

Social costs and benefits of smart grid technologies



FOREWORD

This study was commissioned by The Swedish Smart Grid Forum, The International Smart Grid Action Network (ISGAN) and The Swedish Energy Market Inspectorate. The purpose of the report is to provide investors with decision support to evaluate investments in smart grid technologies, in order to advance implementation.

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SOCIAL COSTS AND BENEFITS OF SMART GRID TECHNOLOGIES

1. Summary

Smart grid technologies represent different ways to enhance the effectiveness of the power distribution and transmission system by making it possible to use existing power infrastructure more efficiently. Implementation of smart grid solutions could for instance, represent an alternative to investment in new power generation capacity or new power lines.

Many new smart grid technologies are available, but not yet deployed. In order to advance implementation, governments and other investors need decision support to evaluate investments in smart grid technologies.

Cost-benefit analysis (CBA) offers a systematic process for comparing the advantages and disadvantages of a smart grid initiative from society perspective.

Purpose of the study

This report presents a mapping and analysis of existing literature on social costs and benefits of smart grid solutions and identifies gaps in current guidance. The study also includes a review on how network regulation affects incentives to invest in smart grid technologies and an analysis on how CBA constitutes an important input to the design of the network regulation. The report also serves as a basis for selecting models and methods to be used by the Swedish Smart Grid Forum in order to assess different smart grid projects and applications.

Smart grid technology

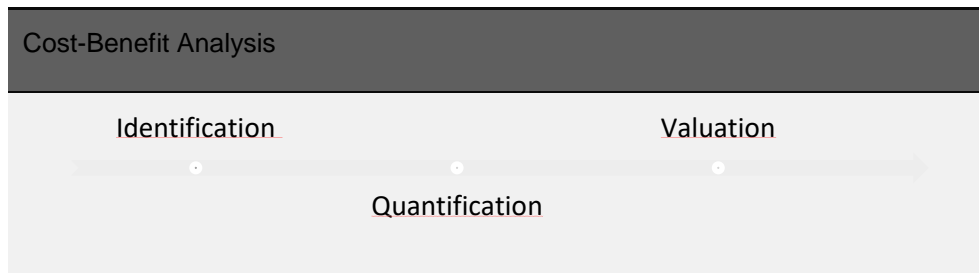
Due to the multifaceted and broad nature of smart grid technologies, CBA of smart grid deployment is complex as smart grid technologies provide benefits on a system level as well as on the project level. Smart grid technologies are also under fast development, which lead to a lack of data and uncertainty when extrapolating results from pilot projects to the system level.

Energy and climate goals as those identified on the European level as well as on a national levels aim to increase renewable energy, improve energy efficiency and reduce carbon emissions. Smart grid technologies contribute to all these goals, not only directly but to large extent indirectly, which calls for comprehensive evaluation methodologies on a system level. Comprehensive analyses on the system level can provide input to CBA.

Cost-benefit analysis method

The aim of CBA is to identify all the gains and losses (benefits and costs) created by an initiative. The intention is to express the gains and losses in monetary terms irrespective to whom they accrue.

On a general level, CBA contains three main steps. These are identification, quantification and valuation of the benefits and costs.



Electricity network regulation and CBA

Investments in smart grid solutions are made by various actors, including vertically integrated utilities, regulated network companies, property owners and households. However, market design and electricity network regulation influences investment incentives for the different actors. If incentives are weak, smart grid deployment might become slower than socially desirable. Several studies suggest that existing regulation often hampers investments in smart grids. Results from previous analyses indicate incentive-based and output based regulatory mechanisms provide stronger incentives than cost-based or rate-of return regulation. Although incentive and output-based regulatory mechanisms perform well, promotion of smart grid investments may call for additional innovation incentives.

Network regulation typically calls for CBA in two steps. In the first step, the purpose is to investigate whether benefits exceed the costs of some particular smart grid initiatives or solutions e.g. roll out of smart meters. If this is the case, the smart grid initiative is assessed as socially desirable. In the second step, the analysis needs to clarify whether the smart grid investment is commercially viable under current regulation for the actor in charge of the investment. The result of the two-step CBA serves as an input to suggest changes in electricity network regulation to promote an outcome desirable from a societal perspective.

Current CBA frameworks within smart grid technology evaluation

The general framework of smart grid CBA, developed by Electric Power Research Institute (EPRI) is in many ways the foundation or origin of several other approaches ("The EPRI Family"). European Commission's Joint Research Centre (EC JRC), the US Department of Energy (DOE) and the Smart Grid Computational Tool (SGCT) are all based on the EPRI approach, even though they have their own indicators, characteristics and analytical tools.

The Smart Grid Forum (SGF) together with Frontier Economics present one example of a somewhat different approach (The real options method), other examples are: the EA Technology “Transform Model”, Qianhai Project Approach, Smart Grid Multi Criteria Analysis SG-MCA, The Navy Yard (TNY) Method amongst other. .

Although developed frameworks have differences, almost all of them have included benefits of smart grid technologies such as reduced costs concerning generation, outages, operational costs of the transmission and distribution systems and carbon dioxide (CO₂) emissions.

Application - CBA of smart grid technologies in the Swedish context

Ambitious environmental goals are expected to increase the need for flexibility in the Swedish electricity system, creating a demand for smart grid technologies as well as accurate comparison tools to evaluate different options for changing the electricity system. There is no one single solution to meet the demands for change in the electricity system or the climate and environmental targets which implies that CBA becomes crucial in comparing different options.

Gap analysis in literature covering CBA of smart grid technologies

Despite the wide range of frameworks for conducting CBA, for smart grid technologies there are still knowledge gaps that need to be addressed. Gaps range from lack of technologies covered to lack of underlying data as well as gaps in knowledge of sufficient handling of uncertainties in CBA.

Conclusions

Several frameworks in available literature are under development, which suggests frameworks and tools are still changing and being refined due to new data from case studies etc.

CBA provides a comprehensive method to assess the value of benefits and costs of smart grid deployment. This makes it possible to compare investment costs to direct and indirect benefits. However, the complexity in identifying the effects of smart grid deployment, calls for quantitative input from complementary analyses of the electricity network and the energy system, which then provide important inputs for CBA.

Identified challenges of CBA for smart grid investments in current methods are the risk of double counting, categorizing impacts in a relevant way, changing costs and benefits, the validity of scenarios, synergies and the possibilities of transferring results from one context to another. However, CBA does not derive impacts from smart grid deployment on other sectors of the economy or employment effects. When there is demand for analysing employment effects and economic impacts, other methods are called for, e.g. economic input-output analysis.

Regulation in itself has no or little impact on overall benefits and costs. In CBA, costs are reflected by opportunity costs, which most often can be represented by

actual production costs. Regulation rather affects how benefits and costs are distributed between different stakeholders. Benefits in terms of e.g. avoided investments in traditional grid extension will most often accrue to network system operators or local grid companies and dependent on regulation partly shared with network customers.

Looking at the methods available for conducting a CBA in the smart grid area the JRC framework is the most suitable to adopt to the Swedish context. The reasons being it is based on the comprehensive EPRI framework and adopted to the European (and thereby also partly to the Swedish) perspective.

Existing literature can also aid by providing input values in the three key steps of the CBA. In the identification stage, costs and benefits in previous studies can be used as well as list of identified stakeholders. In the quantification stage, data from case studies and demonstration projects can be used. In the final step, valuation, shadow prices such as Value of Lost Load (VoLL) and Marginal Costs of Public Funds (MCPF) can be transferred.

From the review of existing literature on CBA the following gaps has been identified and analysed in the report.

- Gap in technological coverage
- Demand for other decision support tools – widening CBA to MCA and economic impact analysis of smart grids
- Regulatory coverage of CBA
- Analysis of certain benefits
- Gap between methods and users: conducting CBA might appear too complicated.
- More relevant data from smart grid demonstrations needs to be collected
- Analysis of uncertainties
- Reassessment of unprofitable projects

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2. Introduction

Smart grid technologies represent different ways to enhance the effectiveness of the power distribution and transmission system by making it possible to use existing power infrastructure more efficiently. Implementation of smart grid solutions could for instance, represent an alternative to investment in new power generation capacity or new power lines. Many new smart grid technologies are available, but not yet deployed. In order to advance implementation, governments and other investors need decision support to evaluate investments in smart grid technologies. Cost-benefit analysis (CBA) offers a systematic process for comparing the advantages and disadvantages of a smart grid initiative from a societal perspective.

Sweden is a member of the International Smart Grid Action Network (ISGAN), which is an initiative under the Clean Energy Ministerial (CEM) also organized as a Technology Collaboration Programme (TCP) within the International Energy Agency (IEA). The aim of ISGAN is to improve the understanding of smart grid technologies, practices, and systems and to promote adoption of enabling governmental policies.

The work of ISGAN is split into seven annexes with different goals and purposes. ISGAN Annex 3 focuses on Cost Benefit Analyses (CBA) and developing tool-kits, including assessing, modifying, and analysing existing benefit-cost analytical tools as well as developing of new tools. CBA is a tool, which evaluates whether or not a decision improves efficiency of resource allocation in society. In a CBA, the cost of a measure is compared to the benefit of the measure.

The Swedish Smart Grid Forum is a national forum appointed by the Swedish Ministry of Environment and Energy. Their mission is to continue the work of the former Coordination Council and National Knowledge Platform for Smart Grids appointed by the Swedish Government in 2012. Their scope of work includes implementation of the action plan, set up by the former council, to further develop a knowledge platform for smart grids and to support Swedish export efforts within smart grid solutions. In line with the Forum's mission, one task is to assess the benefits and costs associated with smart grid applications.

Purpose

In order to complement the work carried out by both ISGAN Annex 3 and the Swedish Smart Grid Forum, WSP was assigned by Swedish Smart Grid Forum and the Swedish Energy Market Inspectorate to map and review existing literature about social costs and benefits of smart grid solutions and to identify gaps in current guidance. The study also includes an analysis of how network regulation affects costs and benefits of smart grid technologies.

The report also serves as a basis of selecting models/methods to be used by the Swedish Smart Grid Forum in order to assess different smart grid projects and

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applications. It will also provide input for discussions and decisions about further work within ISGAN on the topic of CBA for smart grid technologies. The results are also expected to increase international knowledge sharing about established/accepted methods and limitations of undertaking a CBA for smart grids.

This report is one of three reports included in the 2017 work program of ISGAN Annex 3. The Austrian ISGAN Annex 3 member is responsible for the second report and its purpose is to describe asymmetries in distribution of benefits. The Italian ISGAN Annex 3 member will contribute with the third report focusing on multi-criteria analyses. This report will therefore only briefly address the topics covered by the two other reports.

Overview and how to read the report

Chapter 3 gives an overview of smart grid technologies and their purpose. Chapter 4 provides the principles of CBA. Chapter 5 presents different electricity network regulation models and the connection between CBA and regulation. Chapter 6 provides a summary of current CBA methods. Chapter 7 presents an application to the Swedish context as a specific case study. Chapter 8 highlights identified gaps in current literature and chapter 9 summarizes the conclusions and recommendations of the study.

Readers who are primarily interested in general questions and conclusions are recommended to read the summary as well as chapter 8 and 9.

For readers who are interested in an overall compilation of the frameworks of cost benefit analysis can find a summary table in the Appendix.

CIREN Conference

The International Conference on Electricity Distribution (CIREN) arranged a specific round table discussion about societal costs and benefits of smart grids (RT4) to which a memo containing the summary of current frameworks and the gap analysis was presented. The comments received have been included in this version of the report.

List of Abbreviations

List of organizations (in alphabetical order):

CE Delft	CE Delft is an independent Dutch research organization and consultancy
CEER	Council of European Energy Regulators
CIREN	International Conference on Electrical Distribution
DOE	The United States Department of Energy
EA Technology	A company working with assets management solutions for owners and operators of electrical assets.
EC JRC	European Commission's Joint Research Centre. Is the European Commission's science and knowledge service
EEGI	European Electricity Grid Initiative is one of the European Industrial Initiatives under the Strategic Energy Technologies Plan
ENEDIS	Formerly known as ERDF, is the electric grid operator for much of France
ENTSO-E	The European Network of Transmission System Operators, representing 43 electricity transmission system operators (TSOs) from 36 countries across Europe.
EPRI	The Electric Power Research Institute: Is an independent, nonprofit organization for energy and environmental research in the United States
EURELECTIC	The Union of the Electricity Industry - is the sector association which representing the common interests of the electricity industry in Europe.
FRONTIER	
ECONOMICS	Economic consultancy firm
GRID4EU	Brings together a consortium of 6 European energy distributors (ERDF, Enel Distribuzione, Iberdrola, CEZ Distribuce, Vattenfall Eldistribution and RWE).
IEA	International Energy Agency
ISGAN	International Energy Agency Implementing Agreement for a Co-operative Programme on Smart Grids
IRENA	The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future.

RTE	Réseau de Transport d'Électricité. Is the electricity transmission system operator of France.
SGCC	Smart Grid Consumer Collaborative is a nonprofit organization that works to learn the wants and needs of energy consumers in the United States.
SGF	Smart Grid Forum is a hub for smart grid learning and information for industry, government and other key stakeholders in the UK and supported by the Department for Business, Energy & Industrial Strategy and the Office of Gas and Electricity Markets in the UK.
SGRC	Smart Grid Research Consortium is an independent research and consulting firm in the US.

List of other abbreviations

CAPEX	Capital expenditure
CBA	Cost benefit analysis, also known as benefit-cost analysis, social cost-benefit analysis and socio-economic or economic analysis
DSO	Distribution system operator
MCA	Multi-criteria analysis
MCPF	Marginal cost of public funds
OPEX	Operating expenditure
QPA	Qianhai Project Approach
RES	Renewable energy
SGCT	Smart Grid Computational Tool
SGIM	The smart grid Investment model was developed by the Smart Grid Research Consortium (SGRC).
TNY	The Navy Yard Method
TOTEX	Total expenditure
TSO	Transmission system operator
VoLL	Value of Lost Load
WACC	Weighted average cost of capital

3. Smart Grid Technologies

Smart Grid Technologies are defined by IEA as *"an electricity network system that uses digital technology to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. Such grids are able to co-ordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders in such a way that they can optimise asset utilisation and operation and, in the process, minimise both costs and environmental impacts while maintaining system reliability, resilience and stability"* (IEA, 2011).

Due to the multifaceted and broad nature of smart grid technologies, undertaking a CBA of smart grid deployment is complex as smart grid technologies provide benefits on a system level as well as on the project level.

Smart grid technologies are also undergoing fast development which leads to a lack of data and uncertainty when extrapolating results from pilot projects to the system level.

Other complications when assessing cost and benefits of implementation of smart grid technologies are:

- Quantification may require system based models
- Benefits and costs accrue to various stakeholders
- The stakeholders in charge of investments, might not be the ones who gain from the investment

Smart grid technologies can be divided into eight sub-categories (IEA, 2011):

1. Wide-area monitoring and control
2. Information and communications technology (ICT) integration
3. Renewable and distributed generation integration
4. Transmission enhancement applications
5. Distribution grid management
6. Advanced metering infrastructure (AMI)
7. Electric vehicle charging infrastructure
8. Customer-side systems (CS)

The usage of the different sub-categories in the electrical grid is illustrated in the figure below.

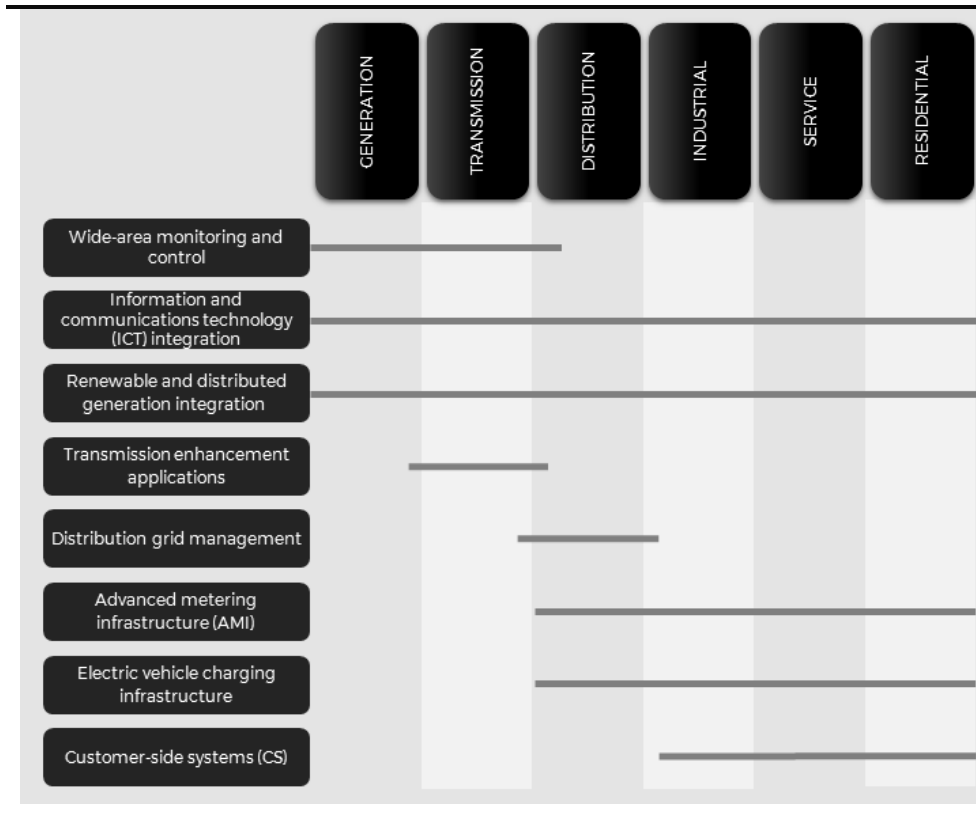


Figure 1 – Smart grid usage in the energy system

Source: modified from IEA (2011)

The purpose of using smart grid technologies varies due to the wide set of technologies. The main purposes of smart grid technologies are listed below:

- Facilitate the introduction and employment of renewable energy technologies
- Make energy usage available, secure, reliable and energy efficient
- Power reduction at peak load
- Enable more active energy consumers
- Reduce the environmental impact of the electricity system

The characteristics of a smart grid identified by IEA (2011) are summarized in the table below.

Table 1 – Characteristics of smart grids

Source: IEA (2011)

Characteristic	Description
Enables informed participation by customers	Consumers help balance supply and demand, and ensure reliability by modifying the way they use and purchase electricity. These modifications come as a result of consumers having choices that motivate different purchasing patterns and behaviour. These choices involve new technologies, new information about their electricity use, and new forms of electricity pricing and incentives.
Accommodates all generation and storage options	A smart grid accommodates not only large, centralised power plants, but also the growing array of customer-sited distributed energy resources. Integration of these resources – including renewables, small-scale combined heat and power, and energy storage – will increase rapidly all along the value chain, from suppliers to marketers to customers.
Enables new products, services and markets	Correctly designed and operated markets efficiently create an opportunity for consumers to choose among competing services. Some of the independent grid variables that must be explicitly managed are energy, capacity, location, time, rate of change and quality. Markets can play a major role in the management of these variables. Regulators, owners/operators and consumers need the flexibility to modify the rules of business to suit operating and market conditions.
Provides the power quality for the range of needs	Not all commercial enterprises, and certainly not all residential customers, need the same quality of power. A smart grid supplies varying grades (and prices) of power. The cost of premium power-quality features can be included in the electrical service contract. Advanced control methods monitor essential components, enabling rapid diagnosis and solutions to events that impact power quality, such as lightning, switching surges, line faults and harmonic sources.
Optimises asset utilisation and operating efficiency	A smart grid applies the latest technologies to optimise the use of its assets. For example, optimised capacity can be attainable with dynamic ratings, which allow assets to be used at greater loads by continuously sensing and rating their capacities. Maintenance efficiency can be optimised with condition-based maintenance, which signals the need for equipment maintenance at precisely the right time. System-control devices can be adjusted to reduce losses and eliminate congestion. Operating efficiency increases when selecting the least-cost energy-delivery system available through these types of system-control devices.
Provides resiliency to disturbances, attacks and natural disasters	Resiliency refers to the ability of a system to react to unexpected events by isolating problematic elements while the rest of the system is restored to normal operation. These self-healing actions result in reduced interruption of service to consumers and help service providers better manage the delivery infrastructure.

The purpose of using smart grid technologies also varies depending on the background and scope of the actual project, demonstration initiative and country. The benefits and costs of the various smart grid technologies differ from one another, which will later be observed in the overview and summary of the different costs and benefits of smart grid technologies in chapter 6.

In order to evaluate the societal gains the main focus of the CBA is therefore the comparison of the benefits and costs from implementation of smart grid technology. The basics of CBA is covered in the next chapter.

Smart grid technology and energy and climate goals

Commonly energy and climate goals identified on regional or national level aim to increase renewable energy, improve energy efficiency and reduce carbon emissions. For instance on European level climate change and energy targets until 2020 and 2030 respectively are:

Target	2020	2030
Greenhouse gas emissions (compared to 1990 levels)	20%	40%
Energy coming from renewables	20%	27%
Increase in energy efficiency	20%	27%

Smart grid technologies contribute to all these goals, not only directly, but to a large extent indirectly, which calls for more comprehensive evaluation methodologies such as CBA. As an example smart meters directly improve energy efficiency and indirectly contribute to lower carbon emissions.

In summary, all smart grid technologies contribute to reduction of carbon emissions indirectly, and directly they affect energy efficiency, while increases in renewable energy is affected indirectly by most technologies.

Table 2 – Smart grid technology and energy and climate goals

	Increase in energy efficiency	Reduced carbon emissions	Increased renewable energy
Wide-area monitoring and control	Directly	Indirectly	Indirectly
Information and communications technology (ICT) integration	Directly	Indirectly	Directly
Renewable and distributed generation integration	Indirectly	Indirectly	Directly
Transmission enhancement applications	Directly	Indirectly	Indirectly
Distribution grid management	Directly	Indirectly	Indirectly
Advanced metering infrastructure (AMI)	Directly	Indirectly	Indirectly
Electric vehicle charging infrastructure	Directly	Indirectly	Indirectly
Customer-side systems (CS)	Directly	Indirectly	Indirectly

4. Cost-Benefit Analysis

The aim of a CBA is to identify all the gains and losses (benefits and costs) created by an initiative. The intention is to express the gains and losses in monetary terms irrespective to whom they accrue. Monetization makes it possible to express the result in a single measure. For this reason, the outcome of a CBA may resemble that of financial analysis. However, there are important differences. Financial analysis considers only monetary costs and revenues, and only those that accrue to the owner of the investment. The scope of CBA is wider and provides a broader perspective than financial analysis.

In literature, different labels are in use to designate CBA: benefit-cost analysis, social cost-benefit analysis and socio-economic or economic analysis. In order to highlight the societal perspective some authors use the prefix social or socio. This memo uses the short terminology: cost-benefit analysis and the abbreviation CBA.

CBA offers a systematic process for calculating and comparing benefits and costs of an initiative. Its purpose is to assess the welfare change of the initiative under investigation. The objective is to find out whether the initiative, e.g. to implement a smart grid solution, provides a more efficient allocation of society's resources than potential alternatives. The theoretical basis of CBA rests on welfare economics, which helps the analyst to decide whether an impact that follows from a decision is a relevant benefit or cost.

Defining social welfare

In order to draw conclusions about the outcome with respect to society as a whole, there is a need for defining social welfare. CBA uses the Kaldor-Hick's criterion. According to the Kaldor-Hick's criterion, social welfare is the aggregate of the relevant costs and benefits. Since the consequences of decisions may extend over time, there is a need to make intertemporal comparisons. In order to express all costs and benefits in a common metric, future impacts are discounted to present values. The decision criterion of CBA is, therefore, that when the sum of discounted benefits exceeds the sum of discounted costs, the decision will improve the efficiency of resource allocation. In other words, social welfare increases when the net present value of CBA is positive.

System boundaries

As mentioned above, CBA should include all costs and benefits irrespective to whom they accrue. A global perspective includes benefits and costs that affect everyone. Usually, however, costs and benefits are delimited to the group of people who are financing the project being analysed. Since public budgets finance most government projects, the residents of a nation are usually included. For smart grid technology, international transmission capacity and increased market integration between countries calls into question whether the relevant system boundary goes beyond the residents of one country.

CBA methodology

On a general level, CBA contains three main steps. These are identification, quantification and valuation of the benefits and costs.

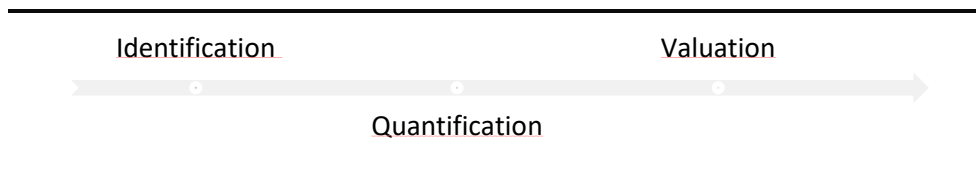


Figure 2 – Main steps of the CBA

The benefits and costs represent the change that follows from the initiative. In order to identify the costs and benefits of the initiative, a minimum of two options (alternatives) must be compared; one baseline option (without the initiative) and the other option representing implementation of the initiative under analysis. The baseline option typically represents the business as usual. Applied to smart grid initiatives, the baseline option needs to take into account grid investments that are expected if the smart grid solution is not implemented, as well as the smart grid solutions that will be implemented irrespective of the investment under analysis.

Since costs and benefits are evaluated during the lifetime of the investment, which for smart grid solutions could range from 10 to 50 years, it is necessary to make projections of impacts in future years. For projections affecting both options, it is necessary to formulate at least one scenario, representing the basic conditions surrounding the analysis (i.e. the exogenous variables) for future years. The scenarios represent probable and internally consistent development paths of relevant variables. In the energy sector typical variables include political priorities, subsidies, available production capacity, evolution of demand, and many other factors including economic growth and demography.

Identification

Having specified the initiative (i.e. the smart grid solution) and the baseline option, the identification step defines the benefits and costs as the difference between the options. Changes in prices and production volumes in relevant markets, generated by the investment (and when relevant, avoided investments), include benefits and costs of the smart grid solution. Impacts that are not valued in markets also need to be included, for example quality of supply (e.g. lower risk of power outages), security, safety, and environmental impacts. Impacts on secondary markets, i.e. impacts not represented at the electricity market, such as industrial productivity, innovation and competitive advantage in export markets, should only be included in the analysis after careful consideration. These impacts are uncertain and difficult to predict.

Risk of double counting

Additionally, there is risk of double counting impacts already valued in power markets. The identification phase, therefore, serves to decide which impacts to include in further analysis.

Double counting of certain costs and benefits in CBA occurs if including the same economic impact more than once. The EU guidelines on CBA give general instruction (European Commission 2014). One example is, if benefits of an irrigation project are based both on an estimated increase in the value of land and on the additional income that accrues to farmers from irrigation. Another instance where the CBA analyst needs to be careful is, if monetary exchanges are included as benefits or costs, but are actually transfer payments. Transfer payments imply transactions where money moves around between different stakeholders without creating economic value. An example would be if a proposed decrease in road tolls on a publicly owned highway is counted as a benefit for motorists. The reduction in tolls is a transfer because the saving of the motorists will result in lower toll income for the public sector. In this case, it could be purposeful to include both the benefits of the motorists and the costs to the public sector. In the overall result, the transfer payments even out.

Quantification

The quantification step is where estimation of the identified impacts takes place. Quantification needs to represent the cause-effect relationship between implementation of a smart grid solution versus the baseline option of not undertaking the implementation of the smart grid solution under analysis. Quantification into physical units can be done by using a variety of tools, such as computerized simulation models for power market analysis, grid modelling, experiments based on data from demonstration projects, other calculation tools and expert judgements. For smart grids, examples of quantification include impacts on energy losses and CO₂ emissions, expressed by kilowatt-hours lost and tons of CO₂-equivalents emitted, respectively.

Valuation

The third step, valuation, converts the physical impacts into monetary values. Often, quantification and valuation takes place in the same step, for example in a simulation model of the power market. Sometimes, however, the analyst needs to convert quantified results into monetary values, e.g. finding the value of lower probability of power outages. Value estimation can be done in a defensible way, for example by making a literature review of shadow prices or by consulting prior studies covering the same impact in other circumstances and adjusting the value through benefit transfer. One potential shadow price needed is the value of lost load (VoLL), which represents the maximum willingness to pay of consumers to avoid disruption in electricity supply.

Impacts should be valued for each year throughout the time horizon. Since the time horizon is the period when benefits and costs are estimated, it is usually purposeful to choose the life time of the investment as the time horizon. Beyond the time horizon benefits and costs are assumed equal to zero. The life time of smart meters range between 10-20 years. However, the longer the time horizon, the greater is uncertainty. Therefore, it is sometimes suggested that the pilot period of smart grids could represent the time horizon. Since pilot projects typically stretch over some years only, such time horizon does not capture benefits that would potentially be realized after the official “end date” of the project.

In the valuation step, all monetized impacts are discounted to the present. Discounting necessitates adoption of an appropriate interest rate. Many countries have prepared national guidance. In some cases, international recommendations are available. The EU commission recommends e.g. a social discount rate of 5 % for projects in Cohesion countries and 3 % for the other Member States (European Commission 2014). The result of the CBA is represented by the net present value, which is the sum of the discounted costs and benefits. If the sum of discounted benefits exceeds the sum of discounted costs, the decision is socially desirable. It is rare, however, that all relevant impacts can be valued in monetary terms or even be quantified. Non-monetized impacts still need to be accounted for, but they should be described in qualitative terms and arguably presented with estimation of their importance relative to the valued impacts.

Complementary decision-making tools

It is suggested at some occasions, that employment impacts represent benefits of a project. However, including employment generation as benefits in CBA implies double counting. Job creation is already included in costs. This is because employment requires use of resources, represented by payment of wages and salaries. Without the project, those employed might have another job or devote their time to more valuable leisure activities. Special treatment of employment is relevant only when there are high levels of unemployment. In these cases, shadow wages, lower than the prevailing wages should be used in cost calculations. When there is a need to study employment impacts in different sectors, economic impact analysis is an appropriate tool, see section below on economic impact analysis. In other cases, project motivation may be that adoption of new technology has potential to create competitive advantages and employment in new industries. Since these effects are difficult to predict and there might be a risk of double counting, CBA treats them as secondary market impacts.

Distributional impact analysis

Distributional impact analysis examines the distribution of costs and benefits by different stakeholders. For decision makers, distributional considerations could be of importance when conducting e.g. regulatory impact analysis (RIA). Distributional impact analysis can be a part of a CBA showing to whom benefits and costs accrue. The Kaldor-Hick's criterion¹ serves as decision rule together with the description of the distribution of impacts by stakeholders. In this case, the

¹ According to the Kaldor-Hick's criterion, a change is socially preferable when the sum of benefits exceeds the sum of costs.

distributional perspective could be seen as an extension of CBA. However, conducting distributional analysis as part of a CBA increases the risk of double counting implying need for additional consideration.

The distributional analysis requires identification about how benefits and costs affect different stakeholders. It is usually convenient to start by listing those stakeholders that will be affected in a noticeable way. Typical stakeholders are consumers, network operators and managers, power utilities, contractors, suppliers, and government. Note that the relevance of stakeholders may vary between contexts.

Multi-criteria analysis (MCA)

Multi-criteria analysis (MCA) offers a systematic tool to evaluate non-monetized impacts. There are several approaches for conducting MCA. Starting from simple evaluations of pluses and minuses to advanced applications that assign points and trade-off weights. Sometimes computerized algorithms are applied in order to rank alternatives. Irrespective of the level of sophistication, all MCAs start out by defining the objectives a decision should fulfil. Although impacts in MCA may overlap with those in CBA, it is not possible to claim that the outcome of MCA rests on welfare based appraisals. This is because MCA considers values and trade-offs suggested by experts, decision makers and/or the analyst, i.e. values of those who were included in the assessment exercise.

Economic impact analysis

Economic impact analysis highlights how increases in spending in one part of the economy affects employment or the economy in aggregate. When there is demand for this kind of analysis, there is need for other methods than CBA. One is economic impact analysis (input-output analysis), which derives production and employment linkages in the economy. The method relies on national account data and provides results on direct, indirect and induced effects on production and employment (direct impacts result from project expenditures, indirect impacts result from the suppliers of the purchasing goods hiring workers to meet demand, induced impacts result from the higher purchasing levels of goods and services at household level). Usually the results are illustrated by multipliers, which are quotas between the number of people employed by the project and total employment impacts in the economy as a whole. Generally, employment multipliers are within the range of 1.2 and 2.0, implying that for each person employed by the project, 0.2 to 1 new jobs are generated in other sectors of the economy. These results cannot be added to the CBA. The results rather provide a description of the impacts in another dimension, not the value of impacts.

5. Electricity network regulation

Electricity network operations are natural monopolies, and, for this reason, it is not efficient with several competing operations in the same geographical area. In order to prevent privately or publicly operated companies from setting too high prices and earning monopoly rents, electricity network companies and distribution system operators (DSO) are subject to regulation. In this chapter, we discuss various regulatory mechanisms in use in Europe and the implications of regulation on CBA.

Regulatory mechanisms

There are different models of regulating the operation of electricity network companies. Most countries apply unique characteristics to their regulatory framework. This makes it difficult to identify pure regulatory models. Instead, literature suggests various ways of categorization the regulatory mechanisms. In a recent report, Copenhagen Economics (2017) identifies four broad categories of regulatory mechanisms: the incentive-based, the cost-based, a hybrid mechanism, which is a combination of the aforementioned two and output-based regulation.

Table 3 – Incentive-based regulation

Incentive-based regulation

“Incentive-based regulatory mechanisms rest on the idea that the regulator beforehand decides, either the price range or assigns a revenue cap for the electricity network companies. The price range or earnings cap is set for a specific time (i.e. regulation period) and adjusted over time (e.g. according to expected inflation) to allow the electricity network companies to obtain profit. By formulating a price- or revenue cap, the regulator delegates the pricing decision to the distribution system operator. Uncertainty remains about cost coverage throughout the regulation period. Other types of incentive-based regulations include revenue and profit sharing, performance measurement (yardstick) regulation, and menus. In the incentive-based models, cost reductions are rewarded through higher profits, but cost cutting put long-term investments to risk.” (Copenhagen Economics, 2017)

Table 4 – Cost-based regulation

Cost-based regulation

“Cost-based regulation (Rate-of-Return) typically puts a cap on prices close to realized costs.

Most often regulations are based on the observed rate of return on capital expenditures (CAPEX) and operating expenditures (OPEX). Regular assessments and analyses are needed in order to check whether prices allow for an authorized level of return. The cost-based regulation reduces uncertainty about cost coverage, but decreases the incentives to invest in cost-effectiveness. The problem with the low incentives to invest in cost-effectiveness can be offset by putting a cap on allowed operational expenses (OPEX), such as in Belgium and Switzerland.”

(Copenhagen Economics, 2017)

Table 5 – Hybrid regulatory models

Hybrid regulatory models
<p><i>“Hybrid models stand for different combinations of incentive- and cost-based regulation models. Most commonly, hybrid models use cost-based regulation for controlling OPEX and incentive-based for CAPEX. Usually hybrid-based regulation applies a profit sharing system, which specifies the share of cost reductions that accrue to customers. Below are two examples:</i></p> <ul style="list-style-type: none"> - <i>Denmark uses a combination of revenue cap and rate-of-return regulation (Eurelectric 2014). The country implemented a rate-of-return regulation in 2000 and switched to price cap regulation in 2004. Denmark added reliability indices in 2007 and included quality measures for both TSO and DSO in 2006.</i> - <i>Finland switched to ex-ante rate-of-return regulation in 2005 and added quality controls in 2008. To find a reasonable level of operating expenditures, a benchmarking analysis is used and is combined with a general efficiency requirement for total expenditures (TOTEX, sum of OPEX and estimated cost of customer outages)”</i> <p><i>(Copenhagen Economics, 2017)</i></p>

Table 6 – Output-based regulation

Output-based regulation
<p><i>“Output-based regulation (or quality-based regulation) aims to direct the electricity network companies by using specific quality standards to affect incentives. In the literature, different definitions are in use. Copenhagen Economics (2017) describes output-based regulation as being based on indicators not related to the costs of grid companies. Often with the purpose to encourage investments. In the classification of Schmidthaler et al. (2015, p. 304), the authors distinguish the output-based regulation from the incentive-based by requiring a binding monetary reward or punishment if certain standards are met in the country’s regulatory framework.</i></p> <ul style="list-style-type: none"> - <i>The UK uses output-based regulation. UK follows up various quality standards, including customer minutes lost, which was introduced in 2002.”</i> <p><i>(Copenhagen Economics, 2017)</i></p>

Following liberalization of electricity markets in the EU, which started in the 1990’s, cost-based regulation dominated. The use of the different regulatory mechanisms in Europe have changed in order to reduce identified problems with earlier regulation, but also due to the technical development leading to a stronger focus on goal definition while at the same time providing a certain degree of flexibility for firms to reach these goals. Both the incentive-based and the output-based models allow for flexibility. However, the distinction between regulatory mechanisms differs between authors. Since available studies do not provide a comprehensive categorization of the four regulatory mechanisms, we refer to two recent papers (Cambini et al. 2016 and Schmidthaler et al. 2015) that classify DSO regulation into

three mechanisms each. The classification of the different regulatory mechanisms in Europe is listed in the table below. Note, however, that the classification by country is not entirely up to date. Italy, for instance, changed its regulatory mechanism in the end of 2016 (Ochoa et al. 2016).

Table 7 – Regulatory mechanisms of EU countries

Sources: Cambini et al. (2016) and Schmidthaler et al. (2015)

Regulatory mechanisms	Mechanisms classified by Cambini (2016)	Mechanisms in 2013 according to Schmidthaler (2015)
Incentive-based	Austria*, Bulgaria, France, Germany, Hungary, Ireland*, Lithuania, Luxembourg, Netherlands, Norway, Romania, Slovenia*, Slovakia, Sweden, United Kingdom*	Austria, Czech Republic, Poland, Romania, Slovakia, Slovenia***
Cost-based	Belgium, Croatia, Cyprus, Greece, Malta, Switzerland,	Belgium, Cyprus, Estonia, Greece, Latvia, Luxembourg, Malta
Hybrid	Czech Republic, Denmark*, Estonia, Finland*, Italy**, Latvia, Poland, Portugal** Spain,	Not defined by the study
Output-based	Not defined by the study	Denmark, Finland, France***, Germany, Hungary, Ireland***, Italy***, Lithuania, Netherlands, Norway***, Portugal***, Spain, Sweden, United Kingdom***

*Adjustment of revenues, **Extra WACC, ***Regulatory framework fosters profitability of smart grid investments (Eurelectric 2016)

Both studies identify incentive-based regulation, but there are dissimilarities in their definitions. Cambini et al. (2016) describe incentive-based regulation as any model where the regulator delegates certain pricing decisions to the firm and that the firm can reap the profit increases following from cost reduction. In order to lessen the drawback of the incentive-based mechanism, some countries have added investment incentives. The study by Cambini et al. (2016) identifies two approaches, which provide innovation incentives. One of them treats innovation initiatives as costs by permitting adjustments of revenues. The other one allows a higher rate of return e.g. by adding a bonus to the weighted average rate of capital (WACC). According to Schmidthaler et al. (2015), incentive-based regulation implies that tariffs are determined by the regulator, based on productivity comparison with other regulated firms and that tariffs are independent of the quality of supply. This implies that many countries categorized as having incentive-based models according to Cambini et al. (2016), become output-based in the other

study. Schmidthaler et al. (2015) distinguish between incentive-based and output-based regulation by their requirement that output-based regulation must include mandatory penalties and/or customer compensation if the DSO does not meet pre-defined quality standards on outage frequency. Applying this definition, Schmidthaler et al. (2015) identify output-based regulation in 14 European countries. However, their definition does not involve encouragement of innovation.

According to a survey amongst experts within each regulatory framework, Eurelectric (2016) finds that seven European countries have a regulatory framework fostering innovation. Five of the seven countries provide innovation incentives (adjustment of revenues or extra WACC). The categorization of Eurelectric (2016) seems to be in line with the description of output-based regulation made by Copenhagen Economics (2017). Six of the seven countries identified by Eurelectric (2016) apply output-based regulation and one incentive-based regulation following the categorization of Schmidthaler et al. (2015). Classification of cost-based regulation overlaps to a large degree between the two studies. Only Cambini et al. (2016) has a definition of hybrid models. The countries with hybrid regulation according to Cambini et al. (2016) are in any of the categories of Schmidthaler et al. (2015).

Innovation-incentives of smart grid technologies

In support, to stimulate innovation and Smart Grid technologies dedicated innovation-incentives have been developed. Cambini et al. (2016) define two broad categories of innovation incentives. As mentioned above, the first framework allows adjustment of innovation-related costs. This approach is most common among European countries. The second one applies particular incentive mechanisms for innovative initiatives. This includes provision of higher rates of return adding a bonus component to the weighted average cost of capital (WACC) and adjustments of revenues by providing extra allowances due to performance targets.

Innovation strategies allowing for adjustments of innovation-based costs is the most common. One country is Finland that uses a hybrid, output-based regulatory mechanism. Finland allows adjustment of revenues for specific innovation-incentives related to smart grid deployment. One such incentive is that operators may deduct up to 1 per cent of the sum of the grid operation's turnover. The costs must be directly linked to new information, new technology etc. and the aim is to encourage new innovative solutions. In the second category, there are both variants adding an extra or bonus component to the regulated weighted average cost of capital or providing specific rewards due to performance targets. In Europe, Portugal and Italy apply a premium on WACC on initial capital costs.

The implications of regulation on smart grid development

There are several studies examining the interaction between the behaviour of the system operators and the regulatory authorities. Schmidthaler et al. (2015) have showed that the introduction of output-based regulation leads to reductions of the annual outage duration when compared to incentive-based systems². Cambini and Rondi (2010) showed that the investment rate was higher under incentive regulation than using cost-based, rate-of-return regulation. Cambini et al. (2016) also notice that a hybrid model can provide investment-incentives, but it is not as powerful as incentive-based schemes.

Rate of return

The implications of regulatory frameworks on implementation of smart grids are reported in several studies. Eurelectric (2011) finds that sub-optimal rates of return and regulatory instability has hampered investments. One indication of sub-optimal rates of return is that DSOs are of the opinion that the regulated rate of return is non-adequate or difficult to achieve. Eurelectric (2014) mentions e.g. that the Danish ex-post benchmarking model had not been published prior to the regulation period, thereby causing inconsistency in the regulatory incentives. Furthermore, Eurelectric (2011) notices that regulators often have a narrow view evaluating cost efficiency, premiering business-as-usual expenditure instead of smart grid demonstration projects. Additionally they point out that the uncertainty about roles and responsibilities of the different market players has further delayed the development of smart grids.

Both reviews from Eurelectric (2014 and 2011) report that instability and uncertainty with power and electricity regulations may affect the smart grid development due to a need of a reasonable rate of return. For this reason, there is a need for a predictable and stable development of the rate of return where there is consistency between policy and regulation on a long term basis.

Frequently changing regulatory framework

Major and frequent changes to the regulations will hamper smart grid investments, especially since a typical investment cycle in the electricity distribution ranges from 30 to 55 years.

Incentive-based regulation

Ter-Martirosyan and Kwoka (2010) found, through an empirical analysis in the USA that incentive-based regulation may lead to deteriorating levels of electricity supply security when regulation is without quality controls. Quality controls is one example of extra incentives that might promote smart grids. As the Swedish study and Cambini et al. (2016) show, the use of innovation-incentives to the regulation such as extra allowances to WACC or adjustment of revenues can be important steps in order to promote smart grid technologies. Investments in these technologies often have a higher risk inherent and regulations should therefore be able to recognize the special character of these investments. (Eurelectric 2014)

Market concentration

² Note that Schmidthaler et al. (2015) use another definition of incentive-based regulation than e.g. Cambini et al. (2016).

The level of market concentration is also an important factor to consider. Cambini et al (2016) show that distribution system operators in less concentrated distribution markets on average invest more and the markets are expected to effectively induce investment-incentives for smart grid pilot projects.

CBA as a tool for regulatory development

Investments in smart grid solutions are made by various actors, including vertically integrated utilities, regulated network companies, property owners and households. If incentives are weak, smart grid deployment becomes slower than socially desirable.

Regulation typically calls for CBA in two steps. In the first step, the purpose is to investigate whether benefits exceed the costs of some particular smart grid initiative. In the second step, the analysis needs to establish whether the smart grid investment is commercially viable for the actor responsible for the investment. This requires consideration of the costs and revenues based on existing regulation.

A CBA application considering regulation is demonstrated by JRC (2015). In their smart grid CBA for the city of Rome they report the results based on two perspectives. The societal perspective, which presents aggregated results. In the second perspective, that of the private sector, the analysis is based on calculations of the financial result of the network company thereby showing the implications on the regulated asset base.

Alternatively, CBA can be used as an aid in defining gaps in the existing regulatory mechanism to achieve the desirable smart grid solutions. The Dutch CBA reported by Afman (2016) and Rooijers et al. (2012) found that the planned national roll out of smart grids was socially beneficial. The result holds under different energy production scenarios. Although the CBA does not explicitly analyse regulatory mechanisms, Rooijers et al. (2012) report that, the demand response of consumers has substantial impact on the benefits components in the CBA. The financial gains, however, mostly accrue to network operators, which implies that tariff design is crucial to realize the estimated impact and calculated benefits. One recommendation of the study is, therefore, to develop legislation in order to allow for time-/site-dependent pricing (ibid.).

Since the time horizon of a CBA is usually based on the life time of the investment, i.e. the smart grid solution, another challenge is prediction of future changes in regulation. Usually CBA solves the latter problem by basing forecasts on known policies. However, assuming existing regulation will continue throughout the time horizon might cast doubt on credibility. However, selecting a time horizon, which only covers the length of the current regulatory period, will underrepresent future benefits and costs. In these cases, sensitivity analysis varying the time horizon would be purposeful. It is also possible to vary calculations according to assumptions about changes in regulatory mechanisms.

Regulation in itself has no or little impact on overall benefits and costs. In CBA, costs are reflected by opportunity costs, which most often can be represented by actual production costs. Regulation rather affects how benefits and costs are distributed between different stakeholders. Benefits in terms of e.g. avoided investments in traditional grid extension will most often accrue to the network companies and dependent on regulation partly shared with network customers.

Regulation does, however, impact on the smart grid deployment - if incentives are weak - smart grid development might become slower than socially desirable. The result of the two step CBA serves as an input to suggest changes to electricity network regulation.

The figure below shows two ways of considering regulation in CBA.

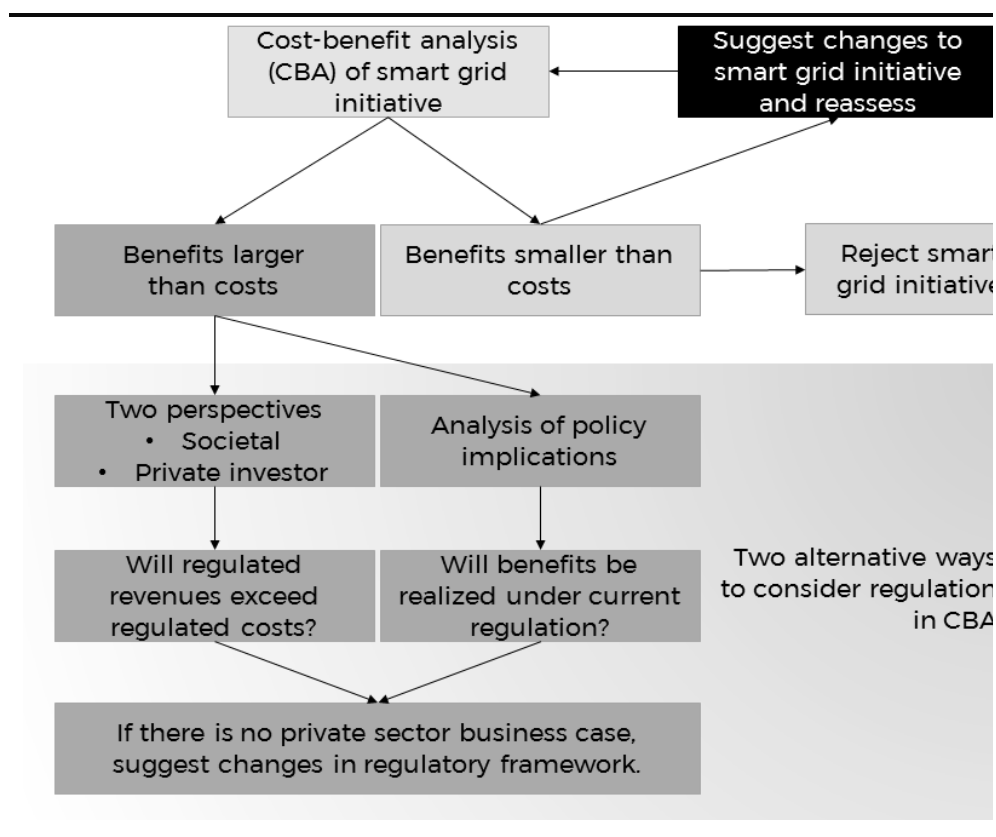


Figure 3 – Two alternative ways to consider regulation in CBA

6. Summary of Current Applications

This chapter presents a summary of the literary review on social costs and benefits of smart grid technologies. The purpose is to provide general characteristics and an overview of a number of established frameworks to analyse the costs and benefits. The first section introduces the costs and benefits dealt with in available studies. The next section compares the analytical frameworks represented in literature. The chapter is concluded by identification of challenges.

Costs and benefits of smart grid technologies

Because of the increasing wealth of smart grid technologies and their various applications, assembling an exhaustive list of all individual impacts of smart grids for all stakeholders in all parts of the energy markets would be a daunting task, likely to render a list that is almost instantly outdated. The fast development of smart grid technologies and the additional impacts of the system perspective, unlikely covered by pilot projects, suggest it is purposeful to list general categories of benefits and costs of smart grid investments. The general categories are associated with the functions and purposes of smart grid deployment referred to in chapter 3. One example is that cutting demand for electricity during peak loads will bring about benefits e.g. by saving generation costs, reduced congestion costs etc. Other benefits include reliability of power supply and lower environmental impact from the electricity system.

Effects from smart grid technologies

Effects from smart grid technologies are included with different frequency in the reviewed literature. Some effects are always included (table 8), some included in most studies (table 9) and some only included in a few studies (table 10).

The effects are listed in the left column in the tables and examples of those welfare effects applied for smart grid meters are shown in the right column.

The welfare effects on society from investments in smart grids are both positive and negative. To illustrate this, the table includes examples from investments in smart metering systems (meters that unlike conventional ones can transmit information, allowing for example better control and management of energy use). The smart metering examples are based on a report from the European commission (2012).

Rather than being exhaustive of all potential individual effects of all various types of smart grid solutions, the impacts listed below cover benefit categories (named Effect Categories in the tables) at a more aggregate level, into which each effect of smart grid investments can be sorted.

The effects in the tables below are based on the case studies and reports listed in the reference list of this report.

Table 8 – Effects included in all reviewed studies

Effects included in <u>all</u> reviewed studies	
Effect Category	Impact, Examples: smart metering systems³
Costs of energy production	<i>Reduced fuel costs for power generation, reduced costs for peak demand production.</i>
Technical energy losses in transmission and distributional grids	<i>Reduced line losses.</i>
Operational costs for transmission and distributional grids	<i>Reduced revenues due to more efficient consumption (depends on regulation), initial costs for failing meters, costs for network management and IT maintenance.</i>
Emissions of CO ₂ , NO _x and SO ₂	<i>Reduced emissions due to control equipment, lower demand and less line losses. Some incremental emissions from vehicles at the installation phase of smart meters.</i>

Table 9 – Effects included in most reviewed studies

Effects included in <u>most</u> reviewed studies	
Effect Category	Impact, Examples: smart metering systems⁴
Investment and reinvestment in production, transmission and distribution	<i>Avoided investment in conventional meters.</i>
Security of supply (value of lost load, fewer disruptions)	
Power Quality	
Congestion costs	<i>Reduced costs related to limitations in transmission capacity.</i>
Costs for reserve capacity	<i>Reduced costs for reserve capacity.</i>
Restoration costs	<i>Reduced costs for restoration.</i>
Management costs	<i>Costs for training staff and consumers.</i>
Monitoring costs (if not included in grid operational costs)	<i>Reduced costs for meter reading.</i>
Customer service costs	<i>Reduced costs for call centre/customer care, higher costs for consumer engagement programmes.</i>
Costs of theft/fraud	<i>Reduced costs of electricity theft.</i>
Security – reduced usage of oil	<i>Reduced dependency on fossil fuels.</i>
Security – wide scale blackouts	

³ The examples are taken from the European Commission (2012).

⁴ The examples are taken from the European Commission (2012).

Table 10 – Effects included in a few reviewed studies

Effects included in a few reviewed studies	
Effect Category	Impact Examples: smart metering systems⁵
Electro technology industry development*	<i>Increased integration of renewables into the electricity grid.</i>
Productivity gains*	
Quality of service*	

*May be included in CBA only after careful consideration.

The impacts in the tables above may be sub-divided and/or re-categorized in order to make further distinctions, and to present results in a different perspective; per stakeholder (consumers, producers, grid owner, government etc.), per function (demand management, supervision, power quality modules etc.) or maybe per part of the electricity grid (transmission, distributional, production end). There is not a single, established categorization in the current literature, which may be confusing when comparing different studies, but this does not imply that the methodology differs per se. Rather, they represent different ways of illustrating the distribution of benefits and costs. Since smart grid technologies have different functions, implies that not all effects are always applicable.

Some studies include in their CBA framework, an analysis about how investments in smart grid solutions contribute to political goals such as sustainability, increased share of renewable energy, and benefits to domestic industries and labour markets. However, effects on secondary markets should only be included in CBA after very careful consideration, and contributions to political goals are best illustrated separately. Positive spill overs might be expected, but these are difficult to verify. For this reason, general instruction manuals on CBA recommend that the CBA analyst, provides a qualitative description of these impacts to better explain the contribution of the project to policy goals (see e.g. EU Commission 2014). In ENTSO-E guidelines on transmission grid development projects, the authors suggest that multi-criteria analysis should be applied in order to provide information about non-monetized impacts such as reduction of carbon dioxide (CO₂) emissions, integration of renewable energy etc. (ENTSO-E 2015).

Summary of Analytical Frameworks

Several frameworks in the available literature have been developed during the past years, which suggests frameworks and tools are still changing and being refined due to new data from case studies etc. The general framework developed by EPRI (EPRI, 2010, 2011, 2015a) is in many ways the foundation and origin of several applications. For example the European Commission’s Joint Research Centre (EC JRC), the US Department of Energy (DOE) or the Smart Grid Computational Tool (SGCT) are all based on the EPRI approach, even though they have their own indicators, sub-division of impacts and analytical tools (see Appendix). There are also similarities between the EPRI “themed” frameworks and other methods.

⁵ The examples are taken from the European Commission (2012).

Differences exist between the benefit categories, but on a general level, benefits usually include reduced costs concerning generation, outages, transmission and distribution system, CO₂ emissions and meter readings. It should be noted, that not all studies show their underlying calculations, especially how quantification and monetization has been done, making it difficult to compare the different studies.

In addition to the difficulties in comparing different frameworks within the “EPRI” family due to the low transparency of the underlying calculations, there are complementary analytical tools outside this group. The Smart Grid Forum (SGF) together with Frontier Economics presents an example of a slightly different framework (Frontier Economics, 2012). This framework applies option valuation technique to assess uncertainties. By allowing for changes in investment strategies in the baseline, they assess how the timing of smart grid investments affects the outcome. In standard CBA the capital-intense alternative might have higher net present value than the alternative with high operation costs, but no upfront costs. The analytical framework of Frontier economics is based on CBA that includes an assessment of the “option value”, which can be compared to a sensitivity analysis in CBA.

Comparing these different frameworks is therefore rather complex. Below a couple of figures are presented highlighting some aspects of the differences between studies. They are only schematic illustrations of some general aspects of the frameworks presented in the literature and listed in the Appendix and it is, therefore, a possibility that specific studies might be misplaced.

Overview of CBA for smart grid investments

The studied frameworks, listed in Table 1 of the Appendix range from specific case studies to general methods, from using monetized decision criteria to the use of qualitative indicators. A schematic illustration of these factors and how some of the frameworks are positioned is presented below:

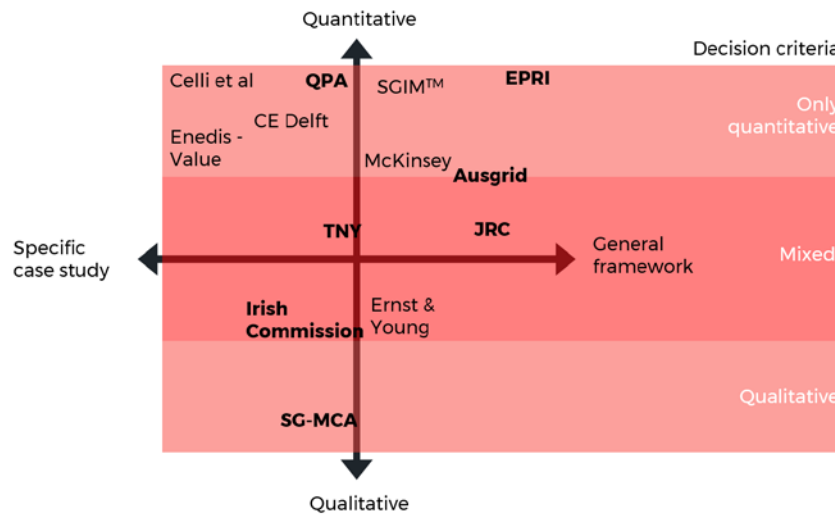


Figure 4 – A schematic illustration of decision criteria of a selection of frameworks and whether the application is specific or general.

The case studies are often tailored to a specific situation or some demonstration project and are therefore influenced by the specific context, e.g. country, smart grid asset etc. This does not imply that the more general frameworks are not influenced by specific market conditions, where e.g. the JRC model used the EPRI/US.DOE as its basis but was updated to fit the European context. For decision support, SG-MCA stands out as it results in a total score of the smart grid demonstration project in comparison to a monetized value. In the figure SG-MCA is placed to the opposite of the completely monetized EPRI framework that does not include qualitative impacts.

The different frameworks also have different data requirements ranging from more moderate data input needs such as SG-MCA, which is based on expert consultation questionnaires to methods such as EPRI and JRC that need large data sets, which are derived from longer demonstration and trial periods. The schematic illustration below also includes the relative transparency of the actual model and its calculations.

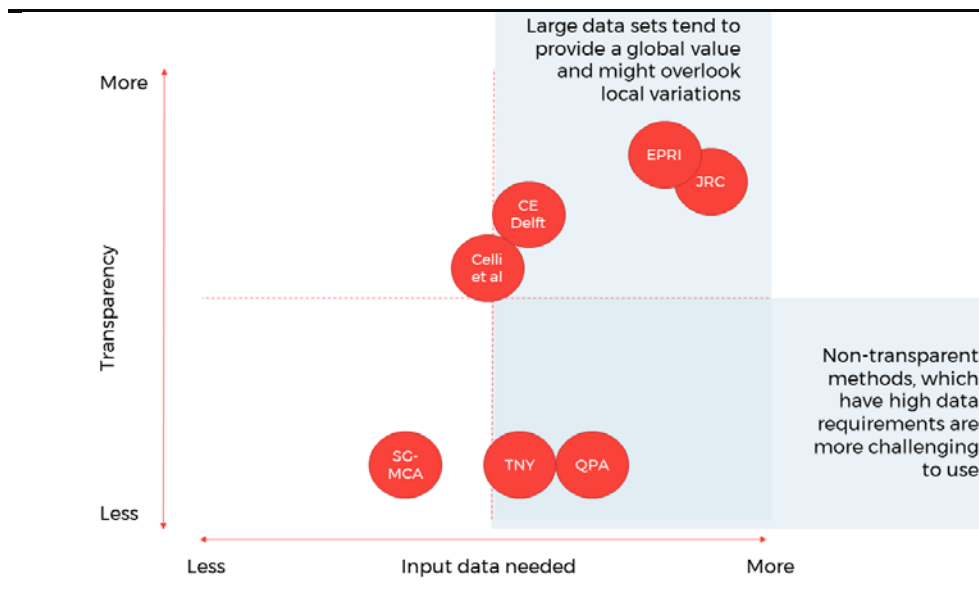


Figure 5 – A schematic illustration of a selection of frameworks on their data requirement and transparency of calculations/methods.

The transparency and data requirements are essential when considering the potential of transferring a framework to another context. Transparency is important in order to replicate calculations to be adopted and used by different stakeholders to assess smart grid projects and devices. Requirements of large data sets imply that the use of these frameworks are more resource intense. Once data has been collected, the advantage is higher precision in calculations. Data sharing and transparent frameworks simplifies replication. However, large data sets might overlook local variations as such data tend to provide global values. The combination of a low transparency and a need for large sets of data makes it difficult to transfer these kinds of frameworks to new applications.

Technological and geographical coverage

Current studies are unevenly distributed when it comes to technological and geographical coverage. Technology and geographical coverage of the literature analysed in this study is illustrated in the table below.

Table 11 – Technical and geographical coverage of literature

Report (Framework)	Year	Technology evaluated	Geographical aspect
Guidelines for Cost Benefit Analysis of Smart Metering Deployment (JRC)	2012	Smart Meters	Intended for EU Member states
A smart grid for the city of Rome - a cost benefit Analysis (JRC)	2015	Automation, monitoring and remote control solutions.	Rome
Smart grids and renewables: A cost benefit analysis for developing countries, IRENA (JRC)	2015	Smart inverters	Developing countries
The integrated grid - A Benefit-Cost Framework (EPRI)	2015	Distributed Energy Resources	
Guidelines for conducting a cost-benefit analysis of smart grid technologies (JRC)	2012	Smart Meters	Portugal
The social costs and benefits of Smart Grid (CE Delft)	2016	Communications infrastructure ensuring that grid connections and grid components meet demand for power transmission and distribution in a smarter and more secure manner.	The Netherlands
Socioeconomic Assessment of Smart Grids, RTE Réseau de transport d'électricité (unclear)	2015	Demand-Side Response, Wind Power Controllability, Low-Capacity Energy Storage Equipped for Frequency Containment Reserves, Distributed RES Generation Observability and Forecasting, Dynamic Line Rating System for Transmission Lines, Automatic Fault Location on Transmission Lines	France
Socioeconomic impacts of developing smart grids, CIRCE (unclear)	2012	Smart metering and electric vehicle integration	Zaragoza, Aragon, Spain
Evaluation of energy storage distribution systems (EPRI)	2014	Energy Storage within distribution	
Benefit Analysis of Smart Grid Projects, US-China Climate Change Working Group, Smart Grid, (EPRI)	2014	Benefits accessed in the ISGD Project: Smart appliances and equipment, Electric energy storage, Distributed generation, Distributed Automation	US

Identified challenges of CBA for smart grid investments

Risks of double counting

When conducting CBA, one always has to bear in mind the risk of double counting. An infrastructure measure can affect several markets and functions at the same time, and it depends on the behaviour of each organization and individual how the impacts are distributed. When each impact is calculated separately, there is a risk that the same impact is partly (or completely) represented in more than one instance. One example of the risks of double counting in the energy sector is that a smart grid investment can reduce the risk of a bad outcome, say a blackout, but can also reduce the costs of the tools already existing to *prevent* such an outcome. The CBA analysts must, therefore, be cautious not to double count impacts. Another example is that, as electricity markets are organized in the EU, power producers are simultaneously active in separate markets; the “day a head market”, “intra-day” market between producers and electricity trading companies, the market for frequency balancing, and the market for reserve capacity. Smart grids can potentially create benefits in all aforementioned markets, but not simultaneously and not to the same degree. It is, therefore, important that consideration is devoted to the identification step. In complex settings such as electricity markets, it might be even more important to rely on computerized network models. In a study from CE Delft (Afman, 2016), benefits cover e.g. avoided investments in grid and storage, as well as energy savings. It is unclear, however, if savings are counted twice, or whether the energy savings in addition to those that motivate avoided investments stem from e.g. operational optimization. Since the original study in Dutch, which Afman (2016) refers to, has been conducted with the help of detailed network models, it is probable that double counting has been avoided. However, in Afman (2016) there is no comment about where these extra savings originate from.

Categorizing impacts in a relevant way

Different guidelines propose different ways of categorizing impacts from smart grid investments. Examples are categorization by industry/household/commercial property, by which part of the network that is affected (transmission, distributional, “user end”, for example in the Socio-economic assessment (RTE 2015)), and by the kind of benefits generated (reduced fuel costs, reduced investment need etc., for example in the CE Delft study by Afman (2016)). In the method suggested by EPRI benefits are categorized by function, i.e. transmission, distribution, substation, customer and energy resource. The application of the EPRI framework to Europe, developed by JRC (2012), allocates benefits to consumers, distribution system operators (DSO), retailers and society at large. Although both EPRI and JRC explicitly map smart grid functionality to benefits, it is still difficult to find results sorted by type of smart grid technology. One reason why benefits are categorized according to other sub-divisions than the type of technology, is that technology alone does not generate benefits. The benefits are related to the changes which are brought about by the use of smart grid solutions. For this reason technology

does not provide relevant categories. The relevant categorization is related to how welfare effects arise. Different ways of categorizing impacts in different guidelines depends on the context, rather than differences in methodology.

Changing costs and benefits

Impact prediction requires projection of future costs and benefits. The investment costs of smart grid technology are likely to decrease over time, as at least some types of infrastructure are standardized and produced in larger quantities. Such development will imply that smaller benefits will be needed to motivate investments. Alternatively, investments in smart grids can become more costly, but more effective and efficient over time, rendering impact estimates from pilot studies and existing literature obsolete.

Importance of valid scenarios

Constructing valid reference scenarios when conducting CBA is a difficult task due to its many dimensions. Assumptions of policy choices, subsidies, taxes, rules and regulations, international integration of power grids, profitability of different types of production and evolution of consumer demand are all important conditions for estimating the return to society of a given investment or measure in smart grids. For example, the outcome of a CBA of an investment in a given smart grid technology will differ between a scenario with generous subsidies and political decisions providing a high market share of renewable energy, and a scenario with less support to renewable energy. As those two scenarios among other things imply different production mix, infrastructure requirements and price levels for electricity, the costs and benefits of a given smart grid investment will differ in magnitude and perhaps even sign. Moreover, smart grid investments, which are profitable from a business or household perspective, and therefore profitable investments without additional government initiatives should be part of the baseline.

Creating a valid scenario requires expertise, and its assumptions must be transparent in order to be meaningful. Here the distinction between a scenario and a sensitivity analysis should be mentioned: whereas a *sensitivity analysis* serves to investigate how robust the CBA results are to varying assumptions about key parameters such as the discount rate and shadow price of CO₂ emissions, a *scenario* must be calibrated to be meaningful and valid. For example, significantly altering the electricity production mix in a sensitivity analysis, without calibrating which production that still would be profitable given different price levels for electricity, may significantly compromise the results of the analysis. The study by CE Delft (Afman 2016) explains the reference scenario in some depth, but in general, the literature is not sufficiently transparent in this regard. Comparing different scenarios is more challenging than changing individual parameters (e.g. discount rate and time horizon). This is because some parameters cannot be altered isolated from other assumptions (e.g. price of electricity).

Synergies

Creating valid scenarios to evaluate will also lead to a discussion about what proposals and projects that should be included. One concern might be that using CBA to a portfolio might result in the inclusion of not cost effective proposals. In certain cases, single project evaluation of major projects might be a more viable approach. But on the other hand, some projects might not deliver all their potential benefits on an individual basis, and are only viable in a portfolio as synergies between other separate projects are delivering the larger part of the benefits.

Difficulties transferring results between different regions

One should be careful in extrapolating results across regions, since the conditions of the grid and the electricity market may vary greatly, as well as other factors influencing the baseline option. Some regions may benefit more from demand flexibility and energy savings, due to less stable and predictable electricity generation overall, and prevalence of more expensive marginal production. Benefits will also be greater in places where major investments in transmission capacity will be needed without smart grid technology.

A useful framework should therefore be flexible enough to allow for the recognition of regional variation. One way to facilitate the use of data from secondary sources, is to compile evidence about how parameter values depend on the regional conditions.

Consumer demand shift

Impacts of smart grids can be pure benefits for the consumer, for example when heating of homes can be managed so that electricity use is low when no one is at home, or if charging of electric cars can be adjusted to periods with low market demand. However, technology that facilitates demand response during peak-load periods may also impose some welfare losses, even if the overall impact to the users is positive. Not all electricity consumption can be redistributed over the day; adapting behaviour often entails some degree of welfare loss. Assumptions about the demand response needs to take into consideration that adjustments might not be as large as expected. Reluctance to adjust demand is further developed by Broberg and Persson (2015), who find in choice experiments that households require significant compensation in order to shift demand between different hours. Discussions about potential overestimation of benefits from demand response are lacking in the reviewed literature on CBA for smart grid applications.

7. Application in a national context - the Swedish example

This chapter provides an example of how to apply the literature reviewed to a national level and in this case the Swedish perspective. CBA application to development of smart grid technology in the Swedish electrical grid is analysed in this chapter

The Swedish electrical grid

The Swedish electricity network consists of 559 000 kilometres of power cables and is divided into three categories: the national grid (transmission grid), regional (higher voltage distribution grid), and local grids (lower voltage distribution grids). The national grid is owned and operated by the state owned Svenska Kraftnät which is also responsible for the operation of the entire Swedish electricity system as the national TSO. The regional and local grids are owned and operated by some 170 electrical grid companies, mostly with municipal ownership. The three largest local grid companies supply more than half of Sweden's electricity users with electricity (EI, 2015)

Sweden has historically benefited from a reliable and stable electricity system and grid. The Swedish electricity system is however currently facing many new challenges which will most likely lead to a restructuring and transformation of the grid. Trends affecting the Swedish electrical grid include further urbanization, increasing number of prosumers (consumers that are also producers of electricity), user flexibility, small scale electricity production facilities, increased share of renewable electricity, electrification of the transport sector amongst others. In summary the challenges facing the Swedish electrical grid (similar to many other electrical grids in Europe) can be summarized to the following figure.

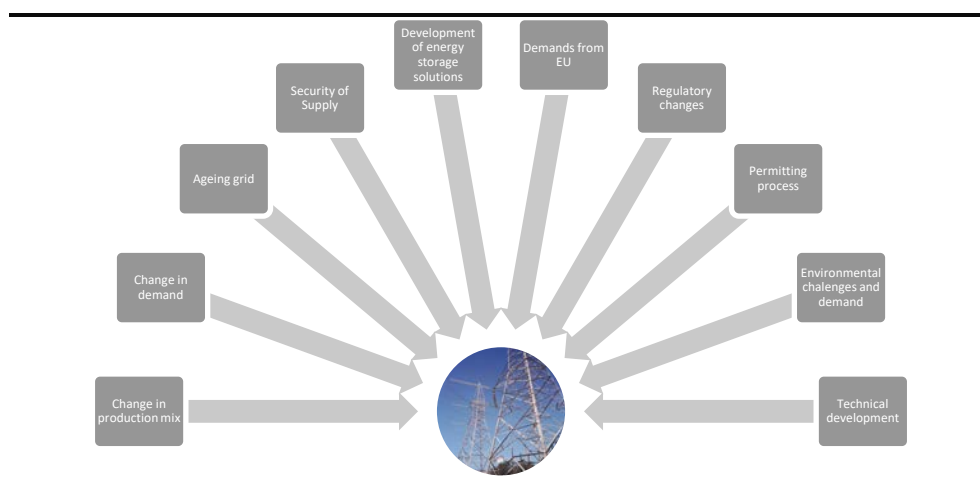


Figure 6 – Factors affecting the development of the Swedish electrical grid

These trends are driven by overall climate goals on the national and EU level carried out by different support schemes for renewables, technology development and innovation resulting e.g. in falling prices for PV, batteries, etc. which have also made it possible for consumers to become prosumers with an increasing amount of electricity now flowing in two ways.

The rapid increase in complexity and flexibility needs in the Swedish electricity system create a demand for smart grid technologies. The development also create a demand for accurate comparison between different options for changing the electricity system. There is not one single solution to meet the climate and environmental targets (see chapter 3) which means that CBA becomes a crucial part in comparing different solutions.

Swedish regulation

Sweden uses an incentive-based regulation of grid operations in which reliability indices have been available since 2004. Revenues for each network company is regulated by providing a revenue cap during a four-year period. If a company's revenue deviates from the cap, this will affect the revenue cap for the next period. The revenue caps aim at providing reasonable rate of return on capital and to cover reasonable costs for network operation, but also takes into account the quality of the network services and their efficiency. The quality is assessed by analysing disruptions in services, while efficiency is calculated by using the proportion of network losses and costs for overlying and adjacent network. This part can affect at a maximum 5 per cent of the revenue cap.

The regulatory capital base is valued by the principle of replacement value according to norm values, and the return is calculated using a real discount rate before tax. The rate of return is calculated using a WACC. The discount rate has been heavily debated and for the first regulatory period 54 per cent of the revenue caps were appealed to the administrative court who changed the discount rate from 5.2 per cent to 6.5 per cent and in the second regulatory period a similar percentage appealed (EI, 2015).

In the recent study by Copenhagen Economics (2017), the Swedish incentive-based regulation model is criticized since it provides too low incentives to invest in Smart Grid applications. This is due mainly to the fact that investments in capital intensive plants are preferred over smart grid applications linked to higher operating costs.

Svenska Kraftnät and its CBA-methodology

The use of CBA has a long tradition in Sweden, starting in the 1960s with prioritizing and comparing different road projects, later to include assessments of higher education, environment, industrial projects and healthcare. The 1990s saw a rise of welfare assessments and environmental quality assessments and in

recent year's requirements from EU-directives has increased the use of Cost Benefit Analysis in different government authorities. The Swedish Transport Administration's ASEK (Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn), which thoroughly presents guidelines for CBA for transport infrastructure appraisals, can be said to have the most solid methodology, (see Trafikverket 2016 for an English summary).

Svenska Kraftnät is also conducting cost benefit analysis for choosing between alternative grid investment projects. Its methodology is less developed than that of the Transport Administration, but nonetheless important steps have been taken to identify and evaluate effects. Much of its methodology is relevant also for smart grid investment. Their work on CBA is summarized below:

- CBA is used to decide between different options to solve an identified infrastructure problem, not primarily to decide whether the problem or limitation should be solved at all. Only measures where the implementation is the responsibility of Svenska Kraftnät are analysed, which for example excludes smart grid investments made on lower voltage levels.
- Effects included in the CBA are geographically limited to Sweden and the Nordic countries, but simulations allow estimation of effects in countries outside the Nordic electricity market as well, for example Germany and Poland.
- Reference alternatives (the alternative to the investment) must be relevant and realistic. In other words, the reference alternative may sometimes also entail limited investments.
- Svenska Kraftnät uses several scenarios to identify how robust CBA results are between different future situations. Robustness checks based on scenarios are important since political decisions, internationally and domestically, technological progress and evolution of oil and gas markets are factors that are both important and hard to predict.
- The most important quantified effect is electricity market benefits, which consists of consumer surplus, producer surplus and income from congestion-based charges (for transmission between bidding areas in the common electricity market). The electricity market effect is simulated on the day-ahead market for electricity. Effects are probably slightly underestimated, as simulation does not realistically capture hourly price variation. The simulation model optimizes one week ahead, based on historic demand and supply data, thereby assuming there is no uncertainty during the coming week. Calculation of consumer and producer surpluses rely on averages of a number of hours, therefore, not capturing the whole range in price volatility.
- Other quantified effects are changes in grid losses, costs for regulating production (paying producers to produce more or less) in order to secure grid stability, and changes in costs for reserve capacity etc.

- Effects included but only described qualitatively include security of supply, visual and physical derogation, and environmental impacts from infrastructure construction and electricity generation.
- Distributional impacts are assessed quantitatively and qualitatively, by stakeholder (producer, consumer, grid owner) and by geographical region.

Effects on secondary markets and other wider impacts are currently not assessed, and before it can be included in CBA, it must be anchored in sound theory. The same goes for whether taxes and subsidies should impact CBA, and whether the consumer surplus included in present methodology actually captures the full consumer surplus.

Further CBA work in Sweden

As mentioned above, Sweden is facing a large restructuring of the electrical system both on the demand side and on the production side. As different options are being considered it is important to conduct CBA analysis work in order to compare different alternatives on a societal level.

The CBA literature provides general support when carrying out the three main steps of CBA and can be used as indicated in the figure below. In the identification stage, costs and benefits in previous studies can be used as well as list of identified stakeholders. In the quantification stage, data from case studies and demonstration projects can be used. In the final step, valuation, shadow prices such as Value of Lost Load (VoLL) and Marginal Costs of Public Funds (MCPF) can be transferred.

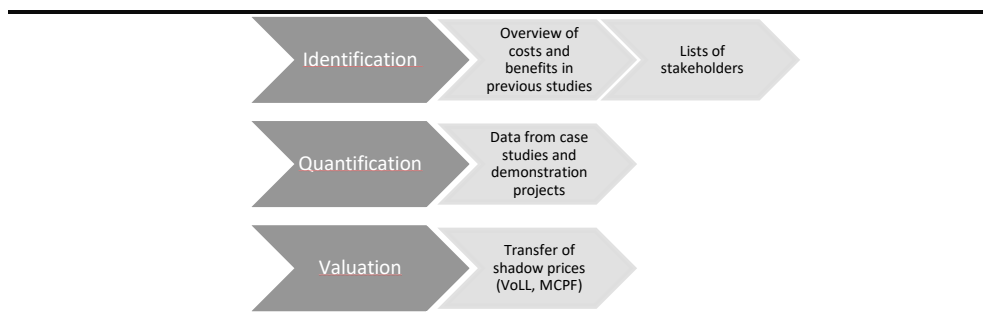


Figure 7 – Support from current literature when performing CBA in the Swedish context

A suggested approach in developing CBA for smart grid projects in Sweden is illustrated below.

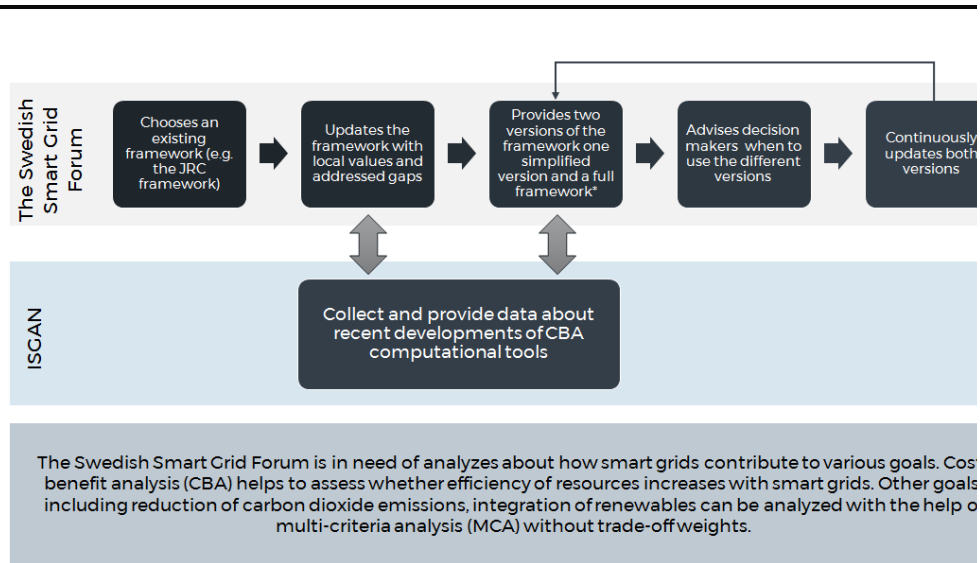


Figure 8 – CBA approach for the Swedish context

Looking at the methods available for conducting CBA in the smart grid area the JRC framework is the most suitable to adopt to the Swedish context. The JRC method is as previously mentioned an adoption of the EPRI framework to the European context.

The adoption of the EPRI framework was done through concretely testing the EPRI methodology on a real case study, InvoGrid in Portugal, in order to modify the EPRI framework to fit the European context (JRC, 2012).

In order to further develop the JRC framework for the Swedish context it is suggested that, in a similar manner to the development of the JRC framework, a real Swedish case is used on the JRC framework and where applicable update the JRC framework to the Swedish context.

In a second step it is suggested that two versions of the framework is created, one simplified version and one full framework version. This ensures a wider adoption as different stakeholders have different demands and need for analysis depth.

These two steps of adopting the JRC framework to Swedish conditions should be complemented with a collection of data from international organizations such as ISGAN in order to get recent developments of CBA computational tools on a continuous basis.

Since the area of smart grid technologies is rapidly changing and new data continuously being available it is important to have a systematic continuous update of the two versions of framework created.

The adoption of the EPRI framework to European conditions by JRC include the following measures:

Table 12 Adoption of the EPRI framework to European conditions by JRC

EPRI (EPRI, 2010) step changes	JRC Change
Step 2 – Identify the functions	<p>Functions have been replaced by European functionalities in order to limit the set of new categories and definitions.</p> <p>Functions = very strong technical dimension (e.g. fault current limiter, feeder switching)</p> <p>Functionalities = general capabilities of the smart grid and do not focus on specific technology (JRC, 2012)</p>
Step 3 – Assess the principal characteristics of the smart grid to which the project contributes	<p>This chapter has been taken out of the JRC method.</p> <p>This step intended to measure the smartness of a smart grid project and the merit of deployment.</p> <p>In the JRC 2012 the merit deployment analysis is based on the assessment framework proposed in EC Task Force for Smart Grids 2010c and is proposed as a complement to the CBA. (JRC, 2012)</p>
Step 4 – Map each function onto a standardized set of benefit types	<p>Same change as for EPRI 2010 step 2 (JRC, 2012)</p>
Step 6, 7, 8 – Identification of benefits, quantification of benefits and monetization of benefits	<p>These chapters have been grouped together and are considered as sub-step of the single step “Quantification of benefits” (JRC, 2012)</p>

8. Gap Analysis

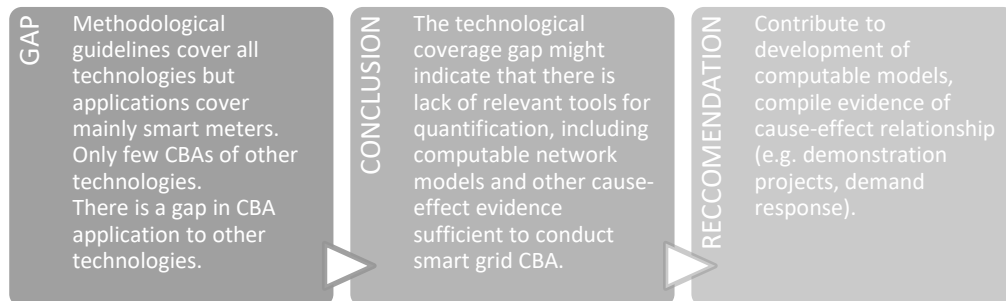
The multitude of approaches identified in literature suggest that there is a wide range of frameworks for conducting CBA, for smart grid technologies. Despite this, there are still knowledge gaps that need to be addressed. This chapter analyses the identified gaps from the review of existing literature on CBA of smart grid solutions. The gap analysis is divided into identified gap-areas and the findings are presented below.

Technological coverage

The literature presenting frameworks for CBA of smart grid technologies cover on a general level all smart grid technologies (i.e. are considered applicable to all smart grid technologies) or rather they are not focused on a specific smart grid solution, but instead more on the method of assessing any smart grid technology. Methodological guidelines include all technologies, but applications of the methodologies cover mainly smart meters. There is a gap in application of CBAs to on other technologies.

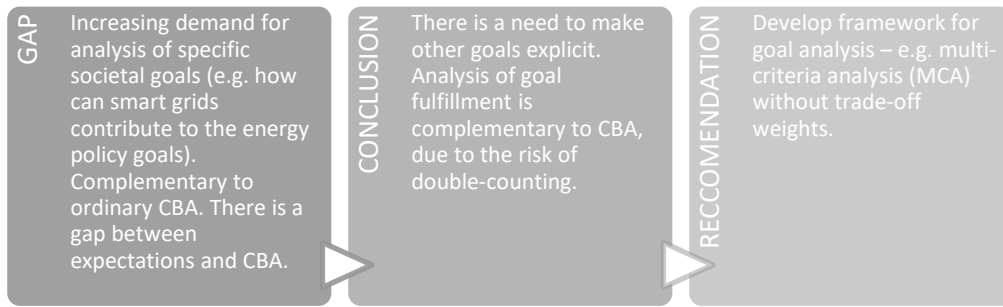
The frameworks of CBA for smart grid technologies are discussed more in detail in Chapter 6 – A summary of current applications and a comprehensive list of frameworks is presented in the Appendix.

Identified studies which cover specific technologies are scarce both when it comes to technology and geographical coverage, a list is provided in Chapter 7.



Demand for other decision support tools – widening CBA to MCA and economic impact analysis of smart grids

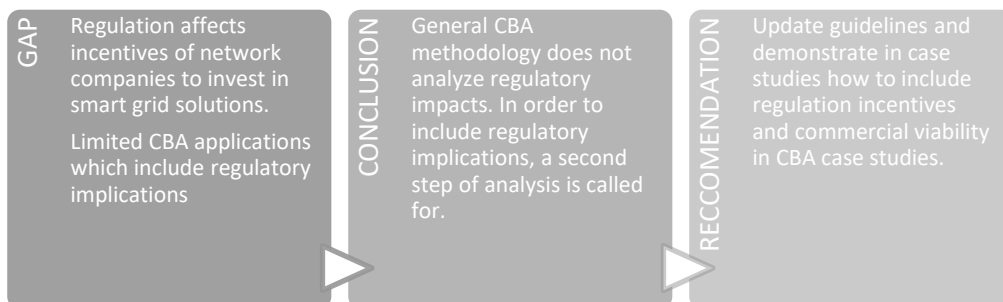
CBA alone does not always provide the demanded decision support. One example is that some recent studies include other impacts than social benefits and social costs. Socioeconomic impacts of smart grids on the supply chain, job creation and export possibilities are some examples (see e.g. RTE 2015). It is important, however, not to mix economic impact analysis and CBA. Another challenge is that analyses of employment impacts may in many cases be biased when they are stakeholder driven, rather than based on verified research results. There is a gap between expectations and CBA methodology. Analysis about how smart grids may help to reach specific societal goals should be complementary to CBA.



Regulatory coverage in CBA

There is a gap concerning CBA and regulatory implications. Only few case studies address how to include regulation in CBA. On a general level, CBA can show whether smart grid development is socially beneficial. Since regulation affects how benefits and costs are distributed between different stakeholders, there is need for additional analysis.

As an additional step of analysis, it is important to establish whether the smart grid solution is commercially viable for those in charge of investments, (i.e. network companies). This requires an analysis of the costs and revenues of network companies based on the existing regulation. The result serves as an input to suggest changes to electricity network regulation.



Additional studies of benefits

Deployment of smart grid technology gives rise to a number of benefits. There is a gap in specific network impacts (e.g. value of lost load and congestion costs). Further studies are needed to establish quantitative estimates and monetary values.

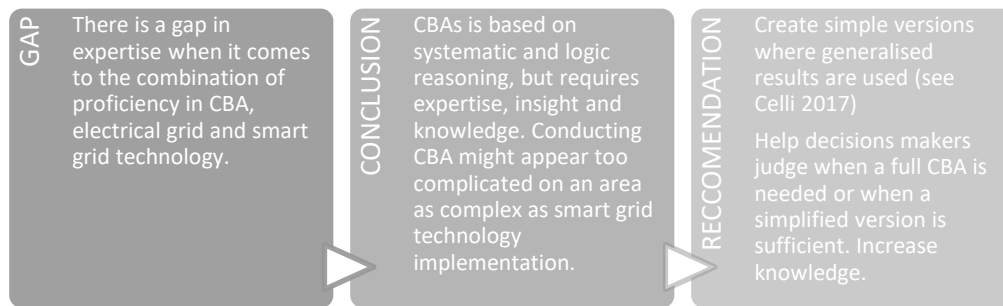


A “gap” between methods and users

The multitude of approaches identified in literature suggest different ways to perform a CBA of smart grid projects, but they also require expertise, insight and knowledge to use them. The expertise needed ranges from welfare economics, knowledge of the electrical grid as well as smart grid applications. In addition to this expertise, CBAs of smart grids apply long time horizons requiring future energy market insights as well knowledge of forecasting methods. These factors combined require user input and experience from using various tools of analysis. There is, therefore, a gap between the method and the user (lack of ability or knowledge to use the CBA tool). One answer to this might be to produce generalized results such as the “look-up tables”, suggested by Celli et al. (CIRED 2017), making it easier for the potential user to estimate benefits. However, transferring results from one country or region, with specific local situation, to another might still be a challenge.

Despite these difficulties, generalization such as “look-up-tables” can be further developed. This process can be divided into two steps. The first is to examine whether there are similarities between the assessed context and previous or other projects (e.g. similarities in the technical functionalities). The second step is to study if it is possible to replicate the impacts at some other location or in another context.

The Transform model by EA Technology in the UK is one example of using similarities in technical functionalities to ease the burden on the user. The techno-economic model calculates impacts of future scenarios by using operating characteristics of devices and their relationship to other technologies in one system. The model is utilized on license by all distribution network operators in the Great Britain and was initiated by the DECC/Ofgem Smart Grid Forum.



Lack of data

Several frameworks presented in this report such as EPRI/US.DOE, JRC etc. have large requirements on data sets to base the input parameters on. However, due to the ongoing development of smart grid technologies and the lack of demonstration projects in several markets, there is a gap between the need of input data and available verified data. This gap increases the uncertainty of the results if data has to be based on estimates. When there is lack of data, multi criteria analysis models serve as a substitute, since they require less quantitative input data and rely more on the assessments of experts and stakeholders.

Performing CBA of smart grid investments is a new application where the vast majority of frameworks, approaches and methodologies have been developed in the last couple of years. The main reason being that public authorities and other stakeholders need tools to identify, quantify and monetize the benefits of the advanced functions that smart grids offer in order to choose the most effective investments. It is therefore research in progress with significant ongoing development, implying that research gaps existing a few years ago slowly are being filled. Current gaps can only be filled, if knowledge and information is collected and shared among stakeholders.



A gap in how to deal with uncertainties

In addition to the data requirements of CBA, the uncertainty or robustness of the CBA results needs further consideration. There is a great deal of uncertainty involved with the smart grid assessments, given the complexity and high-level of integration of novel technologies which are involved.

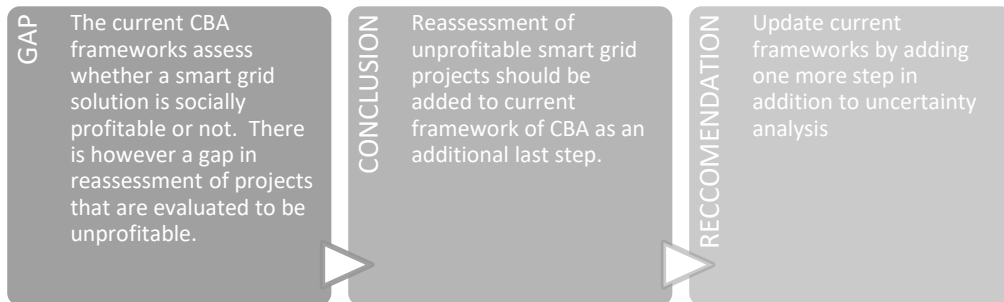
Several of the referred frameworks suggest sensitivity analysis in order to analyse the robustness of individual variables to the variation of the input parameters, but there are only few examples of uncertainty analyses performed in order to describe the range of possible outcomes. Uncertainty analysis can be based on comparing the outcome of CBA in different future scenarios, e.g. one scenario with a high share of renewables in electricity generation and another scenario assuming a smaller share of renewables. Another approach to deal with uncertainties is the option valuation technique (Frontier Economics, 2012).



Reassess unprofitable projects

The current CBA frameworks show whether a smart grid project or package is socially profitable or not. There is however a gap in reassessment of projects that are evaluated to be unprofitable.

In addition to CBA specifically adopted or developed for analysing smart grid technologies there are also general guidelines, which can provide input. One such example is developed by Kriström and Bonta Bergman (2014) at the Swedish University of Agricultural Sciences as a step-by-step approach for conducting CBA of environmental projects. The approach shares many similarities with the step-by-step approach employed by for example by EPRI. One interesting addition to this particular approach is that the additional step, in the end where projects that are socioeconomic unprofitable are re-assessed in order to see what changes there need to be done in order to change the socioeconomic loss to profit (Naturvårdsverket, 2014), see figure 3 for more detail. This is something, in addition to a sensitivity analysis that could give useful insights and could be used as a valuable decision tool sorting between different projects as well as sorting out specific unprofitable technologies from the project.



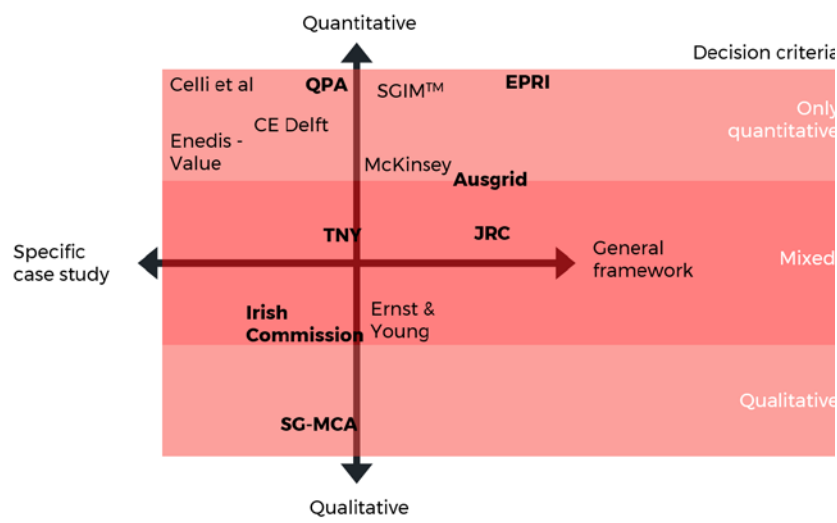
9. Conclusions

The purpose of this study was to map and compare current frameworks in literature about CBA of smart grid technologies as well as to identify gaps. The study also includes an analysis of the implications from network regulation on CBA of smart grid technologies. In addition, the report serves as a basis of selecting frameworks to be used by the Swedish Smart Grid Forum in order to assess different smart grid projects and applications.

Comparison of current framework in literature

The literature review shows that the general framework developed by Electric Power Research Institute (EPRI) is in many ways the foundation or origin of several other approaches (“The EPRI Family”). European Commission’s Joint Research Centre (EC JRC), the US Department of Energy (DOE) and the Smart Grid Computational Tool (SGCT) are all based on the EPRI approach, even though they have their own indicators, characteristics and structure of analysis.

The studied frameworks range from specific case studies to general methods, from using monetized decision criteria to the use of qualitative indicators. There is significant spread among the frameworks. A schematic illustration of these factors and how some of the frameworks are positioned is presented below.



A schematic illustration of decision criteria of a selection of frameworks and whether the application is specific or general.

CBA provides a comprehensive method to assess the value of benefits and costs of smart grid deployment. This makes it possible to compare investment costs to direct and indirect benefits. However, the complexity in identifying the effects of smart grid deployment, calls for quantitative input from complementary analyses of the electricity network and the energy system, which then provide important inputs

for CBA. Identified challenges of CBA for smart grid investments in current methods are the risk of double counting, categorizing impacts in a relevant way, changing costs and benefits, the validity of scenarios, synergies and the possibilities of transferring results from one context to another. However, CBA does not derive impacts from smart grid deployment on other sectors of the economy or employment effects. When there is demand for analysing employment effects and economic impacts, other methods are called for, e.g. economic input-output analysis.

Gaps in current literature

Identified gaps in current literature of CBA for smart grid technologies are listed below:

Gap in technological coverage

The technological coverage gap might indicate that there is lack of relevant tools for quantification, including computable network models and other cause-effect evidence sufficient to conduct smart grid CBA.

Recommendation: contribute to development of computable models, compile evidence of cause-effect relationship (e.g. demonstration projects, demand response).

Demand for other decision support tools – widening CBA to MCA and economic impact analysis of smart grids

There is a need to make other goals explicit. Analysis of goal fulfilment is complementary to CBA, due to the risk of double-counting.

Recommendation: develop framework for goal analysis – e.g. multi-criteria analysis (MCA) without trade-off weights.

Regulatory coverage in CBA

General CBA methodology does not analyse regulatory impacts. In order to include regulatory implications, a second step of analysis is called for.

Recommendation: update guidelines and demonstrate in case studies how to include regulation incentives and commercial viability in CBA case studies.

Additional studies of benefits

Quantification and valuation of specific network impacts need further development.

Recommendation: develop methodologies and compile case studies.

A “gap” between methods and users

CBA is based on systematic and logic reasoning, but requires expertise, insight and knowledge. Conducting CBA might appear too complicated on an area as complex as smart grid technology implementation.

Recommendation: create simple versions where generalised results are used (see Celli 2017). Help decision maker's judge when a full CBA is needed or when a simplified version is sufficient. Increase knowledge.

Lack of data

There is a need to constantly collect and update relevant data about smart grid demonstrations and wider applications.

Recommendation: coordinate information collection and sharing of cost benefit analysis and data of relevant cause-effect evidence of smart grid technologies

A gap in how to deal with uncertainties

Future studies should include uncertainty analysis e.g. by comparing the outcome of CBA in different future scenarios.

Recommendation: Update current frameworks so that they include guidance about how to handle complex uncertainties, e.g. by applying scenario analyses.

Reassess unprofitable projects

Reassessment of unprofitable smart grid projects should be added to current framework of CBA as an additional last step.

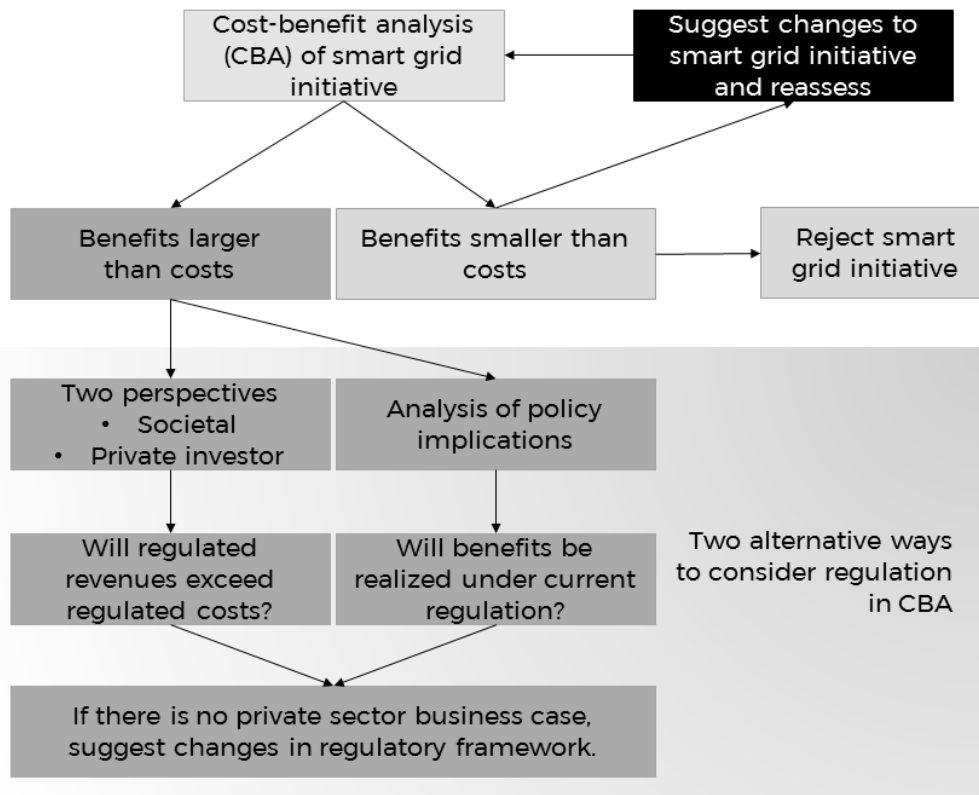
Recommendation: update current frameworks by adding one more step in addition to uncertainty analysis

Technical worldwide collaborations like ISGAN should be used in order to handle some of the gaps such as exchange of gathered data in order to mitigate technical coverage and geographical gaps, spreading knowledge of the different evaluation methods and how and when to use them and provide input with regards to specific benefits such as value of lost load.

Network regulation and CBA

Regulation in itself has no or little impact on overall benefits and costs. Regulation does however impact the smart grid deployment - if incentives are weak - smart grid development becomes slower than socially desirable. Moreover, regulation affects how benefits and costs are distributed between different stakeholders. Benefits in terms of e.g. avoided investments in traditional grid extension will most often accrue to the network companies.

Two ways of considering regulation in CBA assuming that the smart grid initiative has benefits that exceeds the cost is illustrated below. The result of the two step CBA serves as an input to suggest changes to electricity network regulation.



Application to Swedish context

Existing literature can also aid by providing input values in the three key steps of the CBA. In the identification stage, costs and benefits in previous studies can be used as well as list of identified stakeholders. In the quantification stage, data from case studies and demonstration projects can be used. In the final step, valuation, shadow prices such as Value of Lost Load (VoLL) and Marginal Costs of Public Funds (MCPF) can be transferred.

Looking at the methods available for conducting CBA in the smart grid area the JRC framework is the most suitable to adopt to the Swedish context. The reasons being it is based on the comprehensive EPRI framework and adopted to the European (and thereby also partly to the Swedish) perspective.

The adoption of the EPRI framework was done through concretely testing the EPRI methodology on a real case study, InvoGrid in Portugal, in order to modify the EPRI framework to fit the European context.

In order to further develop the JRC framework for the Swedish context it is suggested that, in a similar manner to the development of the JRC framework, a real Swedish case is used on the JRC framework and where applicable update the JRC framework to the Swedish context.

In a second step it is suggested that two versions of the framework is created – one simplified version and one full framework version. This ensures a wider adoption as different stakeholders have different demands and need for analysis depth.

These two steps of adopting the JRC framework to Swedish conditions should be complemented with a collection of data from international organizations such as ISGAN in order to get recent developments of CBA computational tools on a continuous basis.

Since the area of smart grid technologies is rapidly changing and new data continuously being available it is important to have a systematic continuous update of the two versions of framework created.

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11. Appendix

The first table below lists and describes a number of established methods to analyse the benefits and costs of smart grid investments. Several of these methods have been developed during the last couple of years, which also implies that they are still changing and being refined due to new data from case studies etc. This is just a brief overview and is not a comprehensive list of all CBA tools that might be available.

The second table describes specific case studies which have analysed a specific technology or city.

The reviewed literature consists of original studies and summary reports.

Framework	Origin	Description
EPRI/U.S. DOE Method	U.S.	The EPRI/U.S. DOE method uses Cost-benefit analysis to analyse a variety of smart grid projects. This comprehensive step-by-step method was first developed in the US in 2010 and has been updated in 2011, 2012 and 2015: Identification of impacts is based on a matrixes that connect Smart Grid assets to functions and further functions to benefits. Quantitative primary impacts are derived on the basis of experiments on demonstration projects. Secondary impacts on e.g. emissions rest on estimates. Conversion to monetary values is not explicitly described, however. The method concentrates on smart grid performance indicators such as efficiency, environmental impact, reliability, power quality, safety, security and cost reduction. Monetized impacts include the costs and benefits of a smart grid project such as deferred capacity investment, reduced maintenance etc. The EPRI/U.S. DOE method translates all future benefits and costs into present values by the use of a social discount rate (no recommendation though).
JRC Method, 2012	EU	Based on EPRI but tailored to the European market by the JRC in 2012. One difference between the two methods is that the JRC method uses specific functionalities to map and calculate the benefits of new assets. The method also employs sensitivity analysis and uses qualitative assessment defined by different key performance indicators to evaluate qualitative impacts.
Celli et al. (CIRED), 2017	EU	The authors present a Cost-Benefit Analysis of energy storage exploitation in Distribution Systems. Celli et al. (CIRED) use a hybrid methodology combining a Multi-objective optimization (advanced MCA), Cost-Benefit Analysis and clustering techniques to form a "look-up table" that identifies efficient smart grid projects that should be considered acceptable by the regulator. The method has been applied on deployment of storage in medium and low voltage electricity systems in Italy.
EPRI's Integrated Grid (IG) Benefit-Cost Analysis (BCA) Framework	US	EPRI's Integrated Grid (IG) Benefit-Cost Analysis (BCA) Framework is a successor to the EPRI/U.S. DOE Method but focuses more on solutions to technical issues and uses model-based evaluations or quantifications. This in order to optimize the utilities' response to integration of new distribution resources and supporting customer choices.
CE Delft, 2016	EU	Maarten Afman CE Delft conducts a CBA on additional, second phase roll out of smart grid in the Netherlands. The assessment period covers 2011-2050. The baseline alternative covers already decided measures (smart meters to all small scale users, active grid management, simple control strategies to cut peak-loads and smart grids in horticulture and heavy industry). The additional measures are compared to the baseline and evaluated in three different scenarios until 2050. Identified impacts are listed according to whether they are direct or indirect. Quantification of the impacts of changes in consumer behaviour is based on a literature study. The behavioural changes are evaluated in a power system simulation model. The model results suggest the magnitude of grid impacts. Direct monetized benefits are: Avoided grid investment, avoided grid losses, avoided central capacity, avoided storage investment, more efficient power production, energy savings and reduction of imbalance RES. Indirect impacts cover the reduction of external costs by lower levels of local emissions and greenhouse gas emissions. Identified, but not monetized impacts include direct costs of siting equipment and indirect costs of comfort losses due to time shift of power consumption and benefits of time savings.

Framework	Origin	Description
ENEDIS (ERDF): Valuation of Consumption Flexibilities in Distribution System Planning	France	A methodology to estimate how investment costs for primary substations can be reduced by using demand response flexibilities. The method is built on the investment framework of the French ENEDIS, where the basis of decision is “on the comparison of the annualized cost of investing and the probabilistic benefits that the investment brings” in terms of e.g. Expected Energy not Served or losses. The value of the demand response flexibility is derived from the estimation of the reduction of the Expected Energy not Served. There are some limitations to this method, first the flexibilities exactly matches the need which in combination with other assumptions may overestimate the effects and second, effects on the technical losses have not been calculated
GRID4EU	EU	The GRID4EU project is not a cost-benefit analysis method but instead a rapport presenting four methodologies to evaluate specific smart grid impacts, these includes; <ul style="list-style-type: none"> - Improved continuity of supply resulting from reduced sustained outages; where the undelivered electricity is valued. The model is using a general value of lost load but could be updated to include variables such voltage levels and type of interruptions. The report describes the importance of describing the method and baseline scenario being used as well as how the implementation will decrease the number and the actual sizes of the interruptions. - Increased hosting capacity; underlines the importance to have the same renewable energy sources goals in the baseline scenario as in the smart grid scenario in order to correctly calculate the cost savings of advanced investments. It is also important to show the connection between smart grid investments and the increased connection degree of renewable energy sources. - Reduction of the energy losses; should include a description on chosen scenarios, what mechanism that leads to the benefits, simulation model, prognosis models, estimation of technical losses, basis of price calculations and sensitivity analysis of the price. - Reduced restoration costs; should include the method to calculate the error rate, maintenance and repair costs and how the smart grid investment might affect these costs but also impacts on or by employees should be taken into account.
FlexiS “Smart grid plan”	France	Developed in France by a working group with representatives from the state, power system stakeholders, smart grid manufacturers academia etc. It was based on methodological frameworks such as EPRI, JRC etc. but with an addition of short-term functioning of the power system. Especially identifying valued smart grids components such as enhanced flexibility and reduced uncertainty. Even though the scenarios used are heavily influenced by smart grids in the French system and its market projections, the actual methodology could be adopted to other countries, scenarios and technologies. A drawback might be that it does not take into account the distribution networks and its considerations and it is not that transparent where the calculations and assessments have been derived from.

Framework	Origin	Description
Other Methods* ⁶		
Smart Grid Multi Criteria Analysis SG-MCA	China	Combines analytic hierarchy process (AHP) and fuzzy evaluation method in assessing four dimensions; practicality, technological, economic and social. Elements of the program are first divided into a multi-level hierarchy, each level are weighted by comparing them to previous levels which defines the maximum weight or optimal solution. Fuzzy comprehensive evaluation is then used to evaluate different indicators' attributes, first by determine evaluation indices (practical, technical, economic and social) and then by using a multi-dimensional assessment combining these two steps into a composite index score reflecting attributes. There has been some critique of the methodology since it might not represent public and private costs effectively, only their effectiveness in achieving the overall goal (Karali et al., 2016).
QPA (Qianhai Project Approach)	China	Have similarities with a CBA analysing the costs and benefits from each technology which is calculated for every stakeholder (consumers, the power supply bureau etc.) and by using a correspondence table mapping smart grid subsystems, functions and benefits. For investors and stakeholders the benefit evaluation includes both achievable and potential benefits, which will be achievable when the Chinese structural reform of the power system is finalized. Sensitivity and risk analysis is carried out on the evaluation. Main principles are Comprehensiveness; by including different perspectives and categories to reflect smart power grid's benefits. Consistency, being consistent with evaluated targets to ensure rationality and Measurability, well defined quantification of benefit indices that are calculable/measurable by easy collected data. The working order of the method is as follows, first assets are classified followed by matching their functions. It is followed by a CBA analysis of system modules and external markets' internal operational mechanisms. The assessment ends with the economic benefits being evaluated.
The Navy Yard (TNY) Method	U.S.	The method computes and compares an operational scenario to a baseline by using their benefits and costs. First a business context with a problem statement and goals is established. Stakeholders are defined and weighted before the functional grouping of benefit assessments into cost-benefit analysis categories (CBAC) takes place. Benefit and cost assessment variables are defined and computed for the baseline and operational scenarios. A single benefit-cost ratio is calculated (Smith D. et al.)
McKinsey Method	EU	Developed by McKinsey, the method calculates a difference between a baseline and reference scenario and look into four groups of smart grid functionalities; advanced metering infrastructure, customer applications, grid automation and integration of distributed energy resources and electric vehicles. Four smart grid benefits; demand shift and savings, longer life of assets, operational improvements and reliability improvement. Even though the categorization is different from the EPRI model there is still similarities such as the benefits are based on the avoided, saved or reduced costs of a grid between a baseline and a scenario. It is provided as a commercial package.

⁶ The methods listed below the other methods headline were gathered from summary reports.

Framework	Origin	Description
Smart Grid Investment Model	U.S.	<p>The Smart Grid Investment Model (SGIM)TM was developed by the Smart Grid Research Consortium (SGRC). It mainly assesses the load profile of consumers served in order to evaluate the financial impacts of smart grid utilities and therefore has an investor perspective. The model utilizes four basic steps; identify each technology and program, identify benefits including cost savings, operational efficiency etc., identify costs based on utility and customer characteristics, and determine investment returns by comparing benefits and costs.</p> <p>It uses a standard reference period of 20 years and lacks customer benefits, societal or environmental impacts (SGRC, 2017). To apply the model, an excel based standalone program has been developed, allowing the user to form the base case, selecting technologies and provides sensitivity analysis by altering the parameters.</p>
Socio-economic assessment of smart grids, RTE 2015	EU (France)	<p>The analyses on the socio-economic impacts of smart grids in France has been developed by a working group, consisting of stakeholders including national government officials, utilities, producers of smart grid solutions and power suppliers, as well as researchers. Besides calculation of CBA benefits, the purpose is to study potential employment generation of smart grids. The report is a summary covering only a short section on methodology. It is therefore difficult to find detailed information about how impact estimations were conducted. There are very large benefits in the sector "participation of wind power generation in balancing" where benefits and positive environmental impacts are derived from reduced fuel use. The direct employment impacts include jobs created and jobs destroyed, which is relatively straightforward. Induced employment is derived from three different channels. Conventional induced employment through effects on subcontracting sectors. The other are jobs induced via competitiveness impacts and purchasing impacts. There is no information whether the latter two impact-linkages have been verified. The employment impact from purchasing power increase is significantly larger than other employment impacts, and rests on the assumption that household consumption driven by lower electricity prices, will create more than ten times, more jobs than the direct jobs from the smart grid projects. However, information is missing on e.g. how much consumer prices will decrease.</p>
Frontier Economics Method	EU	<p>In evaluating the German smart metering deployment in 2011 a method was used, where costs and benefits were calculated by household category such as consumption behaviour, size etc. and summed up.</p>

Framework	Origin	Description
Smart Grid Forum (SGF) together with Frontier Economics	UK	<p>The real options method, was formulated in 2012 for the UK market and is a way of internalizing sensitivity analysis to the benefit cost analysis. It allows the use of new information about the utility of smart grids to be factored into the analysis at a decision point and define scenarios to consider changing future circumstances. The real-options-based analysis give a basis to find a way to pick the best strategy through uncertainty and was originally adopting two time periods (2012-2023 and 2023-2050)</p> <p>Based on three smart grid investment strategies, Top-down, Incremental and Conventional the framework aims to identify the best available strategy for each scenario and time period. Due to the interdependencies between the smart grid functionalities the model assesses the cost and benefit of investment strategies or packages rather than assessing individual technologies in isolation. The following cost and benefit are considered; distribution network reinforcement, distribution network interruption costs and distribution network losses, generation costs, DSR costs and transmission network reinforcement. The model has a list of 21 possible assets that can be analysed which are translated into 15 functions and a mechanism that translates functions to benefits which are chosen by the user.</p>
European Electricity Grid Initiative (EEGI)	EU	European Electricity Grid Initiative (EEGI) evaluate projects consistency with its defined objectives by complementing benefit analysis methods with key performance indicators.
Smartness Barometer	EU	Smartness Barometer also uses Key performance indicators to evaluate the project's contribution to EU policy goals.
California Public Utilities Commission distribution resources plan	US	California Public Utilities Commission distribution resources plan compares NPV results from different scenarios, which are generated by varying the amount and location of DER. It uses locational net benefit analysis in optimizing the cost-effectiveness and dispatch. It is a complement to Integration Capacity Analysis (ICA) with several similarities to a cost-benefit analysis
Russian Power System	Russia	Russian Power System combines various technical options generation, transmission, distribution and consumption into scenarios or complete electricity systems. Several different scenarios are used to optimize the system, which are compared to a baseline scenario. It is a combination of expert assessment, mathematical models and financial models such as CAPEX and OPEX in order evaluate the impacts for each installation.
Australian Grid operators Ausgrid, and EnergyAustralia's "Smart Grids, Smart City" program	Australia	Australian Grid operators Ausgrid, and EnergyAustralia's "Smart Grids, Smart City" program used a framework or step-by-step approach similar to the EPRI or JRC methods in identifying and quantifying benefits. The quantified benefits were stemming from eight smart grid assets and were supported by data from customer trials.
Duke Energy's MAISY model	US	Duke Energy's MAISY model is an agent-based end-use model where utility customers are displayed and evaluated as agents and there are only economic benefits and no other benefits such as environmental etc.

Framework	Origin	Description
Ernst & Young		Ernst & Young estimates net benefits by comparing them to typical grid reinforcements and therefore not explicitly quantify benefits. It includes some smart grid benefits that several other models neglects such as its impacts on the supply chain, job creation and export possibilities. The report describe a full-scale deployment of EVs as a positive consequence of smart grid diffusion but fails to quantify the benefits of improving the quality of electricity supply.
Irish Commission for Energy Regulation launched the Energy Needs Ireland	Ireland	Irish Commission for Energy Regulation launched the Energy Needs Ireland where a full benefit analysis of a full deployment of smart grids were completed. An accounting approach was used, where data from different costs and benefits from previous studies formed the different scenarios. In addition to quantified values, several non-quantifiable cost and benefits are described in addition to a non-quantifiable risk analysis
Smart Grid Computational Tool (SGCT) by Department of Energy	US	The Smart Computational tool was developed based on the methodology of the first EPRI model and built on the Ms. Excel Macro platform. There are some modifications from the EPRI model, which are; it bypasses and simplifies some of the steps so only a mapping from assets-functions-mechanisms-benefits is needed, the baseline definition for the benefit calculation is already given, monetization and quantification are combined and there are additional analyses provided such as sensitivity analysis.
Smart Grid Consumer Collaborative (SGCC)	US	The Smart Grid Consumer Collaborative (SGCC) reviewed available research quantifying benefits – customer choice, economic, environmental and reliability and costs associated with investments in Smart Grids. Benefit cost analysis was calculated for a number of different capabilities which includes; Integrated volt/VAr control, Remote Meter Reading, Time-Varying Rates, Prepay and remote disconnect/reconnect, revenue assurance, customer energy management, Service outage management including fault location and isolation, Renewable generation integration). A net present value for a 13 year deployment were calculated using a reference case with conservative assumptions and an ideal case based on the achievable. The report showed that the modernization of the grid has significant benefit on the environment and that its direct and indirect economic benefits is larger than the cost of Smart Grid infrastructure (ISGAN, 2015).
European Commission recommendation of 9 March 2012 on preparations for the roll-out of smart metering systems	EU	The European Commission provided some recommendations for methodology for the economic assessment of the long-term costs and benefits for the roll-out of smart metering systems in 2012. The assessment included the following four steps; tailoring to local conditions, cost-benefit analysis (based on the JRC framework), sensitivity analysis, performances assessment, externalities and social impact. The cost-benefit analysis used two scenarios, a business as usual and one with an 80 % roll-out but additional scenarios were also recommended in order to assess synergies between different energy saving measures, feedback to consumers, information and price transparency etc.

Framework	Origin	Description
IRENA – Smart Grids and Renewable, A cost-benefit analysis guide for developing countries	World	The proposed methodology is an adaption of the JRC model. There are two approaches, a predefined renewables goal approach and a no predefined renewables goal approach. The second approach is for countries that don't have a renewable goal and that smart grids will enable deployment of renewables that otherwise wouldn't occur. New renewables that will occur due to the smart grid investments will therefore be included in the CBA (both costs and benefits) therefore add an additional step in the approach after mapping functions to benefits. An observation is that smart grids help reduce electricity theft but might also create a need for subsidized electricity (due to loss of access by people who have been stealing) that is worth considering when quantifying the benefits.
EA Technology "Transform Model"	UK	The transform model was developed by EA Technology and is a four step model based on, scenarios, existing networks, solutions and modelling combinations. The model is parametric representation of the electricity distribution network in Great Britain and describes the impact of future scenarios on the existing network. Initiated in 2012 but DEEC Ofgem Smart Grid Forum, the model is utilized on license by all Great Britain Distribution Network Operators. EA technology continually updates and enhance the model using the input from industry stakeholders and from a number of sources.
Synapse Energy Economics "Benefit – cost analysis for Distributed Energy Resources"	US	Developed by the Synapse Energy Economics to provide the New York Public Service Commission with a benefit-cost analysis framework. The framework outlines the methods for identifying, valuing, and monetizing costs and benefits. It is a parameter-based model, allowing common elements to be used in building a network. Based on real data from a number of sources including the distribution networks and local authorities. Can optimize and assess investment scenarios providing a range of different smart grid and conventional solutions.