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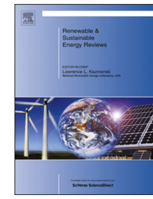

A systematic review of environmental and economic impacts of smart grids

M. Moretti [a,*], S. Njakou Djomo [a,c], H. Azadi [a], K. May [b], K. De Vos [b], S. Van Passel [a,d], N. Witters [a]

[a] Hasselt University, Faculty of Business Economics, Centre for Environmental Sciences, Martelarenlaan 42, 3500 Hasselt, Belgium
[b] KU Leuven–EnergyVille, Department of Electrical Engineering, Kasteelpark Arenberg 10, 3000 Leuven, Belgium
[c] Aarhus University, Department of Agroecology, Blichers Alle 20, P.O. Box 50, DK-8830 Tjele, Denmark
[d] University of Antwerp, Faculty of Applied Economics, Department of Engineering Management, Prinsstraat 13, B-2000 Antwerp, Belgium

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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 analysed. 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 1143 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.

Contents

* Corresponding author. Tel.: +32 11 268742.
E-mail address: michele.moretti@uhasselt.be (M. Moretti).

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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 centre. 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) 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) 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 analysed. 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 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.

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 six estimated only the benefits of SGs [32–34,40–42].

A striking feature of the reviewed studies is the lack of a standardized definition of SGs (Table 1). Of all the analysed studies, only six defined SGs 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 [15,35,36].

The methodologies used to assess the costs and benefits, GHG emissions reduction, and energy savings differ across studies. Three methods were used to estimate the costs and benefits of SG systems. These methods include: (i) costs estimation, (ii) transaction cost methods [34], and (iii) cost-benefit analysis (CBA) [15,16,30,33,28,37,41,42]. Moreover, the latter were also used in combination with stochastic or multi-objective optimization models (OP models) [15,28]. With regard to the assessment of environmental impacts, the methods used include: (i) life-cycle assessment [32] and (ii) carbon footprinting methods [31,36,38] (Table 2). 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. 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 [44].

The OP models aim to assess the optimal solution to a problem [15,28] 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 [45] Moreover, OP models aim to find the optimal solution that will achieve the goals of a project while optimizing the related mathematical objective functions. While 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, making the outcomes of the assessment comparable between two distinct projects [46], the outcomes of OP models cannot be compared if projects have different objective functions is not possible to compare. Therefore, although CBA is a more general methodology they share the same purpose. 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 [47]; therefore, this methodology is best suited for assessing the preconditions for consumers' participation in demand-response or distributed generation systems. Although 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 [48]. 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 [34]. Although the extensive meaning associated to transaction costs theory [49], 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 [50].

Although Life Cycle Assessment (LCA) is the primary methodology used in carbon footprinting, the latter are more limited in scope and impacts than the former. Carbon footprint methods are, indeed, mainly focused on GHG emission, while LCA analysis commonly contemplate a wider array of environmental impacts such as: acidification, eutrophication, natural resources depletion, etc. Moreover, carbon footprints are rarely associated with detailed definition of system boundaries or others methodological accounts. They are therefore difficult to compare with the footprints of similar projects or products [51].

[1] https://www.ecb.europa.eu/stats/eurofxref/eurofxref-hist.xml?08acf7445df8cd19a51f0f885edfe310.

[2] https://data.oecd.org/price/inflation-cpi.htm#indicator-chart

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

Type of analysis	Methodology	SG definition	System boundary	Technology included	Assumptions	Country/region	References
Economic and environmental	CBA/OP		Grid to consumers for Demand Response participation	RET	Three DR programs (Demand Bidding; Ancillary Services and DRSP) combined with wind generation 41-bus radial system with 1 substation feeding a rural area (peak load 16.8 MW) The system include: 1 substation (peak load 16.8 MW); 7 wind power plant (power rated 1.1 MW); 2 diesel generators (power factor 1–0.9)	Canada	[28]
Economic and environmental	CBA	"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-use consumers and their thermostats, electric vehicles, appliances, and other household devices.	How SG technologies in the distribution affect the generation expansion	FFT, RET, ICT	Different combinations according to the level of penetration of SG devices into the current grid and according to different possible non-dominated functions of smart technologies used (Pareto set)	USA	[15]
Economic	CBA		Whole Power Industry	RET	Shift-load for pick to off-pick for Czech households	Czech	[29]
Economic	CBA		Whole Power Industry	ICT (AMI)	(1) AMI costs: mean value 120 to 450 euros from household and non-household metres. (2) Demand reduction due to dynamic pricing form 8-10% to 60-90% (3) Avoided cost of capacity 87euro/KW-year	EU	[16]
Economic and Environmental	CBA		Yokoama-wide energy system	RET,ICT	(1) 6% of energy-use reduction (2) All consumers will change their behaviour. (3) Energy-use reduction of 6 percent. (4) Electricity price 0.21 dollar/kWh (5) Energy savings of 100 dollars per barrel	Japan	[30]
Environmental	Estimation based on energy savings forecasting		TSO and DSO	RET, EV	(1) Energy savings from 9 kWh to 150 kWh and CO_2 emissions based on country statistical data. (2) 5% of the power loss during transmission and distribution (total 9.72%) will be saved using distributed generation (3) Energy savings and GHG emissions are estimated considering an average consumption of 3000 kWh/household –yr	Hungary (EU)	[31]
Environmental and economic	LCA and eco-cost estimation		HEMS production, use and disposal considering and average Dutch household consumption patterns	ICT	Three HEMS systems (energy monitoring, Multifunctional HEMS, Energy management device). (1) Router, PC, and smart metre were not included in the system boundaries. (2) The economic profit is calculated as a 10 percent energy savings. (3) Yearly energy consumption: 3500 kWh and 52,800 m^3 natural gas. (4) Increase in energy consumption 1.5% per year	Netherlands (EU)	[32]
Economic	CBA		Generation, TSO DSO and consumption	ICT, EV	(1) One million consumers involved.	USA	[33]

					(2) AMI is phased in gradually over a five-year time horizon. (3) Costs include: direct smart metre operational benefits and consumer-driven benefits according the mix of technologies they use		
Economic	Transaction cost			EV	(1) 16 kWh vehicle battery pack. (2) Perfect market information: the value includes the degradation costs of the battery pack (4.2 dollar/kWh). Battery replacement $5000 (3) Electricity price for 140–250 US dollars	USA	[34]
Economic	CBA	"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-use consumers and their thermostats, electric vehicles, appliances, and other household devices.	Fully operational SG	ICT, RET	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. (1) The deployment of new technologies is considered a steady process at 2010 (2) The decreasing prices of new technologies have been estimated (3) Maintenance costs have been included (4) NPV for benefits estimated based on 2010 prices level	USA	[35]
Environmental	Estimations based on ICT market penetration	A unified communications and control system on the existing power delivery infrastructure to provide the right information to the right entity (e.g. end-use devices, T&D system controls, customers, etc.) 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.	The whole energy sector	RET, ICT	ITC devices penetration level: (1) 25–75% of devices for direct communication with consumers (2) 25–50% of devices for reducing line losses (3) 5–25% of devices for continuous maintenance of commercial building equipment (4) Potential peak demand reduction from 5% to 20%	USA	[36]
Economic	CBA	Smart Grid is'electricity networks 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.	The whole power sector	RET, ICT, EV	(1) Prediction on future electricity generation and consumption which rises a high degree of uncertainty. (2) Wind generation=50% of annual consumption.	Denmark	[37]
Environmental	Estimation on historical data and future scenario		The whole power sector (virtual power plant[a])	RET,	Electricity savings: (1) In lighting: 55% (2) In motor system efficiency 30%. (3) In electric appliances 10%. (4) In line losses: 10–20%. (5) Load management 1%	China	[38]
Economic	CBA	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]	Distribution network	RET, ICT, EV	(1) Predictions based on past distribution price controls appropriately adjusted for savings that the deployment of a smart grid would generate. (2) Deployment of smart technologies before 2020 and the majority of EV and heat deployment will occur after 2020 (3) Only DSR technology costs to reduce local network costs are included (4) Whether you have a smart distribution grid or not, the costs of generation and transmission are virtually identical	UK	[39]

Table 1 (*continued*)

Type of analysis	Methodology	SG definition	System boundary	Technology included	Assumptions	Country/region	References
Economic	Economic Estimation	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.	The whole power sector	RET, ICT, EV	(1) For consistency, the conservative approach taken throughout this report is to report the minimum level of benefit expected from each application. The key drivers of uncertainty include changes in customer behaviour during peak hours and the performance of specific technologies. (2) $21 m of societal value per minute of System Average interruption Duration Index (3) $40/tCO2-e based	Australia	[40]
Economic	CBA		Distribution network	ICT, EV	(1) Different level of penetration of EV and HP (10–25–50–75–100%). (2) Diversified household load profiles and average national driving patterns applied to all local networks.	UK	[41]
Economic	CBA		Whole power sector	ICT,RET	(1) Only direct benefits have been covered. (2) The 32-year aggregate penetration of smart grid technologies will be 80 percent; (3) the average generation capacity factor will increase to 80 percent in 2030; (4) the discount rate is 6 percent and the exchange rate is ₩[c]1200/$; (5) 80% increases of the average generation capacity; (6) 80% reduction in transmission outage frequency	South Korea	[42]

FFT=fossil fuel technology (coal, natural gas, oil), NP=Nuclear power, RET=Renewable energy technology (Solar, wind, biomass, hydropower), ICT=information and communication technology (Router, sensor, smart metre) Application technology (electric vehicle), NA=network assets.

[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 ($n=17$).

Methodology	System boundary	Composition of the grid			Baseline conditions, conventional grid			Assumptions			SG-Scenario References				Country/region	Discount rate (%)	Intangible/ Intangible costs	References
		%FFT	%NP	%RE	cost[a]	GHG[b]	EE[c]	Time	%RE	%ICT	Cost[a]	GHG[b]	EE[c]	Oth				
CBA/Multiob. Op. demand and reserve sheduling	Three DR programs (Demand Bidding; Ancillary Services and DRSP) combined with wind generation					248.4		Next 24 h				169			Canada[f]		Both	[28]
CBA	Fully functioning Smart Grid							15 yr	30		1.84	196			USA		Tang	[15]
CBA	Whole Power Industry							20 yr			0.59				Chzech (EU)	8	Tang.	[29]
CBA	Whole Power Industry							20 yr			2.55				EU	8	Both	[16]
CBA	Yokoama-wide energy system	68	20	12		285.37		1			0.97	275.04		2.05[d]	Japan		Both	[30]
Estimation based on energy savings forecast	TSO and DSO	55.6				337.69						168.85			Hungary (EU)		Both	[31]
LCA and eco-cost estimation	HEMS production, use and disposal considering and average Dutch household consumption patterns							5					0.031		Netherlands (EU)		Both	[32]
CBA[e]	Generation, TSO DSO and consumption							20							USA		Tang.	[33]
Transaction cost[e]															USA		Both	[34]
CBA	Fully operational SG							20	20 (only wind)+ 135 GW of other		0.03				USA		Tang.	[35]
Estimation based on ICT devices penetration	The whole electricity sector					640			From 52 to 50%			551.4	0.95		USA	5	Both	[36]
CBA	The whole power sector							15		80	87.6				Denmark	5	Both	[37]
Estimation on historical data and future scenario	Whole power sector		25%			700		20	25.4 in 2020 and 37.2 in 2030			520			China		Tang.	[38]
CBA	Distribution network							38			1143.14				UK	3.5	Both	[39]
Estimation[e]	The whole power sector														Australia		Both	[40]
CBA[e]	Distribution network							20							UK	3.5	Both	[41]
CBA[e]	Whole power sector			₩ 3437 million/ MW				22							South Korea	6	Tang.	[42]

[a] Ml€/year.
[b] gCO_2/kWh.
[c] MJ/kWh.
[d] gSO_2/kWh.
[e] Only the benefits are reported.
[f] Average value considering: baseline, cost minimization, costs, and emission minimization scenarios.

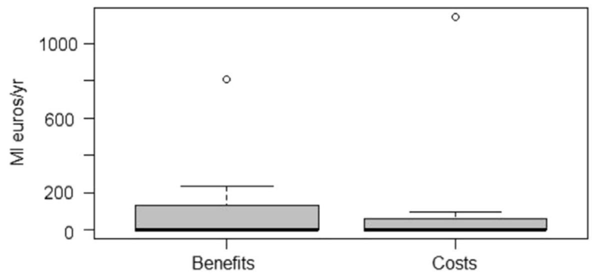

Fig. 1. Distribution of costs and benefits outcomes from the analysed references (Ml€ yr^{-1}, $n=12$). Distribution of costs and benefits of SG systems evaluated in this study**.** $n=12$ is the number of studies included in the analysis of economic costs and benefits.

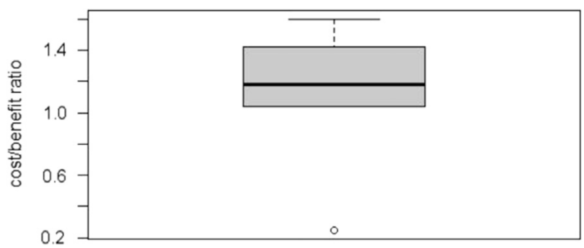

Fig. 2. Distribution of the cost/benefit ratios from the analysed studies ($n=6$). $n=6$ is the number of studies included in the analysis of the distribution of costs/benefits ration.

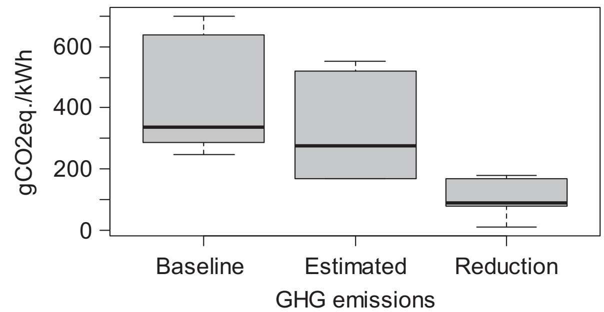

Fig. 3. Distribution of GHG emissions outcomes for the studied and baseline scenarios (gCO_2 kWh^{-1}; $n=5$). Greenhouse gas emission, and emission reductions of SG systems relative to conventional grid baseline GHG. $n=5$ is the number of studies included in the analysis of GHG emission reductions.

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

3.3.1. Economic impacts

The distribution of costs and benefits reported by the examined studies is shown in Fig. 1. The system boundary includes the electricity production, transmission, and distribution network. The reported economic costs of SG systems ranged from 0.03 to 1143.14 M€/yr, (Fig. 1). The minimum cost estimate appeared in the US study, whereas the higher cost was related to the United Kingdom study (Table 2). The potential benefits of SGs varied from 0.04 to 804.41 M€/yr (Fig. 1). Here the minimum benefits originate from the study of Peterson et al. [34] in the US while the maximum potential benefits of SG investment was from the study of Easton et al. [39] in the United Kingdom. On average, the costs exceeded the benefits by 59.1 M€/yr. Fig. 2 corroborates this latest result as it shows that cost-benefit ratios are higher than the unity, as reported by the six studies that present both economic indicators.. Differences in estimates of costs and benefits are mainly due to the scope of the analysis, electricity prices, assumptions about the inclusion of tangible and intangible costs and benefits, the time horizon of interest, space (i.e. geographical area), discount rates, the capacities, utility operating characteristics, and to a lesser extent, the data used for 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.

3.3.2. 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 (Fig. 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 renewables. 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) and eutrophication (NO_x). The reduction in SO_2 emissions range from 2 to 21 gSO_2/kWh, while the range for NO_x was 0.41–12 gNO_x/kWh.

Finally, two studies reported on the energy savings of SG systems in addition to environmental impacts [32,36]. The reported data on primary energy savings ranged from 0.031 to 0.95 MJ kWh^{-1} (mean=49 MJ kWh^{-1}) (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.

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 [15,35,36]. Some authors state that the concept of SGs is difficult to define [52]. 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

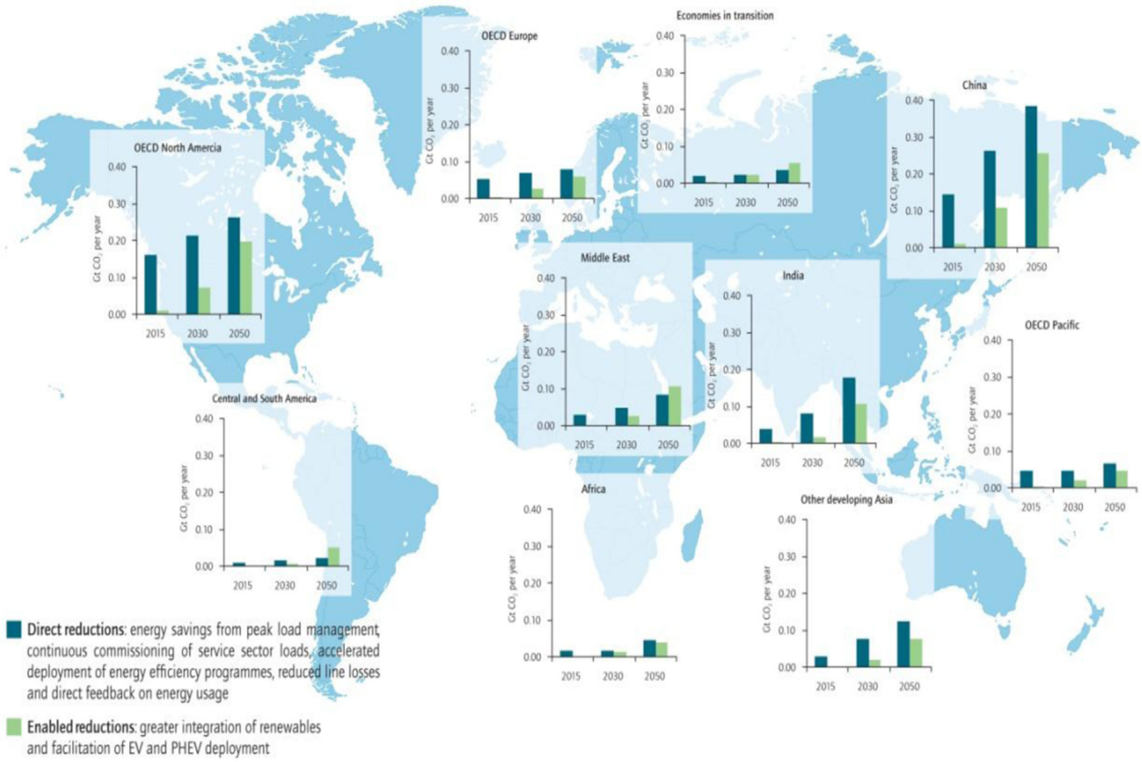

Fig. 4. Regional CO_2 emissions reduction from SG deployment (Adapted from IEA, 2013).

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.

Whit regard to economic impacts, the 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 year 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 [53]. 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. Hence, the overall net present value of SG project depend on the level of which the discount 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 [53,54]. However, different discount rate values may be used and justified on the basic of a specific country macroeconomic condition.

Moreover, 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, this review demonstrates that investments in most cases investments in SGs do not offer significant benefits (Fig. 1). 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 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 metre 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 means non-optimized), these latest conclusions must be interpreted with care. Estimates of costs and 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 (Fig. 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, Fig. 4 shows that the implementation of SGs results, worldwide, 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 (Fig. 4) [55]. 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 (Fig. 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 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 [56,57], 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 is highly relevant.

Although Galo et al. [58] 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 standardized 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 [59,60]. 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. Therefore, 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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