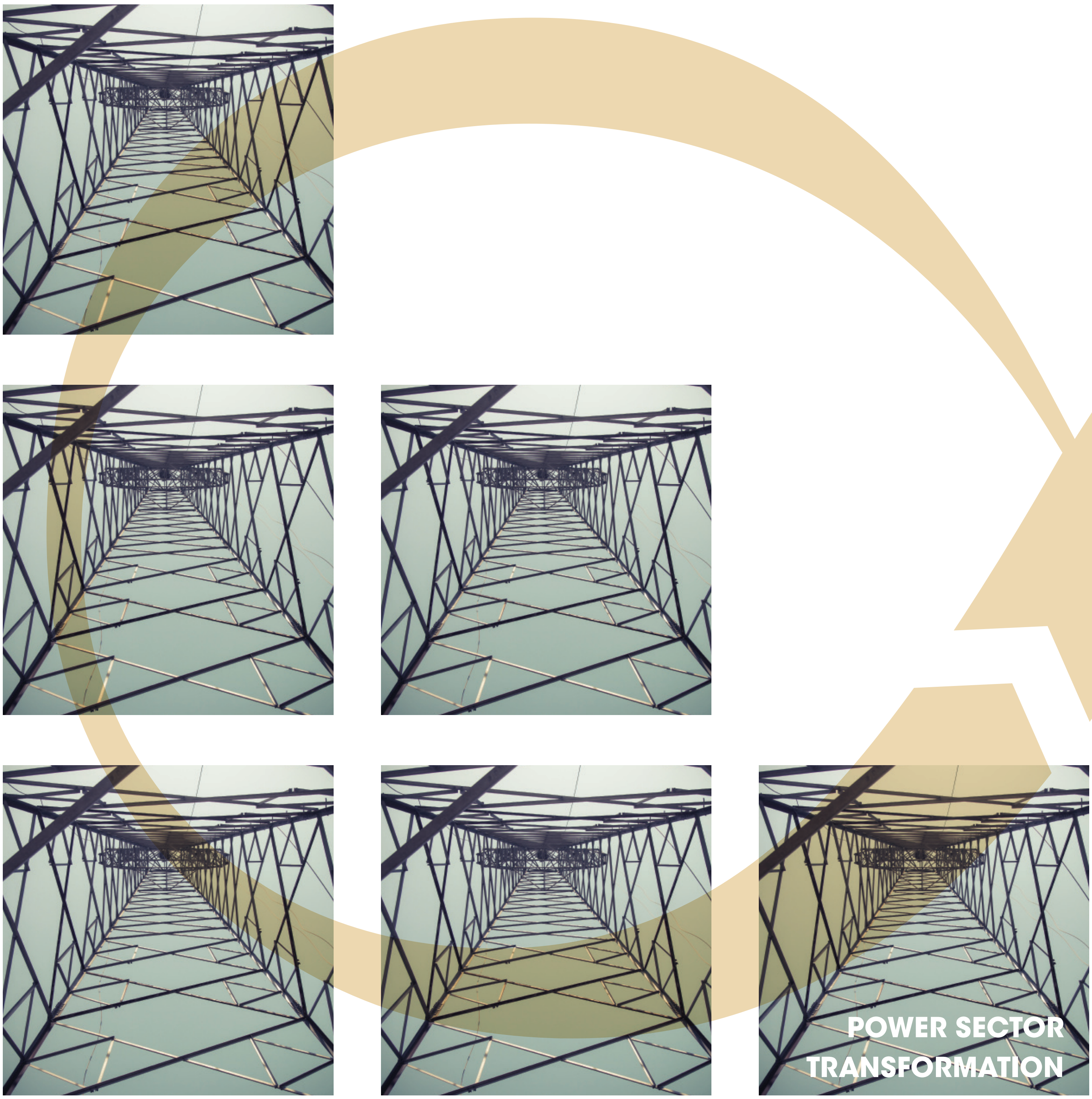
IRENA
International Renewable Energy Agency

# SMART GRIDS AND RENEWABLES

## A COST-BENEFIT ANALYSIS GUIDE FOR DEVELOPING COUNTRIES



## About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

## Acknowledgements

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# Executive Summary

Smart grid technologies can enable higher levels of renewables in electricity systems by making the system more flexible, responsive, and intelligent. As more and more countries, particularly in the developing world, plan to increase their use of renewables, smart grid technologies provide the means to integrate these renewables in a cost-efficient and effective way.

Smart grid projects are often evaluated and justified on an economic basis. The challenge for decision-makers (which can be utilities, policymakers, or others) is to evaluate smart grid proposals rigorously, objectively, and with a well-defined and consistent methodology. Such analyses are critical for ensuring that scarce capital is invested wisely.

Several methodologies exist for economic evaluation of smart grid projects. However, developing countries can benefit from a customised methodology for smart grid project evaluation. This report provides a cost-benefit analysis (CBA) methodology that is designed for developing countries. The proposed methodology allows for analysis of benefits such as reduced theft, grid extension, and significant increases in reliability, and is realistic about system data availability and accuracy.

CBA is an ideal first tool for evaluating a smart grid investment. Its value lies not just in the result it provides but also in how it requires one to define and quantify the expected costs and benefits. Often it is this analytical discipline, rather than the result itself, that is most informative.

Before undertaking a CBA, one needs to consider several issues. First, different stakeholders will value the benefits of a smart grid differently. A societal perspective will account for all benefits; however, one may want to take a narrower perspective, such as that of the utility or of electricity users. Second, undertaking a CBA requires careful definition of a baseline, documenting what would happen in the absence of the smart grid project. Third, CBA requires considerable judgment on the part of the analyst, particularly in estimating uncertain inputs and assessing qualitative benefits. CBA can support better decisions, but it should not be used to make decisions on its own.

This report is accompanied by a number of exercises to demonstrate the methodology and the value of CBA. The fictional country of Ruritania[1] is used to demonstrate a CBA of smart inverters for renewables in a small developing country's electricity system. The results reveal that fewer outages and reduced losses are by far the most valuable benefits of these inverters, accounting for almost three-fourths of the total benefit value. The advantages of smart inverters clearly exceed the costs. This result, however, reflects electricity users' estimated valuation of reduced outages. If the utility values fewer outages only at the value of the lost electricity sales, then the smart inverters are not cost-effective. A second example shows the cost-benefit analysis methodology for a distribution automation programme in case there is no predefined renewable energy target in Ruritania. This exercise demonstrates a situation in which the benefits and costs of the additional renewable energy deployment have to be considered as part of the analysis.

A third exercise is used to present a smart grid investment in an island country, and is loosely based on Jamaica. This exercise focuses on a demand response (DR) project to accompany renewables expansion to defer generation-capacity investment. The project is found to be cost-effective – even with moderate changes in assumptions and with significant incentive payments to DR participants.

[1] A fictional kingdom used as the setting for stories by Anthony Hope (1863-1933), and often used in academia to refer to a hypothetical country


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# Chapter 1

# Renewables, Smart Grids and Cost-Benefit Analysis

**Chapter summary:** Smart grid projects must be evaluated and justified on an economic basis. The challenge for decision-makers is to evaluate smart grid proposals for renewables rigorously, objectively, and with a well-defined and consistent methodology. Developing countries present a clear opportunity for smart grids, including the possibility of leapfrogging over outdated technologies and enhancing electricity access. There are challenges as well, notably capital constraints and political challenges in setting electricity rates that cover costs.

Renewable energy power generation is growing fast. Since 2011, more renewable power generation capacity is added than conventional power generation capacity every single year. In particular, variable renewable energy sources such as solar photovoltaics (PV) and wind are growing fast. 2014 was another record year with around 44 GW of solar PV and 50 GW of wind power added globally.

IRENA's global renewable energy roadmap, REmap 2030, suggests that the growth in renewables will continue (IRENA, 2014). Based on an analysis of 26 countries, covering 75% of global energy consumption, the share of renewables in the power sector may increase from 22% in 2012 to more than 40% by 2030, and the share of variable renewables may increase from 3% in 2013 to around 20% in 2030.

Up to 2012, the growth of variable renewable energy took place in European countries and the United States. However, in the last two years China and Japan have become the major markets for solar PV and wind power. Over the next 20 years, it is expected that this shift continues, especially to those countries with growing electricity demand in Asia, Latin America, and Africa. These countries are rapidly expanding their grid infrastructure to keep up with the demand, and renewable power generation allows them to add capacity in a cost-effective and timely manner.

Renewables are also a solution to improve the low electrification rates in many developing countries. Globally, as many as 1.2 billion people do not have access to electricity and distributed power generation of solar PV and wind could alleviate this situation. However, this would require rapid expansion of existing grids or the development of mini-grids with decentralised control systems.

Achieving high shares of renewables in the final energy mix can substantially benefit from electricity systems that are more flexible, responsive, and intelligent. "Smart grid technologies," can do just that by leveraging the tremendous technical advances in information and computing. Hence, they are an essential component of the REmap 2030 analysis (IRENA 2014, p. 8).

Smart grids use technologies to instantly relay information in order to match supply with demand, support well-informed decisions on dispatch, and keep systems operating at optimal efficiency. These technologies can be implemented from utility-scale generation to consumer appliances.

For example, just as a smart appliance in a private home can switch on and off in response to varying electricity prices, a smart transformer on the grid can automatically notify grid operators and repair personnel if its internal temperatures is too high. Similarly, a smart meter can measure and track the output of a rooftop photovoltaic (PV) system and send that data to the utility, thereby making use of surplus PV energy, or addressing gaps due to solar variability.

There is no universal agreement on what qualifies as a smart grid technology; however, it is generally understood to include communication, information management, and control technologies that contribute to the efficiency and flexibility of an electricity system's operation. The suite of available smart grid technologies and applications continues to evolve at a rapid pace. Table 1A lists the seven major groups of smart grid technologies and more details on these technologies, including costs and market status, can be found in the 2013 IRENA report on "Smart Grids and Renewables" (IRENA, 2013). This list, however, will continue to grow as entrepreneurs find novel applications for improved intelligence and information in the energy industry.

### Table 1A: Smart Grid Technologies

| |
|---|
| Advanced metering infrastructure (AMI) |
| Advanced electricity pricing |
| Demand response (DR) |
| Distribution automation (DA) |
| Renewable resource forecasting |
| Smart inverters |
| Distributed storage |
| Virtual power plants |
| Microgrids |

Smart grid technologies enable high levels of renewables mainly by increasing grid flexibility and facilitating the increased use of variable renewable generation technologies, notably wind and PV systems. However, smart grids also have profound implications for transmission and distribution (T&D) systems, as they can ease T&D system integration of distributed renewable generation and reduce T&D investment needs by optimising use of existing infrastructure. This will become increasingly relevant given that T&D is projected to account for almost half of the power sector investment until 2035, much of that in non-Organisation for Economic Co-operation and Development (OECD) countries (International Energy Agency [IEA], 2013).

IRENA's Smart Grids and Renewables report explains how smart grids enable renewables, discusses the nontechnical barriers to smart grids, and details the costs, performance, and other characteristics of specific smart grid technologies. The report concluded that smart grids, although conceptually attractive for their ability to enable renewables, must be evaluated and justified on an economic basis.

This report is IRENA's second report on smart grids and renewables. The aim of this report is to help decision-makers in developing countries to perform CBAs on smart grid projects. Such analyses are critical for ensuring that scarce capital is invested wisely.

## SMART GRID PROJECTS NEED CAREFUL EVALUATION

Numerous studies have concluded that smart grids can be financially attractive investments. A meta-analysis of 30 business cases for smart meter projects in 12 countries, representing 4 continents, found that on average, the net present value (NPV) of project benefits exceeded the NPV of costs by nearly two to one (King, 2012). In the Middle East and North Africa, studies found that smart grid investments could save the region USD 300 million to USD 1 billion annually while helping to realise the region's potential for solar power (Northeast Group, 2012). A study in the U.S. found that potential investments in sustainable technologies, including smart grid and renewables, have an NPV of USD 20 billion to USD 25 billion based solely on benefits to utilities (Rudden and Rudden, 2012). Although these studies are based on predictions rather than actual project results (hence, they should be interpreted carefully), nevertheless, they suggest that smart grid projects are economically viable options.

A critical question facing utilities, governments, and other decision-makers, however, is whether their individual proposed smart grid project makes financial sense. However, each individual project must be assessed on its own merits.

The costs of smart grid projects are typically well-defined and straightforward to quantify. The benefits, however, may not be. Some of the benefits, such as decreased operations and maintenance (O&M) costs, are relatively clear. Others such as improving consumer information or enhancing grid resiliency clearly have some value, but assigning a monetary value to these types of benefits is quite challenging.

An additional challenge in evaluating smart grids is that the benefits often flow to multiple stakeholders. Improved consumer information is of some value to consumers, but probably of less direct value to the utility. Smart grid projects can enable higher levels of renewables and thereby reduce carbon emissions, but different stakeholders will value that carbon reduction differently.

The challenge for decision-makers is to evaluate smart grid proposals for renewables rigorously, objectively, and with a well-defined and consistent methodology.

## SMART GRIDS IN THE DEVELOPING WORLD

Several methodologies exist for economic evaluation of smart grid projects. Among the most widely known is one developed by the Electric Power Research Institute (EPRI) (EPRI, 2010 and 2013) and modified by the Joint Research Centre of the European Commission (EC, 2012a and 2012b). This methodology is rigorous and well documented, but it does require further modification for use in the developing world.

Developing countries' electricity systems differ from those industrialised countries in several ways. In some cases, these differences create a clear opportunity for smart grids:

- In many cases, the electricity systems are still expanding in order to reach residents without grid access (Table 1B). This provides an opportunity for "leapfrogging," as countries can take advantage of smart grid technologies while building out the T&D grid instead of having to retrofit the existing infrastructure.
- Smart grids enable a number of innovative energy services that could help realise goals of universal access to electricity, possible. These include linking energy payments to mobile phones, installing local charging stations and building mini- and microgrids. (Welsch et al. 2013).
- Sometimes the electricity systems suffer from relatively high levels of theft and technical losses (Table 1B). Smart grids are well suited to tracking and reducing these types of losses by recording electricity load across the lines.
- On average, electricity systems have lower reliability than those in industrialised countries (Table 1C). As is the case for theft and technical losses, smart grids are particularly well suited to provide significant improvements in reliability by tracking any outages or faults in the lines.

There are ways in which these differences create a clear challenge for smart grids:

- Many (utilities in) developing countries are capital-constrained, with limited access to low-cost capital for upgrades and extensions of their electricity systems. This complicates efforts to invest in smart grid projects, even if they are clearly cost-effective.
- Electricity systems may be unable to set electricity rates at a level that covers costs of operation, due to concerns over affordability of electricity for residents, businesses, and industry. This leads to insufficient O&M spending and a backlog of basic maintenance, therefore making it difficult to justify smart grid projects, which may be seen as a luxury and/or not absolutely critical to basic grid functioning.
- Smart grid analyses may require detailed data on system operational characteristics (such as reliability/downtime and minute-by-minute load data), customer demographics, and more. Such extensive data may not be available.
- Regulatory and institutional issues, such as the need for standard setting, harmonisation of different electricity systems, and ensuring data privacy, can limit innovation.

Owing to these substantial differences, developing countries require a customised methodology for smart grid project evaluation. One that can accommodate the benefits such as reduced theft, grid extension, increased reliability, and is simultaneously realistic about system data availability and accuracy.

This report is the first to provide such a methodology for developing countries.

The remainder of this report is organised as follows:

- Chapter 2 provides an overview of how CBA works and what major issues need to be considered before undertaking a CBA.
- Chapter 3 provides a detailed guide on how to estimate the benefits and costs of a smart grid project with our methodology, and how to use sensitivity analysis to incorporate uncertainty and qualitative benefits into a CBA-guided decision. The text will be accompanied by an exercise that will illustrate all of the different steps.. This is the most challenging component of a CBA.
- The appendices provide further details on two additional case studies, and include an illustration of the alternative approach to be used when there is not an explicit renewables goal. Furthermore, the case study provides an explanation on how to calculate the different benefits, and provides starting-point cost data for any analysis.

### Table 1B: Electricity access and T&D losses

| Region | Access to electricity (% of population) | T&D losses (%) |
|---|---|---|
| Sub-Saharan Africa (developing only) | 35 | 12 |
| Least-developed countries: United Nations classification | 32 | 16 |
| Middle income | 85 | 11 |
| European Union | >99* | 7 |

Source: http://databank.worldbank.org/data/home.aspx
*Authors' estimate

### Table 1C: Electricity outages in selected countries

| Country | Value lost due to electricity outages (% of sales/year) |
|---|---|
| Hungary | 1 |
| Samoa | 7 |
| Yemen | 13 |
| Zimbabwe | 18 |

Source: http://data.worldbank.org/indicator/IC.FRM.OUTG.ZS

# Chapter 2

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# Cost-Benefit Analysis: Introduction and Overview

**Chapter summary:** Before undertaking a CBA, one needs to consider several issues, including perspective (whose costs and benefits are relevant) and baseline definition (what would happen in the absence of the proposed smart grid project). There are two basic approaches to a smart grid CBA: one in which there is a predefined renewables goal that will likely be met with or without the proposed smart grid project, and one in which the smart grid project allows for renewables that wouldn't otherwise occur. Our methodology works for both approaches.

## COST-BENEFIT ANALYSIS IN CONTEXT

Used properly, CBA can give an estimate of how a smart grid technology investment will perform, that is, the overall financial attractiveness of the investment. CBA's principal strengths are:

- It is relatively simple.
- It is rigorous and quantitative, enabling evidence-based decision-making.
- Its assumptions and methodology are transparent.
- It lends itself to sensitivity analysis, allowing one to vary the value of uncertain inputs and see how the results change.

However, there are some significant drawbacks as well, namely:

- It is data-intensive. It requires quite a few inputs, some of which may not be known.
- It requires an assessment of the future impacts of present-day investments, which is inherently uncertain.

- Specific (point value) inputs are required and therefore, a sensitivity analysis may be needed if the input values are uncertain.
- Its incorporation of qualitative factors and second-order impacts is imprecise.

CBA is an ideal first tool for evaluating a smart grid investment. Its value lies not just in the result it provides but also in how it requires one to define and quantify the expected costs and benefits. It is this analytical discipline, rather than the result itself, that is often most informative.

CBA is one of several methods that can be used to assess the economic impacts of a smart grid investment. In the private sector, this assessment is referred as the 'business case' and might relate to the profit potential, competitive advantage, market positioning, or other business attributes. However, in most cases, electricity in developing countries is provided by a government agency or a regulated monopoly and therefore, competitive market issues (such as market share) are not of concern. Instead, the overall question is whether the benefits of investing in smart grids are greater than its costs. This is a question CBA can help answer.

## CONSIDERATIONS BEFORE UNDERTAKING A COST-BENEFIT ANALYSIS

Several overarching issues need to be considered before undertaking a CBA.

### Costs and Benefits as Seen by Whom?

A smart grid project will have numerous benefits, all of which will not be equally valued by the stakeholders. For example, smart grid technologies might allow for higher renewables and therefore lower carbon emissions, but an individual electricity user may not place any value on reducing carbon emissions. So the CBA, if done from the individual electricity user's perspective, might value the higher renewables benefit at 0. However, the utility may value those emissions reductions quite highly (due to, for example, a government commitment to reduce emissions), and would therefore place a very different value on that emissions reduction benefit.

### Whose perspective does one take when doing a CBA?

This report generally takes a societal perspective, one that incorporates all costs and benefits as seen by all stakeholders. In the carbon example above, the utility's perceived value of the carbon emissions would be used. In most cases, smart grid projects in developing countries are undertaken by government agencies, and the perspective of these agencies is typically close to that of society.

Note, however, that there is no requirement that CBA take a societal perspective and a more narrow perspective on costs and benefits can be taken. Where possible, this handbook shows how costs and benefits flow differently according to the stakeholders, allowing users to tailor the analysis to different stakeholders perspectives.

### Importance of Qualitative Factors

Some costs and benefits of smart grid projects, such as up-front hardware costs, are straightforward to quantify. Others, such as allowing for increased electricity system reliability, can be valued in monetary terms, but with some uncertainty. Still others, such as providing consumers with greater information and control, certainly have some value, but are extremely difficult to attach a monetary value to. We call these qualitative benefits.

Our CBA methodology, detailed below, stresses the importance of keeping track of all relevant costs and benefits, including those not easily quantifiable. However, in the end, decision-makers will need to make a judgment on the relative value of the qualitative benefits to the decision at hand. CBA can clarify the uncertainties, but cannot eliminate them.

### Second-Order Impacts

Imagine a smart grid project with an up-front hardware cost of USD 10 million. From the utility's perspective, that USD 10 million is clearly a cost. However, from the perspective of the company selling that hardware, that is a USD 10 million benefit. USD 10 million that may flow through the economy would have second- and higher-order benefits to the system as it does so. CBA considers only the first-order impacts.

## Need for a Baseline

A CBA requires defining a baseline, or a prediction of what would happen if the smart grid project were not implemented. Firstly, that prediction is compared to what is predicted to happen if the smart grid project were implemented and secondly, the net benefits and costs are calculated.

The CBA baseline is not necessarily a business-as-usual or "no changes" scenario. In fact, the baseline should include all projects, or components of projects, that are expected to take place with the exception of the smart grid project that is under consideration. For example, consider a utility undertaking a grid extension project to serve new populations that do not have current grid access.

The baseline would be grid extension, while the smart grid analysis scenario is the grid extension with smart grid technologies. Similarly, consider a utility considering how smart grid technologies could assist in reaching a goal of 30% renewables by 2020. That goal would be part of the baseline, as it is predefined and smart grid technologies will not alter that goal. The CBA in this example would evaluate the costs and benefits of implementing smart grid technologies, not the costs and benefits of the goal itself.

## Need to Define Project Boundaries

The boundaries of a smart grid project need to be clearly and carefully defined ahead of the CBA. In general, the narrower the boundaries, the simpler the analysis and the less uncertain the results. Critical boundaries are determined by:

- Time: the period of interest. Notably, for what period the costs and benefits need to be analyzed. For example, a project may define this time frame as 10 years from project launch.
- Space: the geographic area of interest. This is typically the utility service area or the country as a whole.

## Need to Select a Discount Rate

Most of the benefits associated with a smart grid project occur in the future. A discount rate allows one to find the present value of those future benefits—that is, it allows one to unequivocally compare the future benefits with the capital investments costs at the start of the project. Doing a CBA of a smart grid project requires one to select a discount rate. The selection of a discount rate can significantly influence the results, and it is therefore important to give careful thought as to just what discount rate to use.

If a CBA takes a societal perspective that incorporates all costs and benefits accruable to society as a whole, then a societal (sometimes called social) discount rate should be used. The World Bank has adopted a societal discount rate of 5% for certain kinds of debt (IMF, 2003). However, a sensitivity analysis across different different discount rates can be run to explore the CBA results' sensitivity to this assumption.

## CBA Process Overview

At the highest and simplest level, CBA has three major components:

- Estimation of the benefits of the proposed smart grid project. Our methodology, illustrated in Chapter 3, focuses on the benefits related to renewables integration; however, the other potential benefits are addressed as well.
- Estimation of the costs of the proposed smart grid project. This guide focuses on up-front hardware costs and ongoing operations and maintenance (O&M) costs. O&M costs vary considerably according to the project but can be roughly estimated based on published data.
- Comparison of costs and benefits. By combining costs and benefits occurring at different times through use of an overall discount rate, an overall single number (typically net present value, NPV) that can be compared to other projects is obtained.

However, this valuation is complicated by the presence of qualitative benefits and by uncertainty associated with the estimated future cost and benefit values.

## Two Fundamental Approaches

There are two fundamental approaches to smart grid CBA for renewable implementation: (1) Start with an explicit renewables deployment goal, to be met with or without smart grid technologies (the Predefined Renewables Goal approach); or (2) estimate the renewables deployment that would be enabled by the smart grid investment under consideration (the No Predefined Renewables Goal approach). The difference is essentially one of baseline, meaning what one assumes would happen if the smart grid investment were not made.

## The Predefined Renewables Goal Approach

This approach is for situations in which there is a preexisting renewables deployment goal, such as "20% of electricity sold in 2020 must come from renewable sources." The smart grid investment under consideration is one of perhaps several paths to reach the goal.

In this case, the baseline is reaching the goal without the smart grid investment. The CBA considers the incremental costs and benefits—that is, those costs and benefits resulting from the smart grid investment, relative to the costs and benefits of the baseline. Notably, in this approach the benefits of reaching set RE goals, such as the associated carbon reduction, are not included in the CBA, as these benefits are assumed to occur in any case.

## The No Predefined Renewables Goal Approach

This approach is for situations in which the smart grid investment is seen as enabling the deployment of renewables that otherwise would not occur. In this case, the smart grid investment enables additional renewables deployment, and the benefits and costs associated with those renewables become part of the CBA. The baseline is whatever renewables penetration would occur in the absence of the smart grid project. For ease of analysis, this is typically assumed to be zero (or unchanged from the present renewables level). This is more challenging since the amount of renewables that the smart grid investment will enable and the ensuing the costs and benefits, needs to be estimated.

Costs = (smart grid project costs) plus (enabled renewables costs)

Benefits = (smart grid project benefits) plus (enabled renewables benefits)

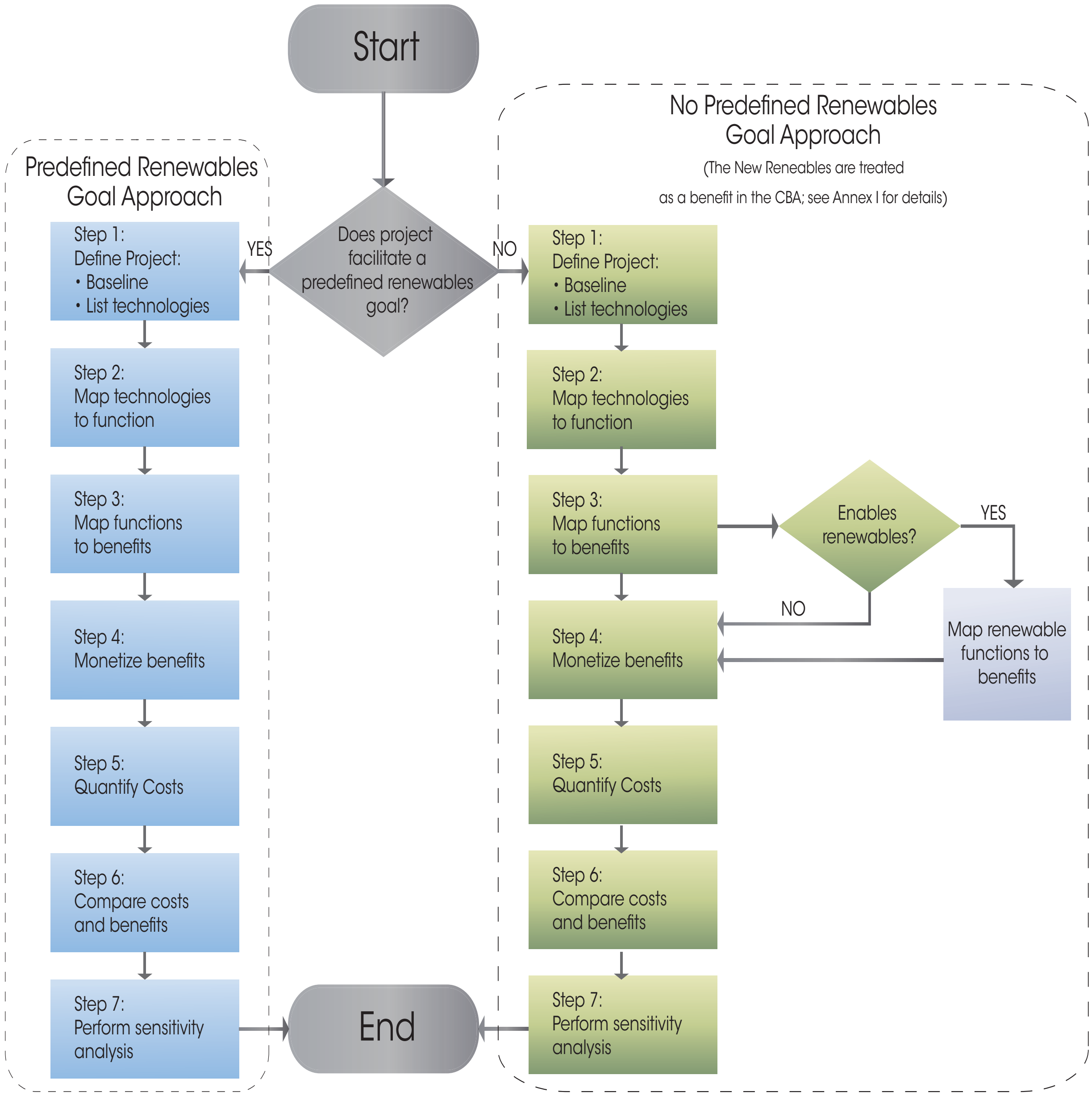
## Overview of Methodology

Our methodology for identifying and quantifying the benefits of a smart grid is adapted from that proposed by the Joint Research Centre EC (EC, 2012a and 2012b) which was in turn adapted from EPRI (2010) and EPRI (2013). Figure 2 shows an overview of this process. After first identifying and defining the boundaries of the project and the baseline against which it is to be valued, the smart grid technologies to be deployed are listed (Step 1). Each technology is then mapped to the functions it provides (Step 2), and then each function is in turn mapped to the benefits it provides (Step 3). Finally, the economic value of each benefit is monetised (Step 4). Costs are then estimated (Step 5), costs and benefits compared (Step 6), and finally a sensitivity analysis is performed (Step 7).

The process is slightly more complicated if using the No Predefined Renewables Goal approach to incorporate the effect of renewables enabled by the smart grid project, as shown on the right-hand side of Figure 2. (As a reminder, under the No Predefined Renewables Goal approach the new renewables are treated as a benefit in the CBA; see Chapter 2 for details). If enabling wind or solar is identified as a potential benefit in Step 3, the enabled renewables are mapped to their benefits and added to the list of smart grid benefits. Then, the complete list of benefits is monetised in Step 4.

This methodology can be complex—particularly in estimating benefits (Steps 1 through 4 in Figure 2). Chapter 3 provides a detailed case study on a fictional country called Ruritania. Ruritania represents a small developing country in which investments in smart inverters are considered. More complex examples, based on a distribution automation programme in Ruritania and a demand response (DR) project in Jamaica, can be found in Annex I and Annex II.

## Figure 2


Start
Does project facilitate a predefined renewables goal?
YES
NO
Predefined Renewables Goal Approach
Step 1:
Define Project:
• Baseline
• List technologies
Step 2:
Map technologies to function
Step 3:
Map functions to benefits
Step 4:
Monetize benefits
Step 5:
Quantify Costs
Step 6:
Compare costs and benefits
Step 7:
Perform sensitivity analysis
No Predefined Renewables Goal Approach
(The New Reneables are treated as a benefit in the CBA; see Annex I for details)
Step 1:
Define Project:
• Baseline
• List technologies
Step 2:
Map technologies to function
Step 3:
Map functions to benefits
Enables renewables?
YES
NO
Map renewable functions to benefits
Step 4:
Monetize benefits
Step 5:
Quantify Costs
Step 6:
Compare costs and benefits
Step 7:
Perform sensitivity analysis
End

# Chapter 3

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# Smart Grid Cost-Bnefit Analysis for Ruritania[2]

**Chapter summary:** The CBA methodology can be a bit complex. To demonstrate its use, it is first applied to a simplified, fictional country called Ruritania. The exercise assesses the impact of smart inverters and reveals that fewer outages and reduced losses are by far the most valuable benefits of these inverters, accounting for almost three-fourths of the total benefit value. The advantages of smart inverters clearly exceed the costs. This result, however, reflects electricity users' estimated valuation of reduced outages. If the utility values fewer outages only at the value of the lost electricity sales, then the smart inverters are not cost-effective.

The exercise illustrates how sensitivity analysis reveals the way in which net benefits vary with critical assumptions.

## RURITANIA CASE STUDY SUMMARY

Ruritania is a country with an electricity system primarily based on coal- and gas-fired power stations, and only 2% of variable renewables (wind). Its electricity system is expected to growth from 10 GW peak to 20 GW peak by 2030. Ruritania has a goal of 20% renewable electricity by 2030, to be met with wind and solar PV. The costs and benefits of upgrading the planned wind and PV systems to include advanced grid support features are analysed. The case study assumes that the renewable energy goal of 20% will not change, so the CBA will only consider the costs and benefits on the electricity system.

The CBA looks specifically at the advanced grid support features. It assumes an upgrade of new wind and PV with smart inverters. The smart inverters will provide grid-friendly features like fault ride-through and assistance with voltage and frequency regulation. The smart inverters will be rolled out alongside the deployment of the renewables to achieve the 20% renewable energy target assuming a project rollout time of 15 years. The CBA will apply to this 15-year period.

## Benefits

The functions (in a smart grid CBA) of the grid-friendly controls are to enable wide-area monitoring and visualisation, power flow control, and automated voltage and volt-ampere reactive (VAR) control. These functions map to 13 out of the 24 possible benefits, as shown in Table 3A[3]. The full list of possible benefits are discussed in Table 3D, and Table 3F will show how these benefits were calculated.

[2] A fictional kingdom used as the setting for stories by Anthony Hope (1863-1933), and often used in academia to refer to a hypothetical country

[3] Only those benefits relevant to this project are listed. Additional benefits may be relevant to a smart grid project, depending on the project specifics.

One qualitative benefit of this project is to provide utility workers with experience in advanced technologies for control of renewables. The smart PV inverters could also be integrated into future DA schemes, acting as distributed reactive power sources for voltage optimisation and thus, resulting in further loss reductions and investment deferral.

### Table 3A: Values of benefits

| Benefit | NPV (thousand USD) | Uncertainty level | Primary beneficiary |
|---|---|---|---|
| Reduced ancillary service cost | 4 300 | Medium | Utility |
| Deferred distribution investments | 2 300 | Medium | Utility |
| Reduced equipment failures | 8 | Medium | Utility |
| Reduced distribution operations cost | 0 | Low | Utility |
| Reduced electricity losses | 17 600 | Medium | Utility |
| Reduced electricity cost | 0 | Low | Customers |
| Reduced sustained outages | 29 000 | High | Customers |
| Reduced major outages | 0 | High | Customers |
| Reduced restoration cost | 70 | High | Utility |
| Reduced momentary outages | 0 | Low | Customers |
| Reduced sags and swells | 0 | Medium | Customers |
| Reduced $CO_2$ emissions | 9 600 | Medium | Society |
| Reduced SOx, NOx , and PM10 emissions | 1 100 | Medium | Society |
| Reduced wide-scale blackouts | 0 | High | Society |

## Costs

The costs relevant to the CBA are any costs that would not be incurred if the grid-friendly renewable controls were not used. For PV systems, an average inverter cost increase due to these grid-friendly controls of 10% is assumed. For wind plants, the total system capital cost is assumed to rise by 1%. In both cases, these costs include the communications and IT infrastructure required. Project costs are summarised in Table 3B.

## Discussion

The total present value of the project benefits is USD 63 million, while the total present value of the costs is USD 38 million. The benefits exceed the costs, so the project is cost-effective.

As shown in Table 3A, reduced sustained outages and reduced electricity losses are the largest components of the benefits NPV. A critical assumption in estimating the benefit of reduced sustained outages is the value of this reduction to electricity users. The results in Table 3A assume a value of USD 3 for each kWh reduction in sustained losses. That value is based on a meta-analysis of a large number of studies. Note, however, that this USD 3/kWh value reflects the electricity user's perspective. The utility, in contrast, might value these reduced outages as worth only the regained electricity sales they yield, at the current retail rate of electricity.

Changing the value of these outage reductions from USD 3/kWh to USD 0.10/kWh changes the NPV from plus USD 25 million to minus USD 2 million. In this case, the project would no longer be cost-effective based on quantified benefits alone; the qualitative benefits would need to be worth at least USD 2 million to make the project cost-effective under this reduced-benefit scenario.

### Table 3B: Values of costs

| Cost | NPV (thousand USD) | Uncertainty level | Primary beneficiary |
|---|---|---|---|
| Advanced PV inverters | 23 800 | Low | Utility and PV owners |
| Advanced wind turbines | 14 200 | Medium | Utility and wind owners |

## STEP 1: DEFINE PROJECT

The first step in analyzing the costs and benefits of a project is to clearly define the project. This includes recording general project information, identifying the technologies being deployed, and determining the baseline for the CBA.

Relevant general project information may include the goals of the project, its stakeholders, its regulatory environment and its dimensions and boundaries. One key dimension is the length of the project, as it will define the window within which costs and benefits should be included in the CBA.

Box 1 shows the project definition for Ruritania.

In this chapter, we illustrate the CBA methodology using a fictional case study: the Ruritania grid support project. The details are described in sidebars throughout this section.

### Box 1: Ruritania Smart Grid Project: Country Information

The Ruritania example is based on a hypothetical power system and shows how the methodology might apply to that system. The intent is to provide an example of each step rather than to show a complete CBA, which would include more detail.

General country information:

- 10 GW peak electricity demand, growing to 20 GW in 2030 (4.7% annual growth)
- 31 TWh annual generation, growing to 62 TWh in 2030
- 1 000 distribution feeders, doubling to 2 000 by 2030; average feeder capacity of 10 MW
- Renewables goal: 20% of electricity from wind and solar by 2030 (currently at 2%); 70% of renewable energy to come from wind plants, 15% from centralised PV plants, and 15% from distributed PV installations
- The capacity factor for wind is taken to be 40%, and the capacity factor for PV is taken to be 21%, based on median data from OpenEI
- Electric utility is owned and managed by the national government
- Average retail electricity price: USD 0.10 per kWh
- Average wholesale electricity price: USD 0.05 per kWh
- Annual discount rate used for government planning: 8%
- Annual price inflation rate: 3%

Proposed smart grid project:

- Goal: facilitate the preexisting renewable deployment goal
- Project term: 15 years (2015 to 2030)
- Project scope: nationwide
- Stakeholders: utility, electricity consumers, society at large

## List Technologies

After compiling general project information, the specific smart grid technologies and renewable assets under consideration should be listed. IRENA's publication 'Smart Grids and Renewables' provides an overview of six categories of smart grid technologies and applications that can be considered as "well-established" or "advanced." Energy storage and microgrids should also be considered as potential technology options, because they may find niche applications in emerging countries (IRENA, 2015). Annex IV provides a summary of these six categories of smart grid options. Box 2 illustrates the smart grid technology chosen in our case study.

### Box 2: Ruritania Smart Grid Project: Introducing Smart Controls

In our illustrative example project, we propose to upgrade the wind turbines and solar inverters to include advanced grid support capability that uses improved controls to help renewables integrate with the grid, assisting with voltage and/or frequency regulation and remaining connected during grid faults. We will refer to this upgrade as grid-friendly renewable controls.

## Select Baseline

If an RE goal has been set prior to the smart grid project (the Predefined Renewables Goal approach), then the baseline for the CBA involves achieving that goal without using smart grid technologies (or without adding smart grid assets if some already exist). Other sources of the flexibility needed to integrate renewables include upgrades to grid infrastructure and investment in more-flexible conventional generators. IEA provides guidance as to amounts of flexibility available from various conventional generators and infrastructure upgrades as well as economic analyses of the different options (IEA, 2014).

When no prior RE goal exists (the No Predefined Renewables Goal approach), the baseline involves continuing with existing grid maintenance and development plans.

Under either approach, the baseline should be carefully chosen to include projected future changes to the electricity system. For instance, if there is a preexisting goal to expand electricity access to unserved areas or to greatly increase the hours of electricity availability, then the baseline for the CBA involves achieving that goal without the proposed smart grid technologies. In this case, the smart grid project may have the opportunity to leapfrog conventional electrification technologies. Box 3 illustrates the baseline selection for our case study.

### Box 3: Ruritania Smart Grid Project: Baseline Selection

Because the smart grid project under consideration facilitates an existing renewables goal, the Predefined Renewables Goal approach will be used. Therefore, the baseline against which the project will be compared involves achieving the renewables goal without using the proposed smart grid technology. Long-term power system modelling should be used to determine which conventional technologies would be needed to facilitate the 20% renewables goal. For the sake of this example, we assume that the country has determined that in order to meet its goal without smart grid technologies, it will need to install 3 GW of combined-cycle gas-fired turbines designed for flexible operation, retrofit 3 GW of existing coal-fired generation for improved flexibility, install 300 kilometers of additional transmission lines with a peak capacity of 2 GW, and install additional switched capacitor banks on 10% of existing and new distribution circuits. As detailed later in this chapter, advanced grid support from renewables will reduce the costs associated with some (but not all) of these upgrades. The baseline includes conventional solar and wind inverters (not capable of volt-VAR control or ride-through).

## STEP 2: MAP TECHNOLOGIES TO FUNCTIONS

Once the technologies under consideration and the baseline have been identified, the next step is to map each technology to its potential functions. Functions, in a smart grid sense, are the roles that various technologies can play in improving grid operation. Functions do not translate directly into monetary values but are monetised in the next step by mapping them to benefits. Thinking through the functions of the smart grid technologies being deployed (rather than trying to jump directly from technologies to benefits) helps ensure a thorough analysis that does not miss any benefits.

In total, there are 12 functions (EPRI, 2010), shown. Choosing from the list, consider which functions each technology may activate and create a matrix like the example for our case study shown in Table 3C.

More than one example of a given technology category may be included in the matrix. For example, one project might include both direct utility control of industrial loads and optimised control of residential water heaters, both of which are examples of DR. Each should receive its own column in the matrix.

If in doubt as to whether a given technology may activate a certain function, include the function for later consideration. Any technology may activate more than one function, and any function may be activated by more than one technology. In addition, users of this CBA method may consider adding other functions as appropriate.

### Box 4: Ruritania Smart Grid Project: Mapping Technologies to Functions

Table 3C shows a matrix mapping the smart grid technology installed in our example project to its functions. The smart grid technology under consideration is listed across the top row. The first column contains all possible functions. Checkmarks indicate where a given technology may provide a certain function.

### Table 3C: Mapping technologies to function

| Functions | Technology: Smart PV Inverters | Technology: Wind turbines with advanced grid support function |
|---|---|---|
| Fault current limiting | | |
| Wide-area monitoring and visualisation | ✓ | ✓ |
| Dynamic capability rating | | |
| Flow control | ✓ | ✓ |
| Adaptive protection | | |
| Automated feeder switching | | |
| Automated voltage and VAR control | ✓ | ✓ |
| Diagnosis and notification of equipment condition | | |
| Enhanced fault protection | | |
| Real-time load measurement and management | | |
| Real-time load transfer | | |
| Customer electricity-use optimisation | | |

## STEP 3: MAP FUNCTIONS TO BENEFITS

After mapping technologies to functions, each function is in turn mapped to the benefits it may provide. A benefit is any impact of the project that may have value to any stakeholder (for example, utility, customer, or society), following EPRI (EPRI, 2010). If using the No Predefined Renewables Goal approach, the potential list of benefits includes enabled renewables (wind and solar). Again, use a matrix to ensure that each function is considered in conjunction with each benefit. Include all benefits that may possibly be activated; the next step will determine what economic value each benefit has, if any.

If using the No Predefined Renewables Goal approach, if any of the functions may enable wind or solar, the benefits of the enabled renewables should be considered as well. In this situation, a new table for the enabled wind and/or solar is needed, and the enabled renewables are mapped to any additional benefits they enable (such as pollutant reductions and/or fuel cost reductions). This additional step appears as a box on the far right in Figure 2.

### Box 5: Ruritania Smart Grid Project: Mapping Functions to Benefits

Table 3D shows how the functions identified in Step 2 are mapped onto the benefits for the case of Ruritania. Note that while this case study only involved one smart grid technology, most eligible benefits received at least one checkmark in Table 3D. However, this does not mean that all checked benefits will have associated value when monetised in the next step.

Because the Ruritania case study uses the Predefined Renewables Goal approach, enabled wind and solar generation are not applicable benefits in the CBA and hence are not evaluated in Table 3D.

## STEP 4: MONETISE BENEFITS

Once a comprehensive list of potential benefits is generated, the next step is to monetise each benefit by estimating its value in monetary terms. The value of each benefit should be considered relative to the baseline case; often the benefit will take the form of a cost savings relative to the baseline.

This step is the crux of the CBA and will likely be the most difficult. Estimating the value of some benefits may require power system modelling and simulation, which in turn requires detailed data on the power system and projections of the future state of the system in the baseline case and with the smart grid project.

While monetising the benefits, determine which stakeholders receive the benefits so that the net cost or benefit to each stakeholder can be estimated. Stakeholder groups will typically include grid operators, consumers, and society at large.

It is also important to determine when during the project each benefit accrues, as this information will be needed to discount all future benefits to their present-day values. The value of each benefit should be estimated for each year of the project. A detailed description of the different benefits, and methods to evaluate their value is provided in Annex III.

### Uncertainty in Benefit Values

There will inevitably be some degree of uncertainty in all benefit values. Estimate the magnitude of uncertainty of each benefit using the four-level scale given in EPRI (EPRI, 2010) as shown in Table 3E. Values with high uncertainty may be good candidates for sensitivity analysis. In addition, uncertainty estimates will allow decision-makers to gauge the overall level of certainty of the CBA.

## Table 3D: Mapping functions to benefits

| Benefits | Function: Wide-area monitoring & visualisation | Function: Flow control | Function: Automated voltage & VAR control |
|---|---|---|---|
| Optimised generator operation | | | |
| Reduced generation capacity investments | | | |
| Reduced ancillary service cost | ✓ | | |
| Reduced congestion cost | | | |
| Deferred transmission capacity investments | | | |
| Deferred distribution investments | ✓ | ✓ | ✓ |
| Reduced equipment failures | | ✓ | ✓ |
| Reduced distribution equipment maintenance cost | | | |
| Reduced distribution operations cost | | ✓ | ✓ |
| Reduced meter reading cost | | | |
| Reduced electricity theft | | | |
| Reduced electricity losses | | ✓ | ✓ |
| Reduced electricity cost | | | |
| Reduced sustained outages | | ✓ | |
| Reduced major outages | | ✓ | |
| Reduced restoration cost | ✓ | ✓ | |
| Reduced momentary outages | ✓ | | |
| Reduced sags and swells | | | ✓ |
| Reduced $CO_2$ emissions | | | ✓ |
| Reduced SOx, NOx, and PM10 emissions | | | ✓ |
| Reduced fuel costs | | | |
| Reduced wide-scale blackouts | ✓ | ✓ | |
| Enabled wind generation | NA | NA | NA |
| Enabled solar generation | NA | NA | NA |

NA = not applicable, as these benefits are relevant only for the No Predefined Renewables Goal Approach. See Annex I for details.

### Table 3E: Categories of uncertainty levels

| Level of uncertainty | Explanation |
|---|---|
| Low | A low level of uncertainty in quantitative estimates and/or in monetisation implies a level of precision where the estimate is viewed to be accurate +/- 20%, with at least an 80% level of confidence, *i.e.*, there is an 80% probability that the actual value is within +/- 20% of the estimate. |
| Medium | This category is for estimates viewed to be accurate +/- 40%, with at least an 80% level of confidence, *i.e.*, there is an 80% probability that the actual value is within +/- 40% of the estimate. |
| High | This category is for estimates that are very uncertain and difficult to quantify. The precision level is viewed as +/- 100%, with a 95% level of confidence. |
| Cannot be quantified | This assignment should be limited to benefits that fall into the speculative category and are so uncertain that they can only be expressed as an order-of-magnitude estimate. |

Adapted from EPRI, 2010, as reproduced in Giordano et al., 2012a and 2012b

### Box 6: Ruritania Smart Grid Project: Monetising Benefits

Table 3F shows the estimated value of each benefit for the case of Ruritania, along with brief notes on how the value was estimated and the uncertainty level of the estimate.

For this simple example, many assumptions were made on monetisation input values for illustrative purposes. A full CBA would incorporate more-detailed modelling and forecasting using the best data available to produce the inputs needed to monetise benefits. For example, our assumption that the use of smart PV inverters with volt-VAR control will avoid the need for 200 switched capacitor banks could be confirmed by modelling and simulation of typical distribution feeders in the region using IRENA's grid stability methodology.

All of the benefits have zero value in the first year because the first grid-friendly turbines and inverters are installed that year. The benefit values increase gradually each year as more installations occur, reaching a maximum annual value in year 15.

The largest benefit comes from reduced sustained outages at USD 19 million in year 15, but note that the uncertainty of this benefit is high. The next largest benefit is from reduced electricity losses, coming in at USD 17 million during year 15. Several of the possible benefits checked in Table 3D turn out to have no quantifiable value in this project; this is to be expected.

## Qualitative Benefits

In additional to monetisable impacts, smart grid projects also produce benefits that are more difficult to quantify. These may include improvement of local workforce capabilities, improved safety, greater inclusion of consumers, and other benefits (Giordano et al., 2012a and 2012b). While the availability of skilled workers may present a challenge in developing countries, building skills in the local workforce may be an especially important benefit for the same reason.

When smart grid projects are used to provide electricity to previously unserved (or underserved) areas, a number of significant benefits may come into play that are difficult to put a price on. These include improved health (for example, fewer health issues due to reduced burning of wood, charcoal and kerosene) and improved access to healthcare services and health clinics. Educational benefits due to improved school conditions and the ability to study after dark can also be significant. Entrepreneurial opportunities can also bring significant benefits, allowing people to better provide for their own needs and those of their communities (World Bank, 2014). It may be possible to put a rough quantitative value on the economic benefits of electrification based on various studies by the World Bank and others. However, when deciding whether these benefits are attributable to a smart grid project, it is important to consider the baseline: Often the most appropriate baseline is not lack of electrification but electrification using conventional technologies, in which case the smart grid project would not get credit for the benefits of electrification since they also exist in the baseline case.

When smart grids help reduce electricity theft, this provides a quantitative benefit to the utility (and indirectly to its paying customers), but the loss of access by people who had been stealing electricity is a dis-benefit or cost to those people. This cost may be hard to quantify, but it is worth considering that reduced theft may create a need for subsidised electricity. This qualitative cost will slightly reduce the quantified benefit.

Smart grid technologies tend to be mutually reinforcing, so a significant benefit of a smart grid project is that it provides a basis for future smart grid projects to build upon. For example, if a DA system and associated measurement and control hardware are first installed with a goal of speeding recovery following electrical faults, that same system could later be used for other tasks such as optimizing system voltage to reduce losses (see the exercise in Annex I). The financial payback of the second project will be greatly improved because it uses already existing assets.

Smart grid projects may also enable future renewable energy deployment that is not currently under consideration. Under the Predefined Renewables Goal approach, this characterisation would be renewable deployments that go beyond the preset goal. Under the No Predefined Renewables Goal approach, this characterisation means renewable energy beyond the amount assumed, to be enabled by the smart grid project under the quantitative CBA.

While the benefits considered in this section are difficult to monetise, it is important to try to quantify them to the extent possible to allow for comparison with other projects. For instance, if a project is expected to develop workforce skills, state specifically what skills are expected to be gained and approximately how many people will gain those skills. A detailed method for quantifying benefits that cannot be monetised is provided by the Joint Research Commission (EC, 2012a and 2012b). In Annex III of this report, guidelines are given for applying weighting factors to nonmonetised benefits so that they may be included in the integrated CBA.

Note that the functions and benefits of smart grid technologies are highly interdependent. Hence, the CBA method presented here risks missing some synergistic benefits (or double-counting benefits that are attributed to multiple technologies). System-level analysis can better manage these synergies, but there are few well-developed methodologies for CBA at a system level.[4]

[4] This cautionary note was prompted by Chapter 4 of (IEA, 2014), which similarly cautions against missing system-level effects when tallying individual renewable integration costs.

### Box 7: Ruritania Smart Grid Project: Assessing Qualitative Benefits

The qualitative benefits of the example smart grid project include giving utility workers experience with advanced renewables control technologies. These skills will be transferable to future renewable energy and smart grid projects. The smart PV inverters could also be integrated into future DA schemes, acting as distributed reactive power sources for voltage optimisation, resulting in further loss reductions and investment deferral.

Table 3F: Monetised benefits of the example system

| Benefit | NPV | Uncertainty level | Primary beneficiary |
|---|---|---|---|
| Reduced ancillary service cost | USD 0 in year 1, ramping to USD 3.6M in year 15 | Renewables' ability to ride through voltage and frequency events (thus not exacerbating those events) is assumed to reduce frequency regulation needs by 5%. High-frequency power curtailment from wind, PV, and virtual inertia from wind are assumed to reduce frequency regulation costs by an additional 5%. This benefit starts from zero and ramps to a total savings of 10% over the project life. The demand for frequency regulation is assumed to average 0.65% of load demand based on data from a U.S. transmission operator (Monitoring Analytics, 2013), and the cost of regulation is assumed to be USD 20/MWh, increasing to USD 31/MWh by year 15 due to inflation. Year-15 savings = (20 GW demand) * (0.0065) * (8760 hours/year) * (USD 31/MWh regulation) * (0.10) = USD 3.6M. | Medium |
| Deferred distribution investments | USD 0 in year 1, ramping to USD 1.4M in year 15 | Smart distributed PV inverters performing volt-VAR control are assumed to avoid the need for 200 switched capacitor banks (a conventional source of voltage control) rated at 500 kVAR each, costing USD 13/kVAR (Eaton, 2014) plus USD 1 000 per bank to install. With inflation, this benefit comes to USD 410K in year 15.<br><br>We also assume that 50% of the distributed PV systems are targeted at capacity-constrained distribution feeders, where the peak load coincides well with PV output, providing a benefit of USD 0.001/kWh of PV in deferred distribution investment, in the lower half of the range identified in (Beck, 2009). This benefit comes to USD 940K in year 15 | Medium |
| Reduced equipment failures | USD 0 in year 1, ramping to USD 5 100 in year 15 | Inverter-based volt-VAR control is assumed to reduce annual equipment failures by 10% once the project is complete, due to reduced switching of capacitor banks, which are assumed to be on 15% of existing feeders for a total of 150 banks. The baseline annual failure rate is assumed to be 3%. This benefit ramps from zero to its full value over the project life. Year-15 savings: (150 capacitor banks) * (0.03 baseline failure rate) * (0.1 reduction in failure rate) * (USD 11 000/bank after inflation) = USD 4 950 | Medium |
| Reduced distribution operations cost | USD 0 | While inverter-based volt-VAR control could result in a reduction in manual capacitor switching operations, this benefit is assumed to have negligible value for this project. | Low |

| | | | |
|---|---|---|---|
| Reduced electricity losses | USD 0 in year 1, ramping to USD 17M in year 15 | By providing distributed sources of reactive power, smart distributed PV inverters are expected to reduce distribution line losses by 5% once all are installed. Total distribution losses are assumed to be 7% of the energy delivered. The USD 50/MWh wholesale electricity cost escalates to USD 78/MWh by year 15 given 3% inflation. Year-15 loss reduction = (62 GWh demand) * (0.07 loss rate) * (0.05 loss reduction) = 217 GWh. Year-15 savings: (218 000 MWh) * (USD 78/MWh) = USD 17M | Medium |
| Reduced electricity cost | USD 0 | While it is possible that the use of grid-friendly controls could lead to a reduction in electricity cost, no such reduction is assumed here. | Low |
| Reduced sustained outages | USD 0 in year 1, ramping to USD 19M in year 15 | In this example, by riding through voltage and frequency events and some momentary outages, and by contributing to voltage and frequency regulation, grid-friendly controls are assumed to reduce sustained outages by 1% once fully installed. An average VOLL of USD 3/kWh and an average load per customer of 1 kW are assumed. By year 15, the VOLL will be USD 4.70/kWh due to inflation. The total annual number of outages per customer is estimated by multiplying SAIFI by SAIDI, assuming a SAIFI of 10 outages per year and a SAIDI of 2 hours per outage. Hence the year-15 baseline outage cost is (10 outages/year/customer) * (2 hours/outage) * (USD 4.7/kWh) * (1 kW/customer) = USD 94 per customer. With 20 million customers in year 15, the total value of this benefit that year is (20 million) * (USD 94) * (0.01) = USD 19M. | High |
| Reduced major outages | USD 0 | No reduction in major outages is assumed for this project. | High |
| Reduced restoration cost | USD 0 in year 1, ramping to USD 47K in year 15 | We assume each feeder has 10 outages per year that require manual restoration, and that restoration costs USD 150 in crew time (or USD 235 in year 15). The 1% reduction in outages mentioned above then results in a year-15 savings of (USD 235/outage) * (10 outages/year/feeder) * (2 000 feeders) * (0.01 reduction) = USD 47 000. | High |
| Reduced momentary outages | USD 0 | No reduction in momentary outages is assumed for this project. | Low |

| | | | |
|---|---|---|---|
| Reduced sags and swells | USD 0 | Grid-friendly renewables can inject real and reactive power into the grid during voltage sags to reduce the magnitude of the event. However, because reductions in such events are of quantifiable value only to customers with sensitive loads, and because the effect is very system-specific, we do not assume any value for this benefit. | Medium |
| Reduced $CO_2$ emissions | USD 0 in year 1, ramping to USD 9.3M in year 15 | Because the solar and wind plants themselves are present in the baseline case, their $CO_2$ reduction is not a benefit of the project. However, $CO_2$ reductions from decreased distribution losses due to local reactive power provision by smart inverters are a benefit of the project. Each MWh saved is assumed to save 0.68 tons of $CO_2$ based on a mix of coal, gas, hydroelectric, and renewable sources. Assuming a social cost of carbon of USD 40/ton $CO_2$ (inflated to USD 63/ton by year 15) and following the assumptions in the Reduced Electricity Losses row above, the year-15 benefit is (218 000 MWh) * (0.68 tons $CO_2$/MWh) * (USD 63/ton $CO_2$) = USD 9.3M. | Medium |
| SOx, NOx, and PM10 emissions | SOx: USD 0 in year 1, ramping to USD 800K in year 15; NOx: USD 0 in year 1, ramping to USD 110K in year 15; PM10: USD 0 in year 1, USD 10K in year 15 | Reduced distribution losses due to local reactive power provision also result in reduced SOx, NOx, and PM10 emissions. We assume that each MWh produced from coal emits 5 kg $SO_2$, 3 kg NOx, and 1 kg PM10 on average. We also assume that 30% of the country's electricity comes from coal at the beginning of the project, and that the amount of energy from coal remains constant throughout the project at 9.2 GWh/year. The social costs of each pollutant are assumed to be half of the U.S. market values, or USD 3.15/kg SOx, USD 0.7/kg NOx, and USD 0.2/kg PM10, and are adjusted for inflation. The year-15 value of SOx reductions is (218 000 MWh loss reduction) * (0.15 portion from coal) * (5 kg SOx/MWh) * (USD 4.94/kg SOx) = USD 800K. Similarly, the year-15 values of NOx and PM10 reductions are USD 110K and USD 10K, respectively. | Medium |
| Reduced wide-scale blackouts | USD 0 | By riding through voltage and frequency events and some momentary outages, and by contributing to voltage and frequency regulation, grid-friendly controls can reduce the likelihood of a large blackout. However, we do not assume any quantifiable benefit in this example. | High |

## STEP 5: QUANTIFY COSTS

The first steps differentiate between the costs associated with the baseline, and the costs associated with the smart grid project. The baseline should include all costs associated with operating the electricity system. Costs attributed to the project, in contrast, should be only those that the project imposes or adds. Costs are by definition negative, or outlays; cost savings or reductions should be tracked as benefits.

As with all cost estimations, there are uncertainties, notably:

- Cost overruns, due to lack of field experience with new smart grid technologies.
- Unexpected marketing costs for those technologies requiring consumer participation.
- Integration of new technologies into existing grid systems, involving multiple vendors.

In general, however, these cost uncertainties will be smaller than the benefit-side uncertainties.

### Cost Categories

Costs can be divided into four categories:

- Up-front hardware costs. Also called capital or initial costs, these expenses are one-time costs associated with purchasing the specific technologies.
- Project implementation costs. These costs are associated with installation, marketing, scheduling, project management, commissioning, and other cost components of project implementation.
- Operating and maintenance costs. These expenses are ongoing, with typical units of USD/year or USD/MWh.
- Qualitative costs. These various expenses are difficult to quantify yet still relevant to the analysis.

Typical capital and O&M costs are shown in Table 3G; however, costs are very project-dependent and actual, firm quotes from vendors should be used whenever possible. As discussed in Chapter 2, if there is no

### Table 3G: Categories of uncertainty levels

| Technology | Typical capital costs | Typical O&M costs |
|---|---|---|
| Advanced metering infrastructure | USD 100–150/meter (meter only); USD 200–250/meter including communications and IT systems | USD 0.5–1/meter/month |
| Advanced electricity pricing | Varies; typically low if AMI already installed | Varies; typically low |
| Demand response | USD 100–250/kW capacity | Varies; USD 2–5/kW/year |
| Distribution automation | Depends on specific technology and installation | Depends on specific technology and installation |
| Renewable resource forecasting | None (typically purchased as a service) | Wind forecasting service USD 2 500/month/plant; PV expected to be similar |
| Smart inverters | < 5% more than conventional inverter; < 1% more than conventional wind turbine | Same as conventional technologies |
| Energy storage | Li-ion: USD 500–1 000/kWh; pumped hydro: USD 500–4 000/kW plus USD 0–200/kWh | 1%–2% of capital costs per year |

Sources: Asmus, 2010; Idaho Power Company, 2013; IEA, 2014; IRENA 2013; Ontario Energy Board, 2011; U.S DOE, 2006; authors' estimates explicit renewables goal, then the new renewables that a smart grid project make feasible do not fall under the baseline. In this situation, the costs of the new renewables need to be included in the CBA.

Extensive data on the costs of renewable electricity generating technologies are available at http://costing.irena.org. Typical costs are summarised in Table 3H.

Project implementation costs are very project-dependent. In general, bids from suppliers should specify which specific project implementation steps are included—for example, is the bid for just delivery of a technology, or does it include installation, testing and commissioning, and/or monitoring? Project management costs should be considered as well, particularly if a technology is new and/or will require adding personnel. In general, technologies that are new and/or unfamiliar to an organisation will have higher implementation costs, as new processes and organisational learning will be needed.

Qualitative costs can include management time and attention, risks associated with going over budget or with technical underperformance, and other similar factors that are difficult to assign a monetary value yet are clearly non-zero and need consideration. In some cases, these costs can fall on electricity users. For example, a smart grid project that enables commercial building load reduction may cycle air-conditioning compressors, thereby have a cost of decreased building occupant comfort.

It is simplest to assume that costs all occur at the beginning of the project. However, it may be more accurate to recognise that some costs—particularly project implementation and some types of qualitative costs—can occur throughout the project life. If that is the case, it is necessary to discount those costs and calculate an NPV of the costs.

### Table 3H: Typical renewable energy capital and O&M costs

| Technology | Typical capital costs (USD/kW) | Typical O&M costs (USD/kW/yr) |
|---|---|---|
| Wind power plant (utility-scale) | 1 280-2 200 | 20-40 |
| PV power plant (utility-scale) | 1 300-2 600 | 25 |
| Distributed PV | 1 600-5 000 | 25 |

Sources: IRENA ,2015a; International Renewable Energy Agency Renewable Cost Database.

### Box 8: Ruritania Smart Grid Project: Quantifying Costs

Our example smart grid project involves upgrading wind turbines and solar PV inverters to provide advanced grid support. The first costs for these upgrades are typically given as a percentage increase in the first costs for these inverters. Advanced wind turbines are penetrating the market rapidly, and we assume that this option increases wind turbine first costs by 1%. For PV, we assume that this upgrade increases the cost of the inverter (not the system) by 10%.

We also assume that there are no additional O&M costs for these upgrades. There are costs associated with operating the wind turbines and PV systems, of course; however, these costs are incurred regardless and thus are defined as being in the baseline.

Similarly, we assume that there are no additional project implementation costs. These technologies are commercially available and require little if any additional effort beyond the baseline technology.

## STEP 6: COMPARE COSTS AND BENEFITS

The benefits of a proposed smart grid project, as discussed in Chapter 2, occur over the lifetime of the project. The costs, in contrast, typically involve a large outlay at the beginning of the project, possibly followed by a much smaller annual spending for O&M. So, how can the different costs and benefits occurring at different times be compared and assessed? Fortunately, there are several financial analysis tools for such a problem.

Net present value (NPV) is a simple and transparent indicator of overall costs and benefits. To calculate NPV, all future financial costs and benefits are transformed into an equivalent current-day cost or benefit. Future costs and benefits are discounted to reflect the time value of money and/or the appropriate societal discount rate. This combines all the costs and benefits into one number, which can be thought of as the current-day value of the entire project. If this value is positive, it can concluded that the project is cost-effective without consideration of the qualitative factors.

Benefit/cost ratio is a variation on NPV where all benefits and costs are discounted and summed to a current-day equivalent. Then a simple ratio of benefits to costs is calculated. If the ratio is greater than 1.0, then it can be concluded that the project is cost-effective without consideration of the qualitative factors.

Cash flow analysis is a third method. The costs and benefits that occur in each year to provide a clear sense of the timing of the costs and benefits, and lends itself to a graphical summary of the project's finances.

### Stakeholder Perspectives

Including all costs and benefits in an NPV or benefits-to-costs ratio calculation implicitly assumes a societal perspective. A stakeholder perspective, in contrast, may intentionally exclude some costs and benefits. The utility, for example, may not value reduced $CO_2$ emissions, and therefore could leave the $CO_2$ reduction benefit out of the analysis. When performing a stakeholder CBA, it is useful to look at the list of costs and benefits, and exclude those that are not relevant or not valued.

### Box 9: Ruritania Smart Grid Project: Comparing Costs and Benefits

In our example, we assess the costs and benefits of smart PV inverters and advanced grid support from wind turbines. We found eight distinct non-zero benefits of these specific smart grid technologies (see Table 3F). The NPV of each of those benefits is shown in Table 3I.

### Table 3I: NPV of benefits in example CBA

| Benefit | NPV (million USD) |
|---|---|
| Reduced ancillary service cost | 4.3 |
| Deferred distribution investments | 2.3 |
| Reduced equipment failures | <0.1 |
| Reduced electricity losses | 17.6 |
| Reduced sustained outages | 28.6 |
| Reduced restoration cost | <0.1 |
| Reduced $CO_2$ emissions | 9.6 |
| Reduced non-$CO_2$ emissions | 1.1 |
| TOTAL | 63.6 |

In Table 3H, we estimated the costs of these technologies. The NPV of those costs are summarised in Table 3J.

### Table 3J: NPV of costs in example CBA

| Cost | NPV (million USD) |
|---|---|
| Advanced inverters for PV | -23.8 |
| Advanced inverters for wind | -14.2 |
| TOTAL | -38.0 |

Note: Values shown are negative, as they are costs.

The net benefit, excluding qualitative factors, is (63.6 – 38.0) = USD 25.6 million. The benefit-to-cost ratio is (63.6/38.0) = 1.67. This project is cost-effective.

### Incorporating Qualitative Costs and Benefits

As discussed throughout this report, qualitative costs and benefits should be tracked through the analysis. When the final result (for example, NPV) is calculated, it should be shown along with the list of qualitative costs and benefits to decision-makers.

One way to incorporate these factors into the analysis is to consider the direction and magnitude these factors would need to change in order to alter the result. In our example, we found that the project had a net benefit of USD 25.6 million and further identified workforce training as an additional qualitative benefit. In this case, there is no need to attach a number to this workforce training benefit, as the project is already cost-effective without considering it.

Think about a different case, in which the proposed project had a net benefit of USD 2.8 million (meaning it was not cost-effective). In this case, the workforce training benefit would need to be worth at least USD 2.8 million to change the outcome of the CBA. This process helps to clarify and bound the qualitative factors.

## STEP 7: SENSITIVITY ANALYSIS

Once a final result, either a NPV or benefit-to-cost ratio is obtained, it is very useful to go back and perform a sensitivity analysis, which is an assessment of how the results vary when various inputs and assumptions are changed. When doing so, focus on those inputs and assumptions that are both uncertain and significant, meaning they strongly influence the results.

As shown in the example above, changing the assumption about the value of reduced outages changes the final result from a positive NPV to a negative NPV. This illustrates the value of the CBA process. If, in this example, decision-makers want to incorporate electricity users' valuation of the benefits, then the project appears to be cost-effective (meaning it has a positive NPV). If, on the other hand, decision-makers want to take a utility perspective, then the project does not appear to be cost-effective. (This places no value on the qualitative benefits.) There is no correct answer here; the conclusion depends on what values and perspective decision-makers want to adopt.

A similar process could be pursued for other inputs and assumptions that are deemed uncertain and critical. An interesting question, for example, might be to calculate the cost assumptions that result in an NPV of 0. If decision-makers are confident that costs will fall below that assumption, then they could be reasonably sure that the project overall will have a positive NPV.

### Box 10: Ruritania Smart Grid Project: Sensitivity Analysis

As shown in Table 3I, reduced sustained outages and reduced electricity losses are the largest components of the benefits NPV. As discussed in Chapter 3, a critical assumption in estimating the benefits of reduced sustained outages is the value of this reduction to electricity users. The results in Table 3I assume a value of USD 3 for each kWh reduction in sustained losses. That value is based on a meta-analysis of a large number of studies. Note, however, that this USD 3/kWh value reflects the electricity users' perspective. The utility, in contrast, might value these reduced outages as worth only the regained electricity sales they yield—that is, at the current retail rate of electricity. As shown in Table 3K, changing the value of these outage reductions from USD 3/kWh to USD 0.10/kWh changes the NPV from +USD 28.6 million to –USD 2.0 million.

### Table 3K: Comparing value from societal and utility perspectives

| Perspective | Assumed value of reduced outage | Resulting NPV of reduced sustained outages benefit | Final net NPV, reflecting all benefits and costs |
|---|---|---|---|
| Society | USD 3/kWh | USD 28.6 million | +USD 25.6 million |
| Utility | USD 0.10/kWh | USD 1.0 million | –USD 2.0 million |
| TOTAL | | | -38.0 |

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# Summary


Smart grid projects in developing countries can enable higher levels of renewables on electricity grids, but these projects need to be rigorously evaluated to determine if their benefits exceed their costs. CBA defines and evaluates those costs and benefits, and can help decision-makers better allocate capital.

Defining and quantifying the benefits of a proposed smart grid project is complex and challenging. However, breaking it down into a series of logical and ordered steps simplifies the process and clarifies the assumptions and uncertainties.

Smart grid project costs can be estimated using published data and/or vendor estimates. The uncertainties are generally smaller than for benefit-side estimates, although qualitative and project implementation costs are project-specific and thus may require additional analysis.

Combining costs and benefits is a straightforward financial calculation. Qualitative costs and benefits can be incorporated by calculating the values they would need in order to change the net benefits from positive to negative (or from negative to positive). Similarly, sensitivity analysis can be used to show how net benefits vary with input assumptions.


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# List of Abbreviations

AC – alternating current

AMI – advanced metering infrastructure

C&I – commercial and industrial

CBA – cost-benefit analysis

CCGT – combined-cycle gas turbine

$CO_2$ – carbon dioxide

DA – distribution automation

DC – direct current

DR – demand response

DSM – demand-side management

DOE – Department of Energy

EPRI – Electric Power Research Institute

EU – European Union

GDP – gross domestic product

GW – gigawatt(s)

GWh – gigawatt-hour(s)

hr - hour

IEA – International Energy Agency

IEEE – Institute of Electrical and Electronics Engineers

IITC – IRENA Innovation and Technology Centre

IRENA – International Renewable Energy Agency

ISO – independent system operator

JPS – Jamaica Public Service Company

JRC – Joint Research Centre

K – thousand

kg – kilogram(s)

km – kilometer(s)

kVAR – kilo-volt-ampere reactive

kW – kilowatt(s)

kWh – kilowatt-hour(s)

LCOF – levelised cost of flexibility

LV – low voltage

M – million

MV – medium voltage

MVAR – mega-volt-ampere reactive

MVAR-hr – mega-volt-ampere reactive-hour

MW – megawatt(s)

MW-hr – megawatt-hour(s) (used for ancillary services)

MWh – megawatt-hour(s) (used for energy)

NOx – nitrogen oxide

NPV – net present value

NRC – National Research Council

O&M – operations and maintenance

OECD – Organisation for Economic Cooperation and Development

PM10 – particulate matter less than 10 micrometers in diameter

PV – photovoltaic

RE – renewable energy

SAIDI – system average interruption duration index

SAIFI – system average interruption frequency index

SE4All – International Year of Sustainable Energy for All

SCC – social cost of carbon

SOx – sulfur oxide

T&D – transmission and distribution

TOU – time of use

UN – United Nations

U.S. – United States

USD - United States dollars

VAR – volt-ampere(s) reactive

VOLL – value of lost load

volt-VAR – voltage-volt-ampere reactive

VVO – volt-VAR optimisation

yr - year

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This report is supported by a number of annexations, which are available online.

Annex I: Ruritania Case Study: Distribution Automation Programme with no Predefined Renewables Goal Approach

Annex II: Jamaica Case Study: Demand Response Programme With a Pre-Defined Renewables Goal

Annex III: Methods of Benefit Valuation

Annex IV: List of Smart Grid technologies for Renewable

Annex V: Smart Grids for Renewables: Real Case Studies

Annex VI: Glossary

Annex VII: Bibliography

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