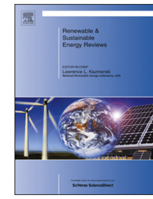
Renewable and Sustainable Energy Reviews ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



A systematic review of environmental and economic impacts of smart grids

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A R T I C L E I N F O

Keywords:
Smart grid
ICT
Electricity grid
Cost/benefits
Energy efficiency
GHG emissions

A B S T R A C T

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

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http://dx.doi.org/10.1016/j.rser.2016.03.039
1364-0321/

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

Please cite this article as: Moretti M, et al. A systematic review of environmental and economic impacts of smart grids. Renewable and Sustainable Energy Reviews (2016), http://dx.doi.org/10.1016/j.rser.2016.03.039