainly due to the scope of the analysis, electricity prices, assumptions about the capacities, utility operating characteristics, and to a lesser extent, the data used and time horizon of the different ICT devices. Therefore, even when studies used the same methods and considered the same system boundary, the assumptions regarding data sources, electricity prices, discount rates, and time scale have a large influence on estimates of the costs and benefits of SG systems.

3.2.2. Environmental impacts (GHG emission reductions, energy savings)

The GHG emission reductions range from 10 to 180 gCO_2/kWh with a median value of 89 gCO_2/kWh, depending on the country grid mix, assumptions on both the type and the level of penetration of renewable energy into the power grid, as well as on the system boundary of the considered SG systems (Figure 3). GHG emissions were larger in countries with a high share of fossil fuels in the grid mix and where a high level of penetration of renewable energy was assumed. The GHG emission reductions due to energy losses on the electric network were three times smaller than the emission reductions due to the penetration small. This finding clearly illustrates that the penetration of renewable energy sources is the key parameter for estimates of GHG savings of smart grid systems. Emission reductions were almost two times higher in studies focusing on only a segment of the electricity grid mix than those considering the full electricity grid mix. The reason for this is that the major contributing processes or stages of GHG emissions were excluded from the system boundary (Table 2). With regard to other environmental burdens, three of the reviewed studies report a reduction of pollutants responsible for acidification (SO_2), eutrophication (NO_x). The reduction in SO_2 emissions range from 2 to 21 gSO_2/kWh, while the range for NO_x was 0.41 to 12 gNO_x/kWh.
Finally, two studies reported on the energy savings of SG systems in addition to environmental impacts [34,36]. The reported data on primary energy savings ranged from 0.031 to 0.95 MJ/kWh (mean = 49 MJ/kWh) (Table 2). As in the case of GHG emission reductions, the system boundary as well as the renewable energy penetration and the composition of the electricity grid mix explains the large variation in estimates. Variation in

estimates is to a lesser extent also explained by the assumptions made for some key parameters such as the time frame and the annual energy consumption. However, the influence of these parameters are weaker than the assumption on the penetration of renewable sources in the electric grid mix.

3.3. Critical evaluation of methods used for economic and environmental impact assessment of SGs

CBA is one of the prevalently used method for evaluating economic attractiveness of SGs (Table 1). It compares in a holistic way the cost and benefits of SGs and hence determine whether the benefits outweigh expected costs. A SG project or technology is cost-saving if the economic benefits exceed its costs. It includes every accountable item as well as externalities that affect investment in SGs, it also has transparent assumptions and can accommodate sensitivity or uncertainty analyses. Although relatively easy and straightforward, CBA has a number of drawbacks such as the ambiguity and uncertainty involved in assigning monetary value to intangible items, the potential inaccuracies in identifying and quantifying all costs and benefits, the sensitivity of CBA to a chosen discount rate, and its inability to handle complex investment decisions (Kornhauser 2000).

The OP models aim to assess the optimal solution to a problem [15,35] and hence are used after the feasibility of a project has been determined. Their combination with CBA improve the reliability of the analysis which commonly assesses the economic impacts of SGs at early planning stages [44],. Moreover, OP models aim to find the optimal solution that will achieve the goals of a project while optimizing the related mathematical objective functions. This intrinsic characteristic entails a vast difference between the two methods. CBA relies on the use of indicators (usually the net present value and internal rate of return) in order to assess the economic and environmental impacts of a project, thus making the outcomes of the assessment comparable between two distinct projects [45]. This attribute is not the case for OP models, whose outcomes cannot be compared with projects that have different objective functions. Nevertheless, both methodologies share the need for several assumptions (time frame and discount rate).

Transaction cost analysis (TCA) belongs to the domain of economic entities' behaviour as governance structure [46]; therefore, this methodology is best suited for assessing the preconditions for consumers' participation in demand-response or distributed generation systems. Though not commonly used for the economic evaluation of a project or product, the TCA method is often used in information system to support the idea that ICT can reduce imperfection in the economic system [47] In SG literature, it has been used to estimate the economic benefits resulting from the integration of EVs into the electricity grid, by modelling the energy arbitrage by owners to balance their electricity consumption [32]. Although the extensive meaning associated to transaction costs theory [48], one advantage of this method is the capability of capturing the broader political, institutional and market environment. However, unlike the CBA method, transaction costs are not commonly included in empirical evaluations of alternative policies [49].

The CBA applied in the papers studied focused on the evaluation of a project from a societal point of view; hence, it encompasses economic and environmental costs and benefits, which are usually measured in monetary units. Given the lack of market prices, often this represents a delicate methodological issue. The main difference between CBA and LCA relates to scope of the assessment. While CBA focuses on the assessment of both economic and environmental costs, LCA accounts only for the environmental impacts, and it needs to be combined with other methodologies (for example, life-cycle costing) in order to provide economic impacts. Opposite of CBA and OP models, LCA focuses on a product's impact assessment instead of on a project [44]. This difference determines the way the methods deal with time-related issues. Moreover, the need to define the full or economic life cycle of each product within the studied project requires the LCA to obtain more data. Hence, a huge modelling effort is requested to broaden the scope of the analysis encompassing the assessment of a whole project.

4. Discussion

4.1. Origin of wide variation in definitions, data, and models

Most of the evaluated studies did not define SG while other have defined it in a variety of ways (Table 1). Thus, despite the fact that SG systems have been researched at various institutions and discussed in many scientific journals and publications, there is still no globally agreed-upon definition for SG systems and their requirements (Table 1). SG systems cover a wide range of innovations and technologies in the energy sector, affecting electricity generation, transmission, distribution, and consumption. Several earlier studies and reports have come to the same conclusion regarding the definition of SG systems [15,34,43]. Some authors state that the concept of SGs is difficult to define [50]. Although still difficult to define, our synthesis shows that a common element in most definitions is the application of digital processing and communication to the electricity grid, making data flow and information management central to the smart grid (Table 1). This common element could be then used for harmonisation of the definition of SG systems and will significantly reduce differences in definition of SG systems.

Significant variation exists among studies in their estimates of the economic and environmental impacts of SG systems. These variation are primarily due to assumption about discount rate, the time horizon, the identification and valuation of intangible benefits of SG systems, and to some little extent to the methodology used. The time horizon of CBA varies according to the nature of investment. In this review, the time frame varies from 1 day to 38 years (Table 2), but no justification for the selection of a specific time frame is provided. Given that energy infrastructure projects are often appraised over a period of 20-30 years [51]. Selection of other time period should be clearly justified and sensitivity analyses performed. Like the time horizon, the discount rate significantly influences CBA analyses and thus the assessment of SG scenario. This is because SG projects have upfront costs, with the benefits occurring in future. So the overall net present value of SG project depend on the level of which the discussion rate is set. The higher the discount rate, the higher the presumed time preference for immediate costs and benefits, and the lower the value on future benefits and costs. The discount rate in the reviewed studies varies from 3.5% to 8% (Table 2). At the European level, a societal discount rate of 3.5%, 4% and 5.5% have been recommended [51,52]. However, different discount rate values maybe used and justified on the basic of a specific country macroeconomic condition. Losses often occur during the transport of electrical energy through the transmission and distribution network. These losses differ from countries to countries because of the difference in physical characteristics between power generation, transmissions, and distribution systems. SG significantly influences these electrical losses, and so, the method used to quantify and to value these losses differ between countries, and can thus influence the CBA analysis of SG systems.

Despite the wide differences in the estimates of individual studies of, this review demonstrates that investments in most cases investments in SGs do not offer significant benefits. Our reported costs (i.e. 0.03 -986.8 M€/yr) was lower than the cost range (275 - 455 billion euros) for modernization of the US power grid as estimated by Langheim et al. [13]. The analysis also show that there is a gap of 51.2 2 M€/yr between the costs and the expected benefits of SG. Although lower, than the cost-benefit gap of 10–15 billion euros reported by Faruqui et al. [16] for the full penetration of smart meter in Europe by 2020, our findings corroborate Faruqui et al. [16] conclusion that smart grid project may not result in cost-savings.

However, given the limited number of studies included in this analysis and the fact that most SG systems are still at laboratory or pilot scale (that is nonoptimized), these latest conclusions must be interpreted with care. Estimates of costs, benefits, may change as new data become available and as SG systems evolve and the intangible costs and benefits are better understood, identified and quantified.

The analysis show that SG systems deployment results in energy saving and GHG emission reduction (Figure 2). Most of the quantified reduction of environmental impacts of SG systems comes from the integration of renewable energy sources and the extent of such reduction will rely in large part on the types of services or technologies pursued once a SG system is implemented. Considering the GHG emission reductions, Figure 4 shows that the implementation of SGs results in a net annual reduction of CO_2 emissions ranging from 0.7 to 2.1 $GtCO_2$/yr. North America and China show the highest capability for CO_2 emission reductions (Figure 4) [52]. Our results corroborate the findings of the IEA, as they clearly identified the United States, Canada, and China as being the regions/countries with the greatest potential CO_2 emission reductions (see Table 2). These countries have a high share of fossil fuels (mainly coal) in their power production mix. Consequently, a high penetration or integration of renewable energy sources through SGs would inevitably lead to high emission reductions. In contrast, SG implementation results in small CO_2 emission reduction in countries with a high share of renewable energy sources or a high share of nuclear power in their electricity grid mix (Figure 3).

The observed wide variations in the estimates of energy savings, and GHG emission reduction across studies are not only due to the difference in physical characteristics between power generation, transmissions, and distribution systems in different in different countries/regions, but also to the inconsistent methodology, data input, and assumptions on the type and fraction of renewable energy technology implemented (Table 2). To reduce variation in estimates between studies the environmental impact analyses should consider actual data from the available SG pilot projects that have been developed or are currently being developed. Some efforts have already been made in this direction [44,50], but the standardization of a SG impacts assessment framework is far to be completed. Such a unified framework will enable the evaluation based on realistic estimates of all kinds of SG systems, thus helping to mitigate investment risks in SG systems and make informed decisions on practical deployment options.

4.2. Research gaps and recommendations

Various methods are used in literature to quantify the economic and environmental impacts of SG systems (Table 2). While each method has its own advantages and drawbacks, it may also lead to the large variation observed in estimates of costs, benefits, and CO_2 emission reduction. As SG capabilities evolve from pilot/demonstration to business as usual operation, the establishment of clear guidelines for the types of costs and benefits that utilities should consider. Although Galo et al. [56] already proposed a priority index to create a precise framework to promote the adoption of SG technologies, there is a need to develop and test a framework for cost-benefit assessments of SG systems. Such a framework could take advantage of the EPRI or its modified version by the EU-JRC and must consider the physical characteristics and deployment of SG systems, capture specifically the spatial variations of power grid mixes among countries or regions, and contemplate the long-term energy and climate policy goals of each country/region. Such a unified framework should incorporate a standardised discount rate, and time period. This could help reduce variation in future estimates of costs - benefits assessment of SG systems.

One striking feature of this analysis is the lack of analyses and discussion of the uncertainties associated with estimates of environmental impacts, costs and benefits over the term of the payback period. The documentation of key assumptions underlying the analyses (especially those that are susceptible to having a high degree of variability and uncertainty) is also lacking in some reviewed studies (Table 1). Uncertainties are unavoidable in both CBA and environmental impact analyses of SG systems because several assumptions need to be made regarding the parameters of the baseline scenario [57,58]. Future efforts should concentrate on quantifying the impacts that these uncertainties have on estimates of costs and benefits and environmental impact analyses and on identifying which parts of SG systems require accurate data collection. Research is also needed to identify and quantify all intangible costs-benefits susceptible to affect the economic valuation and the environmental impacts of SG systems.

Finally, a reason for the relatively small number of studies on economic and environmental impacts of SGs in the literature is the lack of experimental data (especially those on ICT and automation devices) needed for economic and environmental impact analyses. Developing accurate assumptions before gathering specific data from pilots and demonstration projects is difficult given the differences in physical characteristics and spatial variations in power grid mixes in different developed countries and regions. Research is needed to provide data across a wide variety of SG devices and systems. This will help to validate and thus reduce uncertainty in estimates of CBA and environmental impacts.

5. Conclusion

SGs have a central role in the development of the power sector in many developed regions. Over the years, many institutions have made significant contributions to the literature on economic and environmental impacts of SG systems. This review summarizes and analyses the methods used to estimate the economic and environmental impacts of SG systems. It shows that no standardized method currently exists for assessing the economic and environmental impacts of SG systems. Moreover, the context, boundaries, and ICT technologies included should be made very clear so that comparison and extrapolations can be made. Significant variation exists among studies in their estimates of SG systems, so the precise costs, benefits, and GHG emission reductions are uncertain. Standardizing some methodologies and key assumptions (time horizon, discount rates for costs), as well as scrutinizing some key input data (e.g. data related to electricity losses), can result in more consistent estimates of costs, benefits, GHG emission reductions, and energy savings estimates. Despite these variation, the analysis shows that SG systems may not results in cost-savings but contribute to energy and GHG savings due to the large deployment of renewable energies.

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Figure Legends

Figure 1: Greenhouse gas emission and emission reductions of SG systems relative to conventional grid baseline GHG. $N = 5$ is the number of studies included in the analysis of GHG emission reductions.

Figure 2: Distribution of costs and benefits of SG systems evaluated in this study. $N = 12$ is the number of studies included in the analysis of economic costs and benefits.

Figure 3: Distribution of the cost/benefit ratios from the analyzed studies. $N = 6$ is the number of studies included in the analysis of economic cost/benefit ratios.

Figure 4: Regional CO_2 emission reductions from SG deployment (adapted from IEA, 2013).