sustainability

MDPI

Article

Economic Cost–Benefit Analysis on Smart Grid Implementation in China †

Newell Sarpong Boateng [1], Marco Ciro Liscio [1,2,*], Paolo Sospiro [1,2,3,4] and Giacomo Talluri [5]

1 EUAbout, 1000 Brussels, Belgium; paolo.sospiro@uniecampus.it (P.S.)
2 Department of Information, Polytechnic University of Marche, 60121 Ancona, Italy
3 Department of Industrial Engineering, University of Florence, 50121 Florence, Italy
4 Dipartimento di Scienze Teoriche e Applicate (DiSTA), eCampus University, 22060 Novedrate, Italy
5 Department of Energy "Galileo Ferraris", Polytechnic of Turin, 10129 Turin, Italy; talluri.giacomo@gmail.com
* Correspondence: m.c.liscio@pm.univpm.it

† This article is a revised and expanded version of a paper entitled "Smart Grid implementation in China: A Cost-Benefit Analysis" presented at the ICAE2023 Conference, Doha, Qatar, 3–7 December 2023.

Abstract: The last Five-Year Plans (2016–2025) in China emphasise economic modernisation, focusing on boosting the services sector, urbanisation, and the expansion of the social safety net. China's net-zero strategy targets achieving climate neutrality by 2060, necessitating a transition away from coal toward cleaner energy sources, which accounted for 60.6% of total energy consumption in 2023, to Variable Renewable Energy Sources (VRES). By 2021, VRES contributed 23.4% of power generation. To integrate VRES, Smart Grids are critical, as they autonomously manage energy production, distribution, and consumption. These grids support industrial and residential smart devices, electric vehicle charging, and battery storage. This paper applies a cost–benefit analysis using a customised version of the Electric Power Research Institute US methodology to assess Smart Grid investment in China from 2020 to 2050. The results show a benefit-to-cost ratio of 6.1:1, demonstrating substantial economic benefits. The focus on China serves as a valuable case study for Smart Grid implementation worldwide, with the methodology adaptable for use in other countries and across different scales. These findings can assist global decision-makers in evaluating the advancement in technology, policies, and potential economic impact of Smart Grids and also in comparisons with other players such as the US.

Keywords: Smart Grid; sustainable energy management; cost–benefit analysis; Variable Renewable Energy Sources; China; digitalisation; sustainability

Academic Editor: Bowen Zhou

Received: 15 February 2025
Revised: 11 March 2025
Accepted: 25 March 2025
Published: 26 March 2025

Citation: Boateng, N.S.; Liscio, M.C.; Sospiro, P.; Talluri, G. Economic Cost–Benefit Analysis on Smart Grid Implementation in China. *Sustainability* **2025**, *17*, 2946. https://doi.org/10.3390/su17072946

1. Introduction

The Smart Grid (SG) is an upgraded electricity network that leverages advanced technologies to enhance the efficiency, reliability, and sustainability of power generation, distribution, and consumption. This intricate system incorporates cutting-edge sensors, communication networks, and control mechanisms to facilitate two-way communication and real-time monitoring of the electrical grid. Additionally, it integrates automation technologies to optimise power generation, transmission, and distribution, ensuring improved operational performance and sustainability. The traditional electricity grid was designed to be a one-way system, with power flowing from large, centralised power plants to consumers via transmission and distribution lines. This model has limitations in terms of efficiency, reliability, and sustainability. The growing electricity demand, coupled with the increasing use of renewable and distributed energy sources, has highlighted the need for a more flexible and intelligent electricity network.

The benefits of SGs are numerous, including improved energy efficiency, enhanced public safety, reduced greenhouse gas emissions, and economic benefits such as job creation and reduced energy costs for consumers. However, the implementation of SGs is not without its challenges. It requires significant upfront investment; complex technical and regulatory requirements; and collaboration among stakeholders, including policymakers, utilities, and consumers. Aside from these challenges, the potential benefits of SG make it a worthwhile pursuit as the world moves towards a more sustainable and low-carbon future.

The implementation of Smart Grid (SG) technology differs across countries due to various influencing factors. Technical aspects are crucial in this variation, encompassing elements such as cybersecurity, energy storage capacity, data and energy management, communication hurdles, grid stability, interoperability, system incompatibilities, and congestion challenges related to energy transfer capabilities. Moreover, economic, and societal challenges arise from the substantial capital investments needed and the necessity for strong stakeholder engagement, including final users, due to sensitive data-related aspects, as SGs rely on big data to track, monitor, and increase efficiency of the electrical grids [1]. It plays a crucial role in the development of Smart Cities [2], not only in the efficiency of the energy management but also favouring connectivity and communication between infrastructures is several aspects of cities, such as mobility and waste management, particularly improving performances in waste management practices due to a better coordination and communication [3].

Although China has substantial potential for renewable energy production, coal remains the dominant primary energy source, followed by natural gas, hydropower, wind, solar, biofuels, oil, and nuclear power. According to the International Energy Agency's (IEA's) net-zero emissions by 2050 scenario, wind and solar power are expected to contribute 90% of the total energy expansion. Achieving this goal will necessitate upgrading distribution grids and developing new transmission networks to support the transition [4].

Nevertheless, China has appeared as one of the global leaders in the adoption of SGs. The country has ambitious goals to modernise and expand its power grids, allocating a total investment of USD 442 billion for the period 2021–2025, as detailed in its 14th Five-Year Plan. Major stakeholders driving these initiatives include the State Grid Corporation of China, China Southern Power Grid, and several regional energy companies [5].

The 14th Five-Year Plan for Renewable Energy Development seeks to accelerate the country's shift towards sustainable power sources. The plan aims to boost renewable electricity generation by 50%, increasing from 2.2 trillion kWh in 2020 to 3.3 trillion kWh by 2025. Additionally, it sets a target for renewables to contribute 33% of total electricity consumption by 2025 compared to 28.8% in 2020. More than half of the new energy demand during this period is expected to be met through renewables, potentially cutting carbon emissions by up to 2.6 gigatons annually [6].

The plan emphasises integrating renewable energy into China's energy framework, enhancing supply security while meeting climate commitments. Key initiatives include boosting solar and wind power generation in resource-rich areas, expanding offshore wind, and optimising energy layouts. This strategic shift from previous pollution-focused goals reflects a commitment to a sustainable energy transition.

In the United States, the Grid Resilience and Innovation Partnerships Program, facilitated by the Grid Deployment Office, plays a crucial role in enhancing the grid's resilience and adaptability. This initiative provides approximately USD 10 billion in incentives to support advancements in grid modernisation and strengthen energy infrastructure against potential disruptions. Furthermore, the SG Investment Grant (SGIG) under the Recovery Act has played a crucial role in financing ninety-nine projects, offering federal financial support that covers up to 50% of eligible expenses. The deployment of Smart Grid technology is vital for national development, as it enhances energy efficiency, improves grid reliability, and fosters the integration of renewable energy sources. From a social perspective, it enhances reliability and outage management, increases safety, and empowers consumers. The SG also plays a vital role in reducing greenhouse gas emissions, enhancing energy efficiency, and helping energy storage. Therefore, quantifying the costs and benefits of SG implementation is crucial, serving as a reference for governments to assess its practicality [7].

According to the study of the state of implementation of SGs in China, conducted by the authors of this research [8], the SG overall state of play for China, as for 2021, is at 18% against a state of progress for the US and EU, respectively, of 15% and 13%; investments in power grid infrastructure are steadily increasing in advanced economies and China, accompanied by a growing allocation of funds towards the advancement of digitalisation.

China is a global leader in SG implementation, driven by urbanisation, industrial growth, environmental concerns, and advancements in deploying and using renewable sources, particularly hydropower [9,10]. China's State Grid Corporation plans an added USD 350 billion investment by 2025 [11]. The US is also supporting SG initiatives through federal funding and regulatory incentives and has distributed a USD 5 billion fund through the Grid Innovation Program (GRIP) for innovative transmission, storage, and distribution infrastructure projects from 2022 to 2026. The EU is promoting SG technology, aiming to invest around EUR 500 billion by 2050 in the existing electricity grid, with over EUR 1 billion already distributed and EUR 860 million standing for EU support [12]. The REPower EU Plan aims to generate an additional EUR 29 billion in investments for power grid infrastructure by 2030. The adoption of SG technology in China has significant social and environmental benefits, as shown by a cost–benefit analysis based on baseline data and past forecasts, calculating the absolute benefit of the technology [8].

A review of the scientific literature has been conducted to delve into the topic analysing works conducted on SGs in the last fifteen years, especially in China, and with a similar approach towards cost–benefits analysis, to have an overview of what scholars previously analysed.

Information Communication Technologies (ICT) play a fundamental role in the development of SGs for efficient data exchange, entailing a reliable and fast communication infrastructure connecting various distributed elements. SG technology brings significant transformations in diverse ways. Renewable energy using SGs outweighs traditional energy using information flow and the standardisation of SGs [13]. Demand Side Management (DSM) consists of various strategies aimed at optimising the energy system by managing consumption more efficiently. These measures range from enhancing energy efficiency through the use of advanced materials to implementing real-time control mechanisms for distributed energy resources [14]. The next-generation electricity grid is designed to overcome the key limitations of the current infrastructure. The Smart Grid (SG) will enable utility companies to achieve greater control through digital technologies, two-way communication, distributed energy generation, and autonomous remote monitoring [15]. Moreover, machine learning-based techniques applied to smart meter data have demonstrated significant effectiveness in detecting anomalies. These models not only strengthen security and privacy but also improve centralised training performance. Additionally, federated learning (FL)-based anomaly detection models have proven to be highly efficient in terms of memory utilisation, CPU load, and power consumption, particularly when deployed on edge computing devices [16].

Other studies have been conducted using the cost–benefit analysis approach on the SG topic. The installation of smart metering enables two-way communication between energy suppliers and consumers, facilitating the implementation of demand response strategies.

This interactive approach helps optimise energy consumption by adjusting demand based on real-time grid conditions [17], and a comparative analysis of three configuration modes in a case study demonstrates the economic and environmental advantages of demand response initiatives [18]. Additionally, research on grid-scale electrical energy storage (EES) projects in Great Britain highlights the social costs and benefits associated with energy storage systems. A key example is the Smarter Network Storage project, which features a 6 MW/10 MWh lithium-ion battery designed to accommodate the rising local peak demand. The study underscores how strategic investments in energy storage solutions can support the transition toward a reliable, cost-effective, and sustainable power system [19]. Integrating energy storage systems (ESS) with Demand Side Management (DSM) enhances the self-consumption of photovoltaic (PV) electricity, helping to balance supply and demand more effectively within the grid. Furthermore, research has been conducted to evaluate and compare the technical and economic feasibility of both Household Energy Storage (HES) and Community Energy Storage (CES), assessing their potential benefits in modern energy management, resulting in self-consumption of PV power as the largest contributor to the savings obtained when using ESS. Ref. [20] provided a comprehensive overview of various tools and characteristics that are applicable in SGs, covering both the communication and associated ICT infrastructure. They explained and compared three types of simulators: power system simulators, communication network simulators, and combined power and communication simulators. A related study, ref. [21] analysed the benefit of energy management control actions, evaluating their performance across three different scenarios. The findings suggest that, from an economic perspective, the system does not provide direct financial benefits to end users. However, integrating energy management systems with renewable energy sources and utilising on-site energy production can lead to cost-effective energy savings, making the system more financially viable in the long run. Another study [22] explored the advantages of smart network control and demand response technologies in improving grid operation management, resource efficiency, and the integration of emerging energy loads. Projections indicate that the adoption of electric heating systems and electric vehicles will experience significant growth up to 2050, highlighting the need for enhanced grid adaptability. Ref. [23] estimated the cost and benefits of installing smart readers in the EU. The adoption of dynamic tariffs is crucial, and innovative strategies from policymakers and suppliers could increase customer adoption from below 20% to 80%.

Particularly, papers that analysed the topic in the context of China have also been considered. First, it has to be mentioned that the work implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit—GIZ published in [24] offers insights for designing regulatory policies in China to support Smart Grid development, establish electricity markets, and expand RES generation. It also gives recommendations focus on the regulatory framework for Smart Grids, aiming to enhance the understanding of institutional interdependencies in the electric power sector. Moreover, the study by [25] compared innovation policies in SGs across the Pacific—in particular, China and the US. They outlined the policy tools employed by both countries and presented findings that highlighted national preferences for innovation policies, which vary based on the state of the power system. It emphasised China's inclination towards a "supply-side policy" approach, which prioritises public enterprise, scientific and technological development, and legal regulation. From a power source perspective, a case study in ref. [26] illustrated how inter-regional power transmission can impact the regional deployment of technologies under various policy scenarios in China. The findings indicate that energy subsidies and national targets will continue to play a crucial role in the expansion of renewable energy, both in the short and long term. Ref. [27] examined the technical, environmental, socio-economic, and intangible benefits linked to Smart Grids (SGs), emphasising their interactive, real-time capabilities in addressing challenges related to the future power system infrastructure. It explores the development of Smart Grids in China and India, along with efforts to establish a Smart Grid roadmap for Kentucky and the United States. The study highlights how different policy approaches in these regions reflect the varied strategies used to support Smart Grid integration. Meanwhile, ref. [28] investigated how the United States (US) and the European Union (EU) have introduced policies to encourage microgeneration and Smart Grid initiatives. Despite ongoing advancements, the sector is still in its early stages. To speed up adoption and increase private sector involvement, both regions have implemented policy measures that promote sustainable and cost-effective energy production. These policies offer long-term financial incentives for private investors and tax benefits for individuals to encourage participation. The study also highlights that China, Brazil, Canada, and India have made significant investments in renewable energy, further supporting the global shift toward clean energy. The paper by [29] used a survey-based approach to analyse the social perspective of Smart Grid implementation. Through a survey conducted in Hong Kong, complemented by the literature findings, the study provides insights into public perceptions and behaviours regarding Smart Grid adoption. The results indicate a positive reception of Smart Grid technologies, with strong support for energy efficiency, energy conservation, and renewable energy expansion. However, respondents expressed notable resistance to nuclear power. From a technical perspective, ref. [30] explored the application of power line communication (PLC) technology within low-voltage (LV) distribution networks in China. With the country moving towards Smart Grid development, PLC is being considered as a potential solution for enabling seamless communication between end users and electricity providers, ultimately enhancing grid efficiency and operational effectiveness. This paper presents the measurement results of low-voltage PLC systems after giving a general overview of the topologies for the typical LV distribution networks in China. The testing results show that the main reason influencing the reliable communication of high-speed data of the power line is the attenuation of the high-frequency signal, which is more obvious in the branch of the power line.

Additionally, several studies have applied the cost–benefit approach to assess Smart Grid (SG) implementation in China. One such study [31] introduced an optimised design framework for hybrid microgrid systems, integrating solar, wind, and tidal energy to ensure a reliable power supply for a remote rural location in the Fuxin region of Northeast China over a 20-year operational period. To measure the system's overall efficiency, the study incorporated a cost–benefit index, evaluating the economic viability of the proposed microgrid model. Meanwhile, ref. [32] examined the impact of demand response (DR) events on power demand reduction and indoor building temperature. The findings indicate that both factors can be accurately predicted, allowing for better grid management. The study highlights that power demand reduction remains stable and predictable, making it a reliable tool for energy balancing. Moreover, the research suggests that, during DR events, indoor temperature fluctuations are minimised, and thermal comfort is enhanced through the use of small-scale active storage systems. The research by [33] revealed that, within China's renewable energy strategy, concentrating solar thermal (CST) electric power generation was significantly underemphasised. Despite the potential of CST to provide substantial environmental and economic benefits, it has not been prioritised in national plans. The study highlighted the need for greater emphasis on CST to enhance the effectiveness of China's renewable energy policies and to diversify its energy portfolio, contributing to a more sustainable and resilient energy system.

To the best of the authors' knowledge, no prior analysis similar to the one outlined in this manuscript has been conducted. Consequently, this study seeks to address this gap by offering both qualitative and quantitative assessments of the benefits associated with SG implementation, particularly within the context of China, the foremost global leader in terms of energy production and consumption. The methodology is based on the only other similar work, in terms of scale considered, conducted by the Electric Power Research Institute US [34] in a United States context, by maintaining the same approach while adapting it to the data available and the principal aspect to take into consideration, as explained in the next section. The preliminary results were presented in [35]. The aim of conducting this study in the context of China is to potentially replicate the same approach to analyse, and then compare, other contexts such as India, Brazil, South Africa, and more. The approach underlines and will stimulate the analysis on technology and policy advancements, particularly on renewable and clean energy, decarbonisation, circular economy, carbon emissions, etc. In fact, the literature shows a gap in providing holistic cost–benefits analysis on this matter, especially in transitioning countries, while present in contexts like the EU [36] and US [34]. Another gap individuated is related to the lack of data, which appears to be particularly difficult to obtain for contexts like China, while more data were available for the EU and US (e.g., [37,38]). The paper aims at covering these gaps, by providing a methodology that can be replicated and updated in future works and stimulate other academics to collect and share data to apply it.

2. Materials and Methods

To define the economic benefits of the SG deployment, a control scenario has been set, the so-called baseline (BL). Such a scenario defines the current trends of the attribute considered without full implementation of SG-related systems. The method is based on the study conducted by EPRI US [34], considering most of the attributes they analysed. In the SG Baseline (BLSG), a full implementation of SG is forecasted up to 2050 and including the estimated implementation costs for each of the following analysed attributes (thoroughly described in the following sections):

1. Generation mix
2. Generation capacity investments
3. Transmission and distribution capacity investments
4. Transmission and distribution equipment maintenance and operations cost
5. Reduced congestion cost
6. AT&C losses
7. Meter reading cost
8. Reduced equipment failures
9. Outages

The total benefit from SG implementation is therefore calculated as in Equation (1):

$$B_j = BL_j - BLSG_j \tag{1}$$

where B_j represents the benefit function for each different attribute, and i represents the year, ranging between 2020 and 2050.

In accordance with the type of data and the final purpose of this article, the "Simple exponential smoothing" was chosen as a forecasting method. This was implemented to fill in the gaps among data to obtain a full year-to-year forecast.

Exponential smoothing is a method used to renew a forecast by using more recent observations. Exponential smoothing assigns exponentially decreasing weights as the observation becomes older. Thus, it gives more relevance to the latest observations.

This method is one of the most widely used when the data do not show any type of trend or seasonality. In this model, it is assumed that the time series is

$$y_1, y_2, \ldots y_n$$

Thus, the forecast for the next period according to the simple exponential smoothing method is Equation (2)

$$\hat{y}_{t+1} = \alpha y_t + (1 - \alpha)\hat{y}_t \quad (2)$$

where:

y_t is the actual known series value for time period t;
$\hat{y}_t$ is the forecast value of the variable Y for time period t;
$\hat{y}_{t+1}$ is the forecast value for time period $t+1$;
α is the smoothing constant, a selected number, such that $0 < \alpha < 1$.

The forecasting process is based on weighting the most recent observation y_t with α and the most recent forecast $\hat{y}_t$ with $1 - \alpha$.

The analysis focuses on the Average Price of Electricity in China, measured over the years 2015 to 2020. The goal is to forecast future price trends and assess their uncertainty over a 30-year horizon (until 2050). The selected model parameter α = 0.7 (smoothing factor) lends more weight to recent observations.

This choice reflects the assumption that recent electricity prices in China contain more relevant information for forecasting future values than older prices. Since the time series is quite short, it is crucial to prioritise the most recent patterns, as they are likely to better capture the current dynamics of the electricity market. A high value of α (close to 1) ensures that the model responds quickly to changes in the data, making it more sensitive to recent trends or fluctuations. At the same time, although emphasis is placed on newer data, the model still retains some influence from past observations, which helps avoid overreacting to random short-term variations.

To start this process, three values are needed: a first forecast, a contemporary value of the time series, and the smoothing constant.

Since the initial forecast is not available, it is possible to substitute it using two different methods:

- Equal it to the initial value of the time series.
- Use the average of the first five observations for the first smoothed value.

The general equation of this forecasting method is (3):

$$\hat{y}_{t+1} = \alpha \sum_{k=0}^{t-1} (1 - \alpha)^k y_{t-k} \quad (3)$$

This analysis relies on the ETS (Error, Trend, and Seasonal) framework, which, under the chosen parameter configuration, reduces to the simple exponential smoothing (SES) method. Specifically, an AAN (Additive Error, Additive Trend, and No Seasonality) model was selected, as it appropriately captures the underlying trend dynamics in the electricity price data without including a seasonal component, which would not be meaningful given the annual frequency of the observations. The additive form of both error and trend components allows for modelling changes over time as linear increments or decrements, making this specification particularly suitable for small datasets, where more complex nonlinear patterns cannot be reliably identified.

As for the costs, the EPRI [34] provided the summary cost indicators for the deployment of SG in the United States. The costs here considered regards the deployment of the assets (both physical assets, such as, i.e., power transformers, power lines, smart meters, and others, and intangible ones such as software and skilled workforce) needed to enable the SG functionalities underlying the considered benefits. To do so, the assets were identified based on the EPRI report [34], as well as their market prices. By recalculating the specific values of each item identified according to the EPRI approach, the costs obtained were combined with the EPRI data to assess the variance, resulting in a small value and, therefore, were in line with the EPRI results.

2.1. Generation Mix

As for the attributes, the first one is related to the benefit that the implementation of SGs could contribute to the generation mix of the country, allowing a higher implementation of VRES instead of fossil fuels energy sources.

The implementation of Smart Grids (SGs) provides numerous advantages for the integration and optimisation of Variable Renewable Energy Sources (VRES) due to its high adaptability and ability to facilitate bi-directional energy flows. Furthermore, it allows the connection of, for example, plug-in electric vehicles, energy storage systems, and consequently helps to promote energy trading. For China, the energy generation mix is dominated by coal, followed by gas, nuclear power, hydropower, wind, and solar energy. New disruptive advancements in load and generation forecasting and grid management are brought in by the implementation of Artificial Intelligence techniques [39,40] and blockchain-based transactions [41].

First, data on the price of energy from the main generation sources (as LCOE) were collected. Historical data from 2015 to 2020 were collected from the following reports: Ref. [42] reported the prices for coal, natural gas, wind, nuclear, hydropower, and solar as for 2015, while data for 2020 were assumed from [43] for coal, natural gas, wind, nuclear, and solar and from [44] for hydropower. The forecasts up to 2050 were obtained considering the values expected in 2050 from [45], based on BloombergNEF's reports about energy sources such as coal, gas, solar, and wind, while ref. [46] was considered for nuclear power and, due to the unavailability of data, hydroelectricity price was considered almost constant, according to its linear trend. The data are available at the sources indicated under the LCOE table per each source. The generation mix considered in the *BL* scenario was the one envisaged by the EIA in [47,48] in percentage terms and then compared to the forecast on energy generation retrieved from an earlier study from the authors [49], filling in the gaps between every five years linearly. Multiplying by the expected energy prices, based on historical data, and forecasted up to 2050 gives the baseline as the cost of generating power due to the basic energy mix, assumed as the sum of the various power sources (PS_i). Particularly, the *PSs* considered were coal, natural gas, solar, wind, hydropower, and nuclear.

$$BL_1 = \sum_i^n PS_i \times LCOE_i \tag{4}$$

For the *BLSG*, the scenario of the report was considered [50] that forecast for an increase in renewables in favour of a reduction of fossils thanks to the use of SG technologies, changing the power sources composition $(PSSG_i)$. This scenario was also converted into percentage terms and adjusted for each year's forecast to make *BL* and *BLSG* comparable. The difference between the two scenarios represents the benefit.

$$BLSG_1 = \sum_i^n PSSG_i \times LCOE_i \tag{5}$$

2.2. Generation Capacity Investments

For generation capacity investments, it is intended for the need for investments in infrastructure and systems to increase the generation capacity of the country. The implementation of SG should decrease the need for these investments due to the higher efficiency of grid management.

From the IEA [51], report data on global investment (*GI*) in the energy sector were taken, from 2010 to 2019, then forecasted up to 2050. It is assumed, also in accordance with [52], that China attracts 28% of the total. This percentage refers only to the renewable sector, but it was used as a proxy for the entire sector; therefore, *BL* is calculated as (6).

$$BL_2 = \sum_i^n (GI_i \times 28\%) \tag{6}$$

For the *BLSG* (7) and the benefit, the data from EPRI US on this topic [34] has been assumed, which estimates the benefit for deferred capacity investments in 20 years between USD 192 and 242 billion. Based on the implementation costs of the SG in China, which resulted as 8.4% more than the US average scenario (B_{EPRI_US}), after replicating the EPRI US study for the implementation costs, a resulting average of USD 235.23 billion was considered and spread out over 30 years (2020–2050), and it can be considered a benefit equal to about USD 7.84 billion per year of investments deferred.

$$BLSG_2 = \sum_i^n BL_2 - \left[\mu\left(B_{EPRI_{US}}\right) \times (1 + 8.4\%)\right] \tag{7}$$

2.3. Transmission and Distribution Capacity Investments

This attribute refers to the need for improvement of the capacity of the transmission and distribution (T&D) lines. From the IEA [53], energy consumption data in China were assumed, and an exponential smoothing forecast was adopted to fill in the gaps in the years while adjusted according to the forecast of [50] related to energy consumption up to 2050. Based on [51], transmission and distribution capacity investments between 2016 and 2019 were considered, and the linear fit equation applied to the yearly increase in energy consumption was used to forecast the values up to 2050, identifying the BL (8).

$$BL_3 = \sum_i^n (CCCT_i + CCCD_i) \tag{8}$$

where *CCCT* stands for Capital Carrying Charge of Transmission Upgrade and *CCCD* for Capital Carrying Charge of Distribution Upgrade.

CCCT (9) and *CCCD* (10) are both calculated through a linear fit of the available data from 2016 to 2019:

$$CCCT = 0.0378x + 18.281 \tag{9}$$

$$CCCD = -0.0315x + 59.7 \tag{10}$$

To calculate the *BLSG* (11), the value proposed by the EPRI report [34] for this attribute (B_{EPRI_US}) was used and adapted to a Chinese context. Specifically, an average value between USD 8.26 billion and USD 21.42 billion was assumed. This average was then increased by 8.4% to account for China's implementation cost assumption, as explained in the previous section. Using this adjusted value, the benefit over 30 years was forecasted, which allowed it to obtain the BLSG. This value will be 16% attributable to transmission and 84% to distribution, according to the incidence of costs attributed from the cost analysis part.

$$BLSG_3 = \sum_i^n \left(BL_3 - \left[\mu\left(B_{EPRIUS_i}\right) \times (1 + 8.4\%)\right]\right) \tag{11}$$

2.4. Transmission and Distribution Equipment Maintenance and Operations Cost

Other than the investments in the capacity of the transmission and distribution lines, SGs can lower the costs for maintenance and operations due to better management and individuation of issues on the grid. The support of Artificial Intelligence-based techniques allows to further enhance predictive management operations [40] and SG security [54]. The average unit Operation and Maintenance (*O&M*) cost per T&D was assumed by the average value reported in [55] and forecasted, as for the previous attribute, through the application of the linear fit equation based on the yearly increase of energy consumption (*EC*), obtaining the *BL* (12).

$$BL_4 = \sum_i^n (EC_i + O\&M_i) \tag{12}$$

where:

EC is the total electric consumption which is a forecasted dimension;
$(O\&M)$ is the average cost calculated for transmission and distribution O&M.

For the *BLSG* (13), a 10% O&M cost reduction per T&D was considered, according to the [56] report.

$$BLSG_4 = \left(\sum_i^n (EC_i + O\&M_i)\right) \times (1 - 10\%) \tag{13}$$

2.5. Congestion Cost

Congestion cost is considered to calculate the amount of energy produced by coal-fired plants to compensate for curtailed renewable power. Particularly, due to the unavailability of data, only wind curtailment has been considered for this attribute. VRES are usually curtailed due to their variable nature and non-constant availability, which lead to congestion on the grid. Therefore, coal plants are used to fill in the gap of the VRES. The SG can manage better this aspect and therefore reduce the use of coal-fired plants in the avoidance of congestion. From [57], the trend of wind energy curtailment (*Wcurt*) was taken to define the baseline and the consequent forecast, combining them with IEA data, applying the forecast and making the product with total wind generation (*WG*) and coal price have the curtailed wind energy baseline replaced with power generation from coal-fired plants, which represents the congestion cost, with the *BL* calculated as (14).

$$BL_5 = \sum_i^n (Wcurt_i \times Wgen_i \times Coal\_price_i) \tag{14}$$

For the *BLSG* (15), according to the [58] scenarios that assume potentially zero curtailment with the SG full development within 2050, non-curtailed energy is therefore produced by wind turbines, with a cost equal to the price of wind energy (*W_price*), which tends to decrease over the years. This reduces the curtailed percentage, giving the *BLSG*.

The differences between the two baselines, assumed considering the data from [57,58], represent the benefit deriving from the application of SG as an avoided cost of the non-curtailed percentage of wind energy that, in the baseline scenario, is entirely paid with the cost of generating coal. The costs of wind and coal were assumed by the calculation for the generation mix attribute. Moreover, due to a lack of availability of data, other renewable sources have not been considered, so the benefit of non-curtailed energy would be even greater considering the other RES. The authors are not aware of intensive hydropower curtailment; PV curtailment is reported to being strongly reduced in the last years, due to specific policy measures [59].

$$BLSG_5 = \sum_i^n (Wcurt\_SG_i \times Wgen\_SG_i \times Wind\_price_i) \tag{15}$$

2.6. AT&C Losses

The concept of Aggregate Technical and Commercial (AT&C) losses offers an overview of the loss scenario within a given context. It encompasses both energy losses—comprising technical losses, theft, and billing inefficiencies—and commercial losses, which include payment defaults and inefficiencies in revenue collection. From the data by [60], the actual trend for the total transmission losses up to 2050 was forecasted, obtaining an average value assumed as constant, based on data between 2010 and 2019 and applied to the electricity consumption (*EC*) multiplied by the forecast of electricity price (*EP*), and the BL was obtained (16).

$$BL_6 = \sum_i^n (EC_i \times \mu(AT\&C_i) \times \mu(EP_i)) \quad (16)$$

where:

EC is the energy consumption;
$\mu(AT\&C)$ is the average $AT\&C$ loss;
$\mu(EP)$ is the average electricity price.

For the *BLSG* (17), the study [61] estimated the annual savings due to the SG implementation equal to 10%, which was assumed as a constant value.

$$BLSG_6 = \sum_i^n (EC_i \times \mu(AT\&C_i) \times \mu(EP_i)) \times (1 - 10\%) \quad (17)$$

2.7. Smart Meters O&M

Considering the data of [62,63], the value of smart metering (SM) installed in 2017 was averaged, while for data from 2011 to 2025, the CAGR of [62] was used. For the following years, the forecast was conducted. New SMs per year were then calculated as a difference between total SMs installed in the one year and the earlier one (*SMnew*). To quantify the economic value of SM, the cost per unit, the *O&M cost*, and the cost per installation were taken into consideration. To obtain these data, the report of the [64], from which the percentage weights of each aspect were also deducted, and, to strengthen the comparison, the costs per SM were assumed equal to that in India [61]. With these data, it is possible to assume the values of the unit costs, the *O&M costs*, and the installation costs for China. For this attribute of the SG, only the O&M component was taken into consideration. In particular, the cost of O&M, which is an annual cost, is added to that of the previous year in the following years, multiplied by the number of new SM installations. This attribute was calculated based on the scenario that already considers the implementation of smart meters instead of traditional ones. Therefore, it refers to the *BLSG*. For consistency reasons, to be aligned with the previous and following attributes, *BL* (18) is calculated to increase the costs by a factor of 45%, assumed as an average value by [65].

$$BL_7 = \sum_i^n BL_{7_{i-1}} \times (SMnew_i \times O\&Mcost_i) \times (1 + 45\%) \quad (18)$$

Therefore, the *BLSG*, results in (19):

$$BLSG_7 = \sum_i^n BLSG_{7_{i-1}} \times (SMnew_i \times O\&Mcost_i) \quad (19)$$

2.8. Equipment Failures

SG actively reduces the grid equipment failure rate, such as transformers, by detecting in advance malfunctions and wearing of components, allowing predictive maintenance and avoiding failures. The failure rate of transformers in EU countries is less than 1%, while, in developing countries such as India, where [61] stated that the failure rate of the county is 8%. Therefore, it was around 11.6% in the period 2011–2015 in Nigeria, according to [66]. Another had average value of 7%, with an overload failure rate of 22.5%. On this matter, the implementation of SGs can reduce these values. After considering electricity consumption and estimating the value of equipment in China starting from the total installed capacity, the energy consumption/capacity ratio, and the average value per GVA of the installed capacity [67], the failure cost baseline is calculated by applying the failure percentages to the current presence of equipment expected based on data from [68], obtaining (20).

$$BL_8 = \sum_i^n (EQcost_i \times FR \times OFR) \quad (20)$$

where:

EQ_cost is the forecast of the value of equipment.
FR is the failure rate.
OFR is the overload failure rate.

In [61], the percentage reduction from energy distribution is shown and recalculates the failure rate in the case of the SG, being able to calculate the benefit, as it is assumed as a 5% reduction of failures, applied on the BL to obtain the $BLSG$ (21).

$$BLSG_8 = \sum_i^n (EQcost_i \times (FR \times (1 - 5\%) \times OFR)) \quad (21)$$

2.9. Outages

Interruptions in the electricity supply represent economic losses and are an ongoing challenge, so preventing them can help guide resilient investments. Their nature can be remarkably diverse. In [69], the costs associated with outages were analysed, denominated as business interruption costs (BICs), reaching CNY 1.44 billion per month, equal to USD 2.419 billion yearly. These data were assumed as the BL (22).

$$BL_9 = \sum_i^n (BIC_i) \quad (22)$$

For the BLSG, fully automated switching has shown greater improvements in reliability compared to remote switching initiated by operators with manual validation. The use of Fault Location, Isolation, and Service Restoration (FLISR) technology is essential for detecting faults and quickly restoring power after outages. Utilities that have integrated FLISR systems experienced a 55% decrease in the number of customers impacted by prolonged outages and a 53% reduction in outage duration. These findings highlight the role of automation in strengthening grid reliability and enhancing operational efficiency [7].

Other project reports state that, thanks to SG technologies, there is a reduction in the number, frequency, and duration of outages, as was the case for a project in Bosnia and Herzegovina, where the percentages dropped by 51% for the number of outages and 58% in terms of duration [70]. Therefore, for the BLSG (23), it is estimated that Smart Grid (SG) implementation can help prevent approximately 54% of outage-related costs, contributing to improved grid reliability and economic efficiency in the power sector.

$$BLSG_9 = \sum_i^n (BIC_i) \times (1 - 54\%) \quad (23)$$

3. Results

In Table 1 are presented the results for China and the comparison with the US in terms of implementation costs.

Table 1. Implementation costs comparison between the EPRI US case study and its methodology replication for China.

	US Scenario		China Scenario	
	Low—B USD	**High—B USD**	**Low—B USD**	**High—B USD**
Transmission	102.86	108.98	58.73	66.41
Distribution	222.93	333.39	255.79	394.57
End Users	22.82	45.08	39.38	91.48
TOTAL	348.61	487.45	353.90	552.47

As can be seen from the results in the above table, the cost of the Chinese SG is higher than that of the US one, especially at the upper end of the spending spectrum. Therefore, an average value was taken to define the SG's costs in China, amounting to USD 468.29 billion. The baseline was assumed based on the EPRI US methodology applied to the Chinese context and following as much as possible the approach presented in [34].

The BL column expresses the total specific costs in the scenario where the implementation investments are not pursued, and the forecast follows the actual trajectory.

In the BLSG column, the results refer to the case where the implementation investments have been pursued, and the implementation level of the SG is much higher.

The latter scenario has lower specific costs due to the beneficial effect that would be experienced with a higher value of SG implementation. The difference between the two scenarios thus configures the resulting benefits, as shown in the last column of Figure 1.

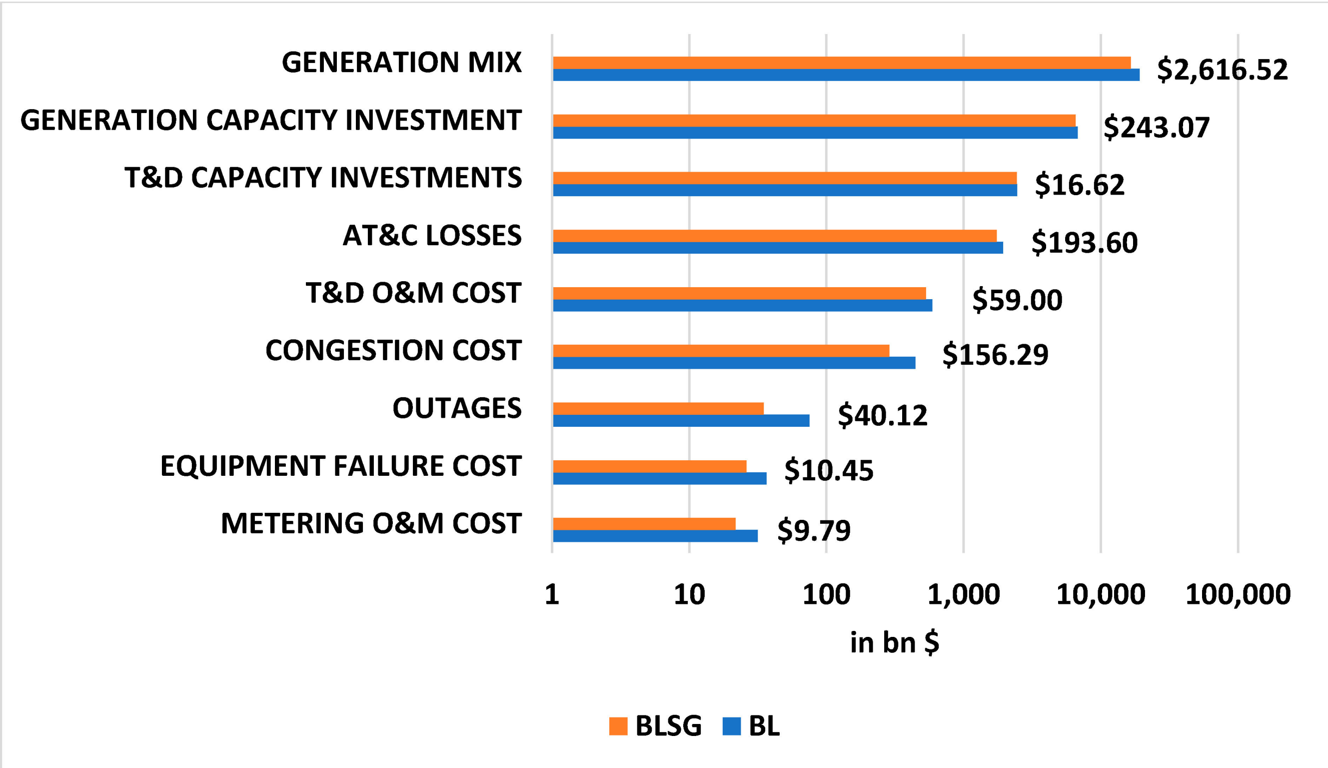

Figure 1. Total costs for nine attributes with and without SG implementation, with benefits as the difference (BL–BLSG) over a 30-year forecast.

Figure 2 presents each benefit for attribute due to Smart Grid (SG) deployment. This highlights the potential advantages associated with SG implementation.

Figure 3 illustrates the total benefit, calculated as the difference between the baseline (BL) (blue line) and the combined values of the BLSG (grey area) and implementation costs (orange line). The figure demonstrates that the benefits increase progressively over time, largely due to the anticipated decline in the costs of Variable Renewable Energy Sources (VRES). The detachment between blue and grey lines represent the benefits over time.

- Total Costs (Baseline): bn USD 31,595.24
- Total Costs (With SG): bn USD 28,249.77
- SG Implementation Costs: bn USD 468.29
- Total Benefits (With SG): bn USD 2877.18
- Benefit–cost ratio (B/C): 6.1

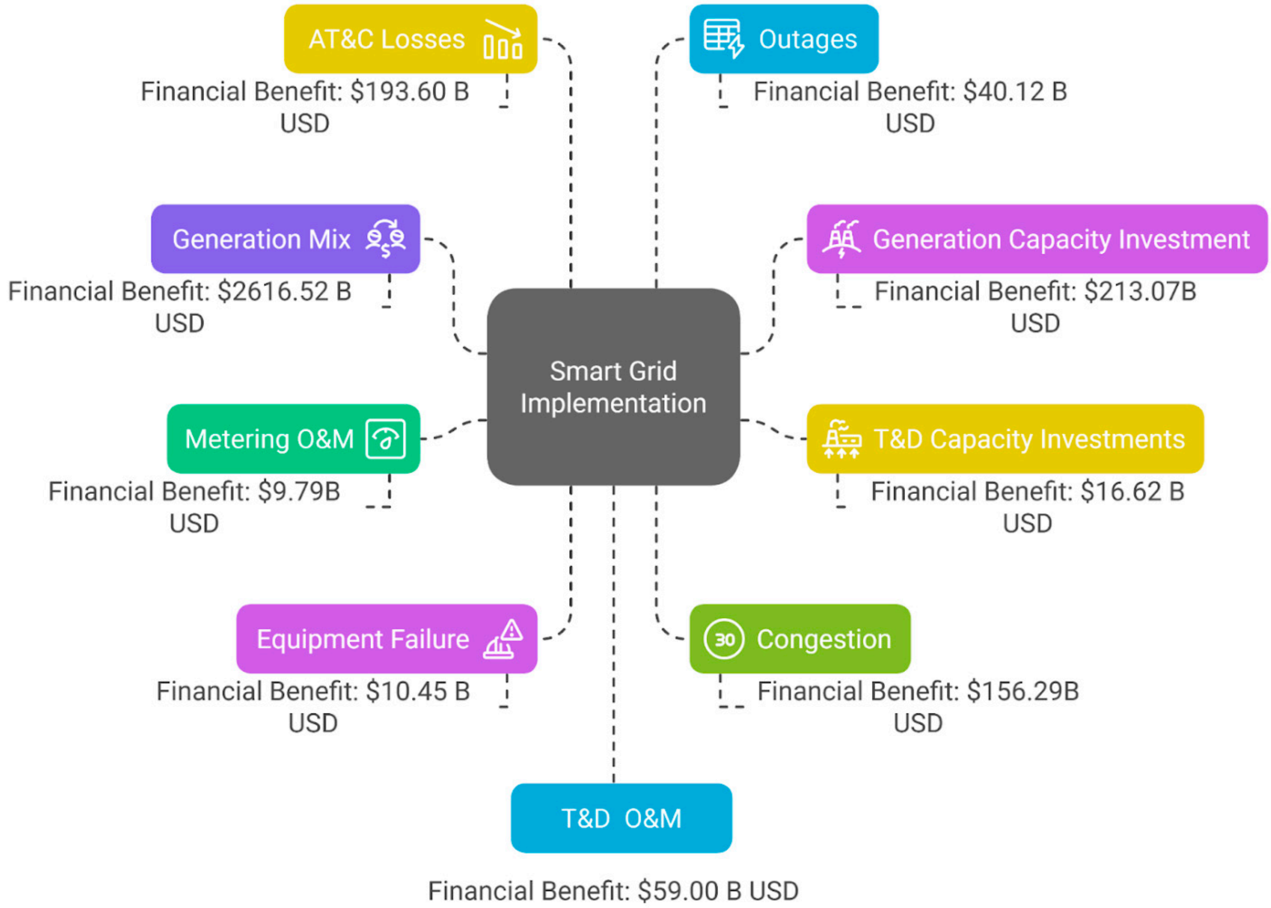

Figure 2. Smart Grid (SG) implementation across nine attributes after a 30-year forecast.

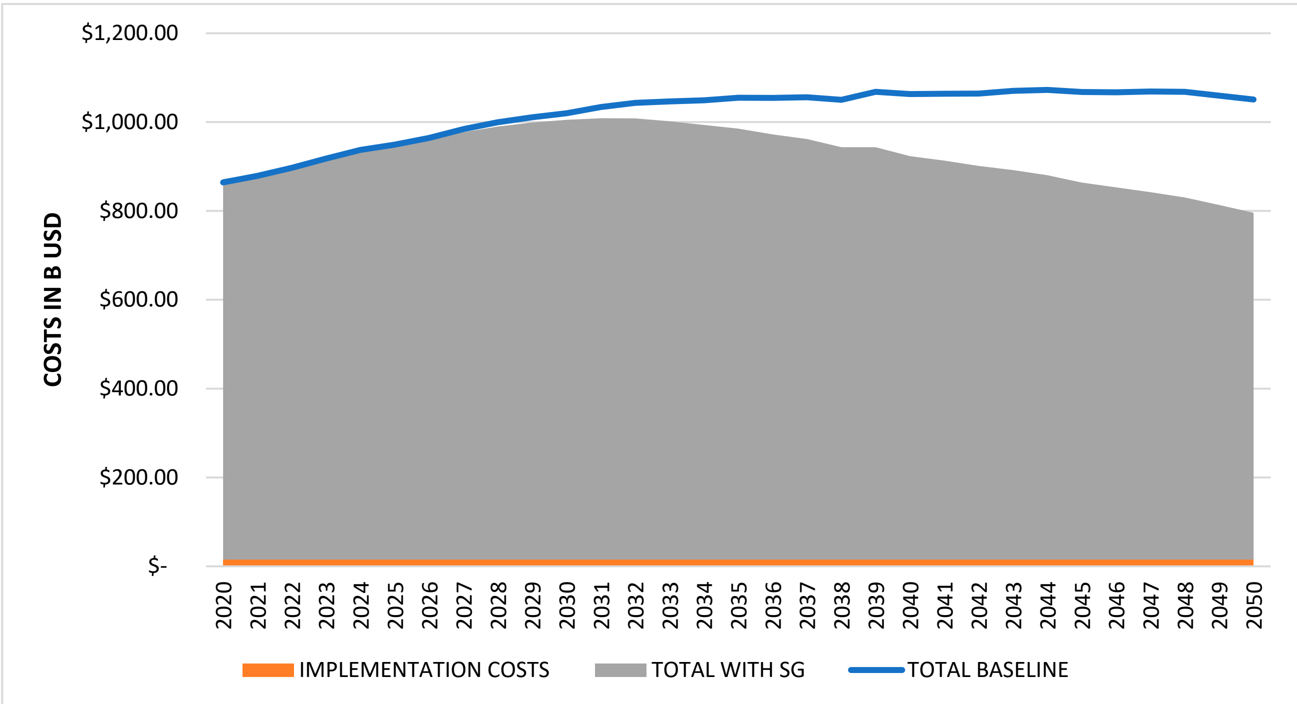

Figure 3. Cost forecast for SG implementation (orange) without SG (BL—blue), and with SG (BLSG—grey). A B/C ratio of 6.1:1 was achieved, highlighting the SG's potential to deliver significant benefits despite the associated implementation costs.

Finally, Figure 4 illustrates the Average Price of Electricity in China from 2015 to 2020, followed by a forecast extending to 2050. The *x*-axis represents the time horizon, covering both historical data and the projected period, while the *y*-axis represents the electricity price in USD. The predicted values follow a relatively stable trend, showing minor fluctuations over time.

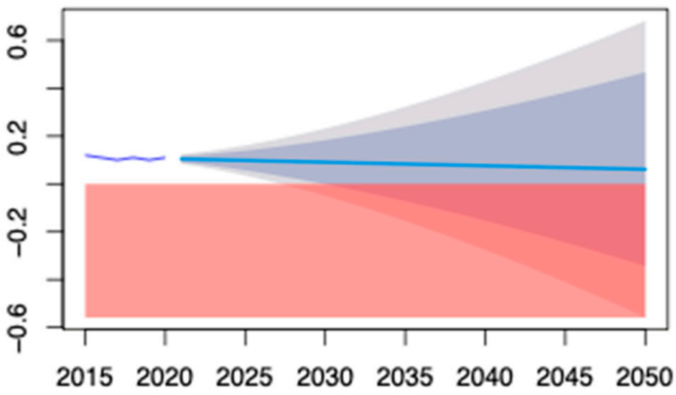

Figure 4. Confidence interval for the analysis.

To illustrate the uncertainty associated with the forecast, the graph includes confidence intervals:

- The 80% confidence interval (represented by the light blue-shaded area): This interval indicates the range within which the predicted values are expected to fall with an 80% probability.
- The 95% confidence interval (represented by the wider grey-shaded area): This provides a more conservative estimate of future variability, covering a broader range of potential values with a 95% probability.

4. Discussions

The results of this study reveal a comprehensive and detailed analysis of the economic benefits of SG deployment in China, highlighting the potential improvements in various attributes related to energy generation, distribution, and grid efficiency, by comparing the baseline (BL) scenario, which assumes no full SG implementation, with the SG-enhanced scenario (BLSG) in China's energy grid by 2050.

One of the key findings relates to the energy generation mix. The adoption of Smart Grid (SG) technologies enables a greater integration of Variable Renewable Energy Sources (VRES), including wind and solar power. This transition reduces dependence on fossil fuels, contributing to a more sustainable and resilient energy system. The results indicate that the shift towards a more sustainable energy generation mix not only aligns with China's environmental goals but also offers substantial economic benefits. China can reduce the costs associated with fossil fuel-based energy generation, thanks to the bi-directionality of the SG in exchanging energy among facilities and structures, allowing a more efficient management of peaks and lows that are typical in VRES. This is further supported by the forecasted reduction in coal dependency, which remains a dominant energy source in the baseline scenario. The SG scenario promotes a gradual shift toward renewables, thereby reducing the levelized cost of energy (LCOE) over time.

In terms of generation capacity investments, SG deployment should significantly reduce the need for new infrastructure investments. The higher efficiency of grid management enabled by SGs mitigates the necessity for capacity expansions. The study estimates an annual deferred investment benefit of approximately USD 7.84 billion, highlighting the cost-effectiveness of SG implementation in this area.

Similarly, the results for T&D capacity investments also indicate substantial savings. The optimisation of T&D infrastructure, driven by SG technologies, lowers the need for extensive upgrades, thus resulting in an economic benefit over the 30-year period. These savings are further enhanced by the reduction in maintenance and operational costs, which are estimated to decrease by 10% due to improved grid management and fault detection capabilities.

The analysis of congestion costs provides another important insight, as the implementation of SG is projected to significantly reduce energy congestion by minimising the curtailment of renewable energy (for the purpose of this study and lack of data, only wind power has been considered) and decreasing reliance on coal-fired plants.

Furthermore, the reduction in Aggregate Technical and Commercial (AT&C) losses is another critical benefit. The study estimates a 10% reduction in these losses, highlighting SG's role in improving the overall efficiency and reliability of the grid.

Moreover, the results show a clear economic benefit in the context of smart meter O&M costs, particularly the readings. By facilitating more accurate and efficient energy management, SG could reduce the O&M costs associated with smart meters, providing a further economic incentive for their adoption. Additionally, the implementation of SGs is expected to reduce equipment failures by enabling predictive maintenance and early fault detection, which translates into lower costs associated with equipment replacement and repairs.

Finally, the reduction in outages is one of the most tangible benefits of SG deployment. The study highlights a potential 54% reduction in the costs associated with outages, attributed to the improved fault location, isolation, and service restoration (FLISR) capabilities provided by SG technologies. This reduction not only offers significant economic benefits but also enhances the reliability and resilience of the grid, which is crucial for supporting China's growing energy demand and to avoid commercial and residential interruption of services.

The development of Smart Grid (SG) technology has been a critical focus for modernising power distribution systems worldwide. Various projects have been analysed to compare their results in terms of cost–benefit analysis, providing a comprehensive understanding of the economic feasibility and potential advantages of SG implementations. This analysis examines key case studies from different regions, offering insights into the investments, benefits, and benefit-to-cost (B/C) ratios associated with these initiatives.

The scenario developed by the Electric Power Research Institute (EPRI) [34] in the United States is widely recognised as a foundational reference for SG cost–benefit analyses. The EPRI conducted a detailed study to estimate the investment required to develop the future power distribution system of the SG across the United States. The projected investment was estimated to range between USD 338 billion and USD 476 billion. The study projected that these investments would yield total benefits ranging from USD 1294 billion to USD 2028 billion. This translates to a benefit-to-cost ratio ranging between 2.8:1 and 6.0:1. The high B/C ratio underscores the significant potential return on investment associated with SG development in the United States, driven by improved grid reliability, reduced energy consumption, enhanced efficiency, and lower operational costs. The EPRI scenario provides a broad, national-level analysis of SG implementation, considering various SG components such as smart meters, advanced communication infrastructure, and automation technologies. The study's findings have been instrumental in shaping SG investment strategies across the United States, highlighting the substantial economic benefits that can be achieved through large-scale SG adoption.

A project implemented in Isernia, Italy [71], represents a more localised SG implementation compared to the broader national analysis by EPRI. Conducted by the Italian utility company Enel, this project aimed to modernise the power distribution network in the town of Isernia, focusing on integrating renewable energy sources, enhancing grid automation, and improving energy efficiency. The total cost of the Isernia project was significantly lower than the EPRI scenario, reflecting its smaller scale. The project demonstrated a B/C ratio ranging from 1.1:1 to 1.8:1, indicating that, even on a smaller scale, SG implementations can offer considerable economic benefits relative to their costs. The Isernia project included the deployment of advanced metering infrastructure (AMI), the integration of distributed generation, and the implementation of automated demand response systems. The project's positive economic outcomes were driven by reduced energy losses, improved grid stability, and enhanced energy management capabilities.

As a study conducted within the city of Rome, Italy, in 2011 and 2014, ref. [72] sought to map the capabilities and benefits of various SG implementations. This study involved several sub-initiatives, each targeting various aspects of SG technology, such as smart metering, grid automation, and energy storage. The analysis revealed considerable variations in the outcomes of these sub-initiatives, with benefit-to-cost ratios ranging from a low of 0.1:1 in the worst-case scenario to a 2.5:1 and 12.9:1 in more favourable scenarios. The worst-case scenario indicated projects that faced technical or operational challenges, while the best-case scenarios demonstrated the significant economic benefits that could be achieved under optimal conditions. The Rome SG study highlighted the importance of context-specific factors in determining the success of SG projects. The wide range of B/C ratios reflects the diverse nature of SG applications and the varying degrees of success depending on the specific technologies and approaches employed.

In another significant case, an SG project conducted in India provided insights into the economic feasibility of SG implementations in emerging markets. The project, supported by the Indian government and various international partners, focused on modernising the grid infrastructure in select urban areas. The project required an investment of approximately USD 22.1 million. The benefit-to-cost ratio varied from 1.27:1 to 1.66:1, suggesting a positive economic outcome despite the challenges associated with deploying advanced grid technologies in a developing country context [73]. The project included the installation of smart meters, the integration of renewable energy sources, and the enhancement of grid management systems. The positive B/C ratio was driven by reductions in technical and non-technical losses, improved billing accuracy, and enhanced customer satisfaction.

In the Middle East and North Africa (MENA) [74] regions, SG investments have been projected to offer substantial economic benefits. A comprehensive analysis of SG projects in these regions highlighted the potential for significant annual savings. The investments in SG technologies across the MENA regions were estimated to save between USD 300 million and USD 1 billion annually. This analysis, which encompassed thirty performance cases of smart meter projects across twelve countries, revealed an average B/C ratio of 2:1, demonstrating consistent positive outcomes across diverse international contexts. The MENA SG initiatives included a wide range of projects, from smart meter rollouts to grid automation and renewable energy integration. The analysis emphasised the transformative economic impact that SG technologies could have in these regions, particularly in terms of energy efficiency, reduced operational costs, and enhanced grid reliability.

The comparative analysis of these various SG projects across different regions highlights the economic feasibility and potential advantages of SG implementations. The benefit-to-cost ratios observed in these case studies demonstrate that SG investments, whether on a national scale or in more localised contexts, can offer significant returns. However, the success of these initiatives often depends on factors such as the scale of implementation, the specific technologies employed, and the local context. The EPRI scenario in the United States presents a particularly compelling case for large-scale SG investments, with a B/C ratio that underscores the transformative potential of SG technologies. Meanwhile, projects like the Isernia and Rome implementations in Italy, as well as the initiatives in India and the MENA regions, provide valuable insights into the diverse applications and economic outcomes of SG technologies across different geographical and economic contexts. Moreover, this and other studies conducted, such as [8], allow for a comparison of the differences in SG implementation across various regions, such as China, the EU, and the US. For instance, China must increase its investment in transmission and distribution (T&D) to better serve rural areas, compared to the approaches taken by the US and EU. Another aspect to consider is that there may be overlapping effects or scalable relations between aspects considered in the SGs, as can be seen in [8], and it requires data and studies focused on the relationships between factors and benefits and how they affect the overall results for SG implementations.

5. Conclusions

China is a key global investor in the energy sector and has substantial potential for integrating Variable Renewable Energy Sources (VRES) into its electricity grid. To reduce the dependence on coal for energy production, efforts have been made to implement Smart Grids (SGs) that enable the seamless integration of renewable energy sources. In 2023, China's State Grid Corporation declared a planned investment of CNY 77 billion into the transmission sector for the year and CNY 329 billion through the whole 2021–2025 14th Five-Year Plan period

To evaluate the feasibility of similar initiatives, a cost–benefit analysis (CBA) was performed using the methodology developed by the Electric Power Research Institute (EPRI). To the best of the authors' knowledge, this methodology was never applied on a nation-wide scale in prior analyses, especially outside the EU and US. A similar approach, even if maintained at high-level scale due to the inherent difficulties in data collection, allows to present a wide perspective on the development of the SG network. The analysis yielded a benefit–cost (B/C) ratio of 6.1:1, indicating that the overall benefits of the project significantly exceed its costs. The highest costs for SG implementation are expected in the power distribution sector, which would need strong improvement for new capacity, observability, and operations automation. Of great interest and importance is also the result related to the end user sector: in the high costs scenario, it becomes the sector with the second highest implementation costs. This result highlights the importance of deploying policy measures that support the end users in both bearing the cost of energy transitions and on increasing their conscious use of energy.

Such as in US and in the EU, there are some limitations on the development and deployment of the SG in China, namely the huge costs of the investment, the time needed to complete the SG deployment, some technical bottlenecks (particularly, digitalisation of the infrastructure), and, last but not least, the social and policy dimensions of the SG implementation, which also require the promotion of smart appliances and machineries.

Despite these promising results, further research is necessary to enhance accuracy and refine the evaluation process. Future studies may involve adjusting assumptions or developing improved forecasting models for the nine key attributes examined in this study. Additionally, the next phase of research will focus on applying this enhanced methodology to assess Smart Grid implementation in other countries, broadening its scope and potential impact.

The analysis presented here is not without limitations; the most significant is the lack of comprehensive information. To bridge this gap, certain assumptions were necessary, inevitably introducing some degree of uncertainty into the results. Another major limitation is the challenge of making long-term predictions over a 30-year period in a rapidly evolving global context. Despite these challenges, the assumptions and projections aim to provide a balanced overview of potential benefits and costs. These projections are intended to offer insights that, while possibly varying in detail and timescale, can be substantiated through further case studies. This groundwork is expected to be adaptable to other contexts, such as India, Brazil, and South Africa, providing a framework for updating and comparing different regions, thereby aiding decision-makers in evaluating the costs and benefits of SG implementation. To summarise, the implementation of Smart Grid technology in China promises substantial improvements for both the energy sector and the wider community. Benefits include heightened energy efficiency, cost savings, better grid stability, and a reduction in carbon emissions. Despite the challenges in deploying Smart Grids, the potential rewards justify continued efforts towards achieving a more sustainable and low-emission future.

Author Contributions: Conceptualization, M.C.L., P.S. and G.T.; Methodology, M.C.L., P.S. and G.T.; Validation, M.C.L. and P.S.; Formal analysis, M.C.L. and P.S.; Investigation, N.S.B., M.C.L. and G.T.; Data curation, M.C.L.; Writing—original draft, N.S.B., M.C.L., P.S. and G.T.; Writing—review & editing, N.S.B., M.C.L., P.S. and G.T.; Visualization, N.S.B., M.C.L. and G.T.; Supervision, M.C.L. and P.S.; Project administration, M.C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Salkuti, S.R. Challenges, issues and opportunities for the development of Smart Grid. *Int. J. Electr. Comput. Eng.* **2020**, *10*, 1179–1186.
2. Bregoli, D.; Liscio, M.C.; Nabiti, N.; Sospiro, P. Exploring the Evolution of Smart Cities: A Review on Energy, Mobility, and Waste Management Aspects. In *Smart Cities—Foundations and Perspectives*; IntechOpen: London, UK, 2024.
3. Chioatto, E.; Fedele, A.; Liscio, M.C.; Sospiro, P. Testing data envelopment analysis models on the performance of European Union regions in sustainable waste management. *Waste Manag.* **2024**, *175*, 170–182. [PubMed]
4. IEA. *Net Zero by 2050—A Roadmap for the Global Energy Sector*; International Energy Agency: Paris, France, 2021.
5. Statista. State Grid Corporation of China's Investment in Grid Expansion from 2010 to 2020 with an Estimate for 2024. 2023. Available online: https://www.statista.com/statistics/302453/china-state-grid-corporation-grid-expansion-investment/ (accessed on 2 December 2023).
6. EFCHINA. China's 14th Five-Year Plans on Renewable Energy Development and Modern Energy System. 2022. Available online: https://www.efchina.org/Blog-en/blog-20220905-en (accessed on 2 December 2023).
7. United States Department of Energy. *Smart Grid System Report 2018*; UOE: Washington, DC, USA, 2018.
8. Sospiro, P.; Amarnath, L.; Di Nardo, V.; Talluri, G.; Gandoman, F.H. Smart Grid in China, EU, and the US: State of Implementation. *Energies* **2021**, *14*, 5637. [CrossRef]
9. Nibbi, L.; Sospiro, P.; De Lucia, M.; Wu, C.-C. Improving Pumped Hydro Storage Flexibility in China: Scenarios for Advanced Solutions Adoption and Policy Recommendations. *Energies* **2022**, *15*, 7918. [CrossRef]
10. International Hydropower Association. Pump it up: Recommendations for urgent investment in pumped storage hydropower to back the clean energy transition. In Proceedings of the International Forum on Pumped Storage Hydropower, Virtual Event, 25 May 2021.
11. Wantenaar, A. State Grid to invest $77 billion in the power grid in 2023. *Transformes Magazine*, 18 January 2023.
12. Sospiro, P.; Liscio, M.C.; Boateng, N.S. Smart grid in China, EU, and US: State of Implementation. *Magazine of EU-China Energy Cooperation Platform*, June 2023; pp. 29–33.
13. Cagri Gungor, V.; Sahin, D.; Kocak, T.; Ergut, S.; Buccella, C.; Cecati, C.; Hancke, G.P. A Survey on Smart Grid Potential Applications and Communication Requirements. *IEEE Trans. Ind. Inform.* **2013**, *9*, 28–42.

14. Palensky, P.; Dietrich, D. Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. *IEEE Trans. Ind. Inform.* **2011**, *7*, 381–388. [CrossRef]
15. Hassan, F. The path of the smart grid. *IEEE Power Energy Mag.* **2010**, *8*, 18–28.
16. Jithish, J.; Alangot, B.; Mahalingam, N.; Yeo, K.S. Distributed Anomaly Detection in Smart Grids: A Federated Learning-Based Approach. *IEEE Access* **2023**, *11*, 7157–7179. [CrossRef]
17. Xiang, Y.; Cai, H.; Gu, G.; Shen, X. Cost-benefit analysis of integrated energy system planning considering demand response. *Energy* **2020**, *192*, 116632.
18. Sidhu, A.S.; Pollitt, M.G.; Anaya, K.L. A social cost benefit analysis of grid-scale electrical energy storage projects: A case study. *Appl. Energy* **2018**, *212*, 881–894.
19. van der Stelt, S.; AlSkaif, T.; van Sark, W. Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances. *Appl. Energy* **2018**, *209*, 266–276.
20. Mets, K.; Aparicio Ojea, J.; Develder, C. Combining Power and Communication Network Simulation for Cost-Effective Smart Grid Analysis. *IEEE Commun. Surv. Tutor.* **2014**, *16*, 1771–1796.
21. Miceli, R. Energy Management and Smart Grids. *Energies* **2013**, *6*, 2262–2290. [CrossRef]
22. Pudjianto, D.; Djapic, P.; Aunedi, M.; Gan, C.K.; Strbac, G.; Huang, S.; Infield, D. Smart control for minimizing distribution network reinforcement cost due to electrification. *Energy Policy* **2013**, *52*, 76–84.
23. Faruqui, A.; Harris, D.; Hledik, R. Unlocking the €53 billion savings from smart meters in the EU: How increasing the adoption of dynamic tariffs could make or break the EU's smart grid investment. *Energy Policy* **2010**, *38*, 6222–6231.
24. Brunekreeft, G.; Luhmann, T.; Menz, T.; Müller, S.-U.; Recknagel, P. (Eds.) *Regulatory Pathways for Smart Grid Development in China*; Springer: Berlin/Heidelberg, Germany, 2015.
25. Lin, C.-C.; Yang, C.-H.; Shyua, J.Z. A comparison of innovation policy in the smart grid industry across the pacific: China and the USA. *Energy Policy* **2013**, *57*, 119–132.
26. Guo, Z.; Ma, L.; Liu, P.; Jones, I.; Li, Z. A multi-regional modelling and optimization approach to China's power generation and transmission planning. *Energy* **2016**, *116*, 1348–1359.
27. El-hawary, M.E. The Smart Grid—State-of-the-art and Future Trends. *Electr. Power Compon. Syst.* **2014**, *42*, 239–250.
28. Izadian, A.; Girrens, N.; Khayyer, P. Renewable Energy Policies: A Brief Review of the Latest U.S. and E.U. Policies. *IEEE Ind. Electron. Mag.* **2013**, *7*, 21–34.
29. Ngar-yin Mah, D.; van der Vleuten, D.M.; Hills, P.; Tao, J. Consumer perceptions of smart grid development: Results of a Hong Kong survey and policy implications. *Energy Policy* **2012**, *49*, 204–216.
30. Zhai, M.-Y. Transmission Characteristics of Low-Voltage Distribution Networks in China Under the Smart Grids Environment. *IEEE Trans. Power Deliv.* **2011**, *26*, 173–180.
31. Zhou, J.; Xu, Z. Optimal sizing design and integrated cost-benefit assessment of stand-alone microgrid system with different energy storage employing chameleon swarm algorithm: A rural case in Northeast China. *Renew. Energy* **2023**, *202*, 1110–1137. [CrossRef]
32. Cui, B.; Gao, D.; Wang, S.; Xue, X. Effectiveness and life-cycle cost-benefit analysis of active cold storages for building demand management for smart grid applications. *Appl. Energy* **2015**, *147*, 523–535.
33. Chien, J.C.L.; Lior, N. Concentrating solar thermal power as a viable alternative in China's electricity supply. *Energy Policy* **2011**, *39*, 7622–7636.
34. Electric Power Research Institute. *Estimating the Costs and Benefits of the Smart Grid*; EPRI: Palo Alto, CA, USA, 2011.
35. Boateng, N.S.; Calle Garcia, C.A.; Liscio, M.C.; Sospiro, P.; Talluri, G. Smart Grid implementation in China: A Cost-Benefit Analysis. In Proceedings of the 15th International Conference on Applied Energy, Doha, Qatar, 3–7 December 2023.
36. Giordano, V.; Onyeji, I.; Fulli, G.; Sanchez Jimenez, M.; Filiou, C. *Guidelines for Conducting a Cost-Benefit Analysis of Smart Grid Projects*; Publications Office of the European Union: Luxembourg, 2012.
37. ENTSO-E. Data & Standardisation. Available online: https://www.entsoe.eu/data/ (accessed on 2 December 2023).
38. U.S. Department of Energy. *Electricity Industry Insights.*. Available online: https://www.energy.gov/electricity-insights (accessed on 2 December 2023).
39. Babayomi, O.; Zhang, Z.; Dragicevic, T.; Hu, J.; Rodriguez, J. Smart grid evolution: Predictive control of distributed energy resources—A review. *Int. J. Electr. Power Energy Syst.* **2023**, *147*, 108812.
40. Sankarananth, S.; Karthiga, M.; Suganya, E.; Sountharrajan, S.; Bavirisetti, D.P. AI-enabled metaheuristic optimization for predictive management of renewable energy production in smart grids. *Energy Rep.* **2023**, *10*, 1299–1312.
41. Daiyan Kaif, A.M.A.; Alam, K.S.; Das, S.K. Blockchain based sustainable energy transition of a Virtual Power Plant: Conceptual framework design & experimental implementation. *Energy Rep.* **2024**, *11*, 261–275.
42. International Energy Agency. *Projected Cost of Generating Electricity 2015*; International Energy Agency: Paris, France, 2015.
43. International Energy Agency. *Projected Cost of Generating Electricity 2020*; International Energy Agency: Paris, France, 2020.

44. Trinomics, B.V. *Study on Energy Costs, Taxes and the Impact of Government Interventions on Investments in the Energy Sector*; Publications Office of the European Union: Luxembourg, 2020.
45. Energy Transitions Commission. *China 2050: A Fully Developed Rich Zone-Carbon Economy*; ETC: London, UK, 2018.
46. International Energy Agency. *Nuclear Power and Secure Energy Transitions: From Today's Challenges to Tomorrow's Clean Energy Systems*; International Energy Agency: Paris, France, 2022.
47. Energy Information Administration. *International Energy Outlook 2021 with Projections to 2025*; EIA: Washington, DC, USA, 2021.
48. Energy Information Administration. *International Energy Outlook 2021—Data Tables*; EIA: Washington, DC, USA, 2021.
49. Sospiro, P.; Nibbi, L.; Liscio, M.C.; De Lucia, M. Cost–Benefit Analysis of Pumped Hydroelectricity Storage investment in China. *Energies* **2021**, *14*, 8322. [CrossRef]
50. Energy Research Institute. *National Development and Reform Commission China 2050 High Renewable Energy Penetration Scenario and Roadmap Study*; Energy Research Institute: Beijing, China, 2015.
51. International Energy Agency. *Total Power Grid Investments in China, 2015–2019*; International Energy Agency: Paris, France, 2020.
52. Murdock, H.E.; Gibb, D.; André, T. *Renewables Now—REN21 Trends in China: Facts from the Renewables 2021 Global Status Report*; REN21 Secretariat: Paris, France, 2021.
53. International Energy Agency. *Electricity*; International Energy Agency: Paris, France, 2021.
54. Ali, S.S.; Choi, B.J. State-of-the-Art Artificial Intelligence Techniques for Distributed Smart Grids: A Review. *Electronics* **2020**, *9*, 1030. [CrossRef]
55. China Energy Portal. Tracking China's transition to sustainable energy. 2016. Available online: https://chinaenergyportal.org/en/2016-detailed-electricity-statistics/ (accessed on 1 November 2023).
56. National Energy Technology. *Laboratory Understanding the Benefits of the Smart Grid*; U.S. Department of Energy: Washington, DC, USA, 2010.
57. Ye, Q.; Lu, J.; Zhu, M. *Wind Curtailment in China and Lessons from the United States*; Brookings Institution: Washington, DC, USA, 2016.
58. International Energy Agency. *China Power System Transformation: Assessing the Benefit of Optimised Operation and Advanced Flexibility Options*; International Energy Agency: Paris, France, 2019.
59. Global Solar PV Brain Trust. *Solar PV Curtailment Drivers and Solutions*; Global Solar PV Brain Trust: Berlin, Germany, 2024.
60. Statista. Electricity Transmission Losses in China from 2010 to 2021. 2021. Available online: https://www.statista.com/statistics/302292/china-electric-power-transmission-loss/ (accessed on 3 January 2022).
61. Pillai, R.K.; Bhatnagar, R.; Thukral, H. AMI rollout strategy and cost-benefit analysis for India. In Proceedings of the 2016 First International Conference on Sustainable Green Buildings and Communities (SGBC), Chennai, India, 18–20 December 2016; pp. 1–6.
62. Research and Markets. *Global & China Smart Meter Market Outlook 2020–2026: Focus on Smart Electric, Water, Gas & Heat Meters with Profiles of 6 Global and 17 Chinese Manufacturers*; Research and Markets: Dublin Ireland, 2020.
63. Largue, P. *China Leads Smart Electric Meter Market*; Smart Energy International: Maarssen, The Netherlands, 2018.
64. Department for Business, Energy and Industrial Strategy. *Smart Meter Roll-Out Cost-Benefit Analysis—Part II—Technical Annex*; Department for Business, Energy and Industrial Strategy: London, UK, 2016.
65. U.S. Department of Energy. *Operations and Maintenance Saving from Advance Metering Infrastructure*; UOE: Washington, DC, USA, 2012.
66. Amadi, H.N.; Izuegbunam, F.I. Analysis of Transformer Loadings and Failure Rate in Onitsha Electricity Distribution Network. *Am. J. Electr. Electron. Eng.* **2016**, *4*, 157–163.
67. CEIC. *China Capacity of Transformer*; CEIC: Warsaw, Poland, 2022.
68. CEIC. *China Transformer, Rectifier & Inductor: Current Asset*; CEIC: Warsaw, Poland, 2015.
69. Chen, H.; Yan, H.; Gong, K.; Geng, H.; Yuan, X.-C. Assessing the business interruption costs from power outages in China. *Energy Econ.* **2022**, *105*, 105757.
70. USAID. *Smart Grid Technology Reduces Power Outages in Bosina and Herzegovina*; USAID: Washington, DC, USA, 2016.
71. Flego, G.; Vitiello, S.; Fulli, G.; Marretta, L.; Stromsather, J. *Cost-Benefit Analysis of Smart Grid Projects*; JRC: Isernia, Italy, 2018.
72. Karali, N.; Flego, G.; Yu, J.; Vitiello, S.; Zhang, D.; Marnay, C. *Uncertainty in Benefit-Cost Analysis of Smart Grid Demonstration Projects in the U.S., China, and Italy*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2016.
73. Padmini, V.; Omran, S.; Chatterjee, K.; Khaparde, S.A. Cost Benefit Analysis of Smart Grid: A Case Study from India. In Proceedings of the 2017 North American Power Symposium (NAPS), Morgantown, WV, USA, 17–19 September 2017; pp. 3–4.
74. Abdallah, Z.; Oleik, I. *Smart Grids, The Science and Technology of Energy*; American University of Beirut: Beirut, Lebanon, 2020.