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UNCERTAINTY IN BENEFIT-COST ANALYSIS OF SMART GRID DEMONSTRATION PROJECTS IN THE U.S., CHINA, AND ITALY

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1. Introduction

Early in this century, it became clear that the technology embedded in the developed world's electricity supply system had become seriously inadequate to cope with the challenges that we are facing, and to generally meet rising expectations for grid performance, often assumed necessary to support the emerging digital economy (Tapscott, 1995). *Smart grid* emerged as an umbrella term to describe a number of technologies that had mostly already been proposed or actually developed separately, but which had failed to gain broad deployment. The notable example is advanced metering infrastructure (AMI), whose capabilities had been recognized as necessary for several decades. The motivations for smart grid can be boxed into three types. The first involves establishing an appropriate AMI infrastructure to enable price-elastic demand, and hence an efficient market. The second concerns improved operation of the legacy centralized grid. And the third, and perhaps most radical, leg of the smart grid stool is decentralized control of the power system, i.e. microgrids and community power (Marnay and Lai, 2012).

Given the substantial investments required, there has been keen interest in conducting benefits analysis, i.e., quantifying, and often monetizing, the performance of smart grid technologies. Analysis to calculate and publicize these results has been a central objective in many jurisdictions. Smart grid projects are typically characterized by high initial costs and uncertain benefit streams over the long-term. Making a decision with long-term implications requires a thorough understanding of likely or possible future situations and also the ability to balance a large number of controllable and uncontrollable parameters (Bhushan and Rai, 2009). Thus, there is a need for common method development and application. In this study, we compare two different approaches; (1) Electric Power Research Institute (EPRI)'s benefits analysis method and its adaptation to the European contexts by the European Commission, Joint Research Centre (JRC), and (2) the Analytic Hierarchy Process (AHP) and fuzzy logic decision making method. These are applied to three case demonstration projects executed in three different countries; the U.S., China, and Italy, considering uncertainty in each case. The U.S. (United States) example demonstration is Southern California Edison (SCE)'s Irvine smart grid Demonstration Project (ISGD), which is an American Recovery and Reinvestment Act (ARRA) project within the under the smart grid Regional Demonstrations (SGRD). This project is evaluated with EPRI Benefits Analysis method. The China demonstration covers several smart grid aspects of a Sino-Singapore endeavor in Tianjin, called here the Tianjin Eco-city project. This project is evaluated using AHP together with fuzzy logic, a method developed by State Grid Corporation of China (SGCC). The Italy demonstration involves a pilot project in Rome conducted by ACEA, Italy's third largest Distribution Network Operator (DNO). This project is evaluated with JRC Cost Benefits method, which is a derivative of the same approach used ISGD.

This work is conducted under the U.S.-China Climate Change Working Group, smart grid, with an additional major contribution by the European Commission. The following is a brief description of the three demonstration projects.

a. Tianjin Eco-city

Eco-City is located in an important strategic area of about 30 km², within the Tianjin Binhai New Area. The Eco-city demonstration project involves six *domains* of an energy system (generation, transmission, substation, distribution, electricity supply-scheduling, and the communication-information platform), thus covering the power supply side, the grid side, and the electricity end use side. There are twelve Sub-projects within these six domains, only 3 of which, shown *italics* below, are included in this analysis, as shown below:

- Sub-project 1: Distributed power supply side access
- *Sub-project 2: Microgrid with energy storage*
- *Sub-project 3: Smart substation*
- *Sub-project 4: Distribution automation*
- Sub-project 5: Equipment integrated monitoring system
- Sub-project 6: Power quality monitoring system
- Sub-project 7: Visualization platform.
- Sub-project 8: Information collection system
- Sub-project 9: Intelligent Community / building
- Sub-project 10: Electric Vehicle (EV) charging facilities
- Sub-project 11: Intelligent operating room
- Sub-project 12: Communication and information network

Tianjin Sub-Project 2: Microgrid with Energy Storage

The microgrid and energy storage system is composed of a 30 kW photovoltaic (PV) array, 6 kW of wind turbines, 15 kW × 4 h of lithium-ion batteries, 5 kW of electricity for lighting, 19 kW of EV charging. This total 15 kW microgrid load has intelligent control and economic operation using a microgrid energy management system. The system includes distributed power sources, an energy storage system, an energy management system, a distribution system, harmonics reduction and reactive power compensation, load control, and micro-network protection systems. The energy management system includes the two distributed power sources, the energy storage inverter, microgrid intelligent terminals, the microgrid system controller. An operator station running on a host server is used to deliver microgrid system optimization scheduling, and meet security and stability requirements.

Tianjin-Sup-project 3: Smart Substation

The smart substation is one of the crucial smart grid installations to achieve energy conversion, and control of the core platform is an important part of the smart grid, as it allows the integration of new energy sources like wind and solar into the grid. The smart substation covers smart grid power generation, a transmission substation, key distribution feeders, and scheduling. A 110 kV substation, Cheong Road, uses electronic transformers, primary equipment on-line monitoring, and other intelligent devices; a network of secondary equipment, 110 kV line protection and monitoring, with three layers of the two networks, and direct monitoring using the IEC61850 communications standard and unified messaging platform technology.

Tianjin Sub-Project 4: Distribution Automation

Tianjin Eco-city intelligent distribution automation system relies on a strong distribution network grid, a power distribution master station with electronic stations, distribution terminals, and communications channels. A complete distribution network SCADA (Supervisory Control and Data Acquisition) system manages control functions, and self-healing features, such as intelligent analysis, flexible operation mode, and RES access requirements to the grid. Data exchange with the automated dispatching system, generation management systems, a geographic information system, marketing and management systems, and other business systems allow achieving business operations in line with modern power intensive business processes. Regional planning started construction of 110 kV substation 1 (Cheong Road substation), the 10

kV feeder 36. Distribution Site Planning region totaled 123 construction items, including 52 distribution stations, and 15 switching stations. Since Cco-city has been developed together with the construction of a new city, build out of the distribution network will be combined with urban development of the area.

b. Irvine smart grid Demonstration

SCE operates the ISGD project primarily in the California's Orange County City of Irvine, Many of the project components are located on or near the University of California, Irvine (UCI) campus, which is 60 km southeast of the Los Angeles airport (LAX). The project includes four *domains*. Each domain includes one or more sub-projects with distinct objectives, technical approaches, and research plans. There are eight Sub-projects within these four domains, only 3 of which, shown *italics* below, are included in this analysis, as shown below:

- Smart Energy Customer Solutions (Sub-projects 1 & 2)
 - Sub-project 1: Zero Net Energy Homes (ZNE)*
 - Sub-project 2: Solar Car Shade
- Next-Generation Distribution System (Sub-projects 3, 4, 5 & 6)
 - Sub-project 3: Distribution Circuit Constraint Management Using Energy Storage*
 - Sub-project 4: Distribution Volt/VAR Control (DVVC)*
 - Sub-project 5: Self-healing Distribution Circuits
 - Sub-project 6: Deep Grid Situational Awareness
- Interoperability & Cybersecurity (Sub-project 7 only)
- Workforce of the Future (Sub-project 8 only)

Irvine-Sub-project 1: Zero Net Energy Homes

Customers are modifying how they consume and, increasingly, generate electricity. The project uses one block of 9 homes to evaluate strategies and technologies for achieving ZNE. A building achieves ZNE when it produces at least as much (usually renewable) on-site energy as it consumes over a given period, typically on an annual basis. The concept of ZNE buildings is widespread and has been incorporated into California's next Title 24 building code, effective in 2017 (CEC-CPUC, 2015). The project is also seeking to understand the impact of ZNE homes on electric grid performance.

ZNE Homes in this domain includes a variety of technologies designed to directly reduce energy use, e.g. solar water heaters, to help empower customers to make informed decisions about their energy production and use, e.g. programmable appliances, and to improve grid performance, e.g. demand response capability. Sub-project 1 involves a residential neighborhood with four blocks of homes on the UCI campus used for faculty housing¹. ISGD has equipped three blocks of homes with an assortment of advanced energy components, including smart devices capable of demand response, energy efficiency upgrades (see Table 3), energy storage, and rooftop solar PV arrays. The fourth block is aimed to provide baseline data in benefits analysis, although in this work a time series comparison is used. Three levels of home retrofits are as follows:

1. Zero Net Energy (ZNE) block (9 homes)
 - a) Demand response devices
 - b) Energy efficiency upgrades
 - c) Residential energy storage units (4 kW/10 kWh)
 - d) Solar PV arrays (~3.9 kW)
2. Residential Energy Storage (RESU) block (6 homes)
 - a) Demand response devices

¹ There are total of 38 homes on 4 blocks participated to Sub-project 1: 9 of 9 homes on ZNE block, 6 of 8 homes on RESU block, 7 of 9 homes on CES block, and 16 of 20 homes on control block to provide baseline data.

- b) Residential energy storage units (4 kW/10 kWh)
- c) Solar PV arrays (3.2-3.6 kW)
- 3. Community Energy Storage (CES) block (7 homes)
 - d) Demand response devices
 - e) Community energy storage unit (25 kW/50 kWh)
 - f) Solar PV arrays (3.2-3.6 kW)

ISGD is evaluating two types of residential-scale batteries in this neighborhood, and additionally, a utility-scale battery was demonstrated in Sub-project 3, as described more detailed below. All batteries used in ISGD are Li-ion, but from 3 separate vendors. Individual residential energy storage units have been installed in 15 homes as mentioned above, and they are being evaluated using a variety of control modes. In addition, 7 homes share a community battery, which is also being evaluated using a variety of control modes. Both devices can provide load leveling, storage of daytime PV output for later use, and a limited amount of backup power during electricity outages.

Irvine-Sub-project 3: Distribution Circuit Constraint Management Using Energy Storage

This project domain includes a distribution-level battery energy storage system (DBESS) to help prevent a distribution circuit load from exceeding a set limit, to mitigate overheating of the substation getway, and reduce peak load on the circuit. The DBESS, which has a rating of 2 MW of real power and 500 kWh of energy storage, connected to the Arnold 12 kV distribution circuit. This circuit receives power from MacArthur Substation and is the same circuit where the project test homes in sub-project 1 are located.

Irvine-Sub-project 4: Distribution Volt/VAR Control

DVVC optimizes the customer voltage profiles in pursuit of conservation voltage reduction. A 1 % voltage reduction potentially yields an approximate 1 % reduction in customer energy consumption, in most cases. This often proposed measure is required in California where the voltage should be maintained as close as possible to the minimum acceptable level, nominal voltage minus 5 %, and nominal, i.e. between 114-120 V, at the customer connection. While maintaining the voltage closer to its minimum acceptable level is simple and attractive in principle, it proves quite difficult to implement accurately in the field. DVVC technology significantly improves capability, and can also provide VAR support to the transmission system, i.e. control high voltages to maximize capacity. The DVVC application underwent multiple rounds of factory testing and site acceptance testing, and is now operating on seven distribution circuits out of MacArthur Substation. Field experiments showed an average 2.6 % energy savings making this demonstration a major success, and SCE intends to gradually roll the technology out system wide; however, it may not be applicable to all distribution networks depending on pre-existing equipment.

c. City of Rome

The project was conducted between 2011 and 2014 in the Malagrotta area, west of Rome, and involved the installation of new technical solutions on 6 feeders, about 69.5 km of medium voltage (20 kV) and low voltage (8.4 kV) lines, both underground and aerial. The selected grid portion presents several characteristics that well represent future smart grid challenges: in addition to managing different voltage levels (from 2 primary substations to 76 secondary substations): there are 4 distributed generation plants directly connected at MV (1 PV array and 3 biomass plants accounting for about 20 MW of installed capacity), and 7 users directly connected to the MV grid accounting for about 3.5 MW of load by electric vehicles and batteries. These latter are meant to be used for several purposes: back-up during short-term interruptions, peak shaving and compensation for PV fluctuation. All the solutions tested are meant to be rolled out throughout Rome's electricity network, starting in 2015. The project is made up of 3 main additive components:

1. *MV grid automation* focuses on enabling the automatic selection of fault line segments, and allows remote distributed generator management based on actual grid conditions

2. At both MV and LV levels, ACEA set up a *remote control and monitoring* system that allows remote operation of more than 60,000 switches. This sub-project included real-time measurements at secondary substations including technical characteristics of the grid at both voltage levels.
3. Centrally, the development and set up of a new *grid management algorithm* will allow further benefit capture from sub-projects a and b, allowing: load flow management, optimization of load profiles, and minimization of technical losses.

One key aspect of the Malagrotta project is the speed of telecommunication infrastructure required to implement the automatic fault detection. Two MV substations should be able to communicate within the 10 ms range, therefore ACEA chose to test a HyperLAN that was the first choice in terms of communication system, other solutions as optic fiber, LTE, PLC (Power Line Carrier).

The project was shaped under a favorable regulatory regime set up by the National Regulatory Authority, Autorita per l'energia elettrica, il gas e i servizi idrici,(AEEGSI) that in 2010 provided for a particularly favorable incentive for smart grid pilot projects testing innovative solutions at medium voltage level. The Italian regulatory framework for DNOs has three main incentive components: an output regulation, setting monetary rewards and penalties for quality of supply performance (reliability), i.e. in terms of SAIDI and SAIFI, while the DNO can recover its usual operational costs (OPEX) through the CPI-X mechanism. For investments (CAPEX), operators recover through the network tariff at a pre-determined rate of return that corresponds to an extra Weighted Average Cost of Capital that for smart grid projects is set at an additional 2% on top of the usual Rate of Return, defined for each regulatory period by AEEGSI for any infrastructural investment.

2. Methods

Demonstration and deployment of smart grid technologies and related practices 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 accurate well-defined and consistent methods. Such analyses are critical for ensuring that the capital is invested wisely and a balance between economic, social, and environmental targets is secured. Estimating the benefits of smart grid demonstration projects is challenging since social and environmental aspects are not always easy to incorporate into an analysis. Literature on benefits analysis of smart grid projects is fairly new, and largely began because of the need to evaluate the US's ARRA projects. The following is a brief description of the benefits analysis methodologies that have been used to analyse the three projects covered in this study.

a. Benefit Analysis with AHP and Fuzzy Logic (Tianjin Eco-city)

smart grid Multi Criteria Analysis (SG-MCA) is a method combining AHP and fuzzy logic to assess the benefits of smart grid projects. This method defines a decision matrix to represent the expert opinion in an organized way without need of any conciseness test, thereby incorporating the vagueness of expert judgment. Compared to the conventional approach, it combines both the fuzzy set theory and AHP by using triangular fuzzy numbers instead of numerical values, i.e., 1 to 9.

The Tianjin Eco-city smart grid demonstration project includes *six parts and one platform* of power generation, transmission, transformation, distribution, consumption, plus dispatch and communication. It covers all processes of the distribution network, and is the first comprehensive smart grid project has been constructed and operated in China. This demonstration project can improve the security, reliability, environmental protection, and practicality of the power grid by the construction of an intelligent substation, a power distribution automation system, and other power grid technologies.

According to SG-MCA mentioned above, a general evaluation index system for the integrated demonstration project is put forward, and 4 large and 17 small classifications of 45 evaluation indexes are established. In addition, the synthesis evaluation method is adopted to establish the index weight for the 4 large and 17 small classifications.

Tianjin Sub-Project 2:

(1) Technology:

The microgrid is equipped with a power quality monitoring system, which can track conditions and automatically control the system. The frequency and voltage were maintained within limits 100% of the time, resulting in an excellent technology index.

(2) Social:

Firstly, the microgrid is near to load so transmission energy losses are relatively small. Secondly, renewable energy sources, such as solar and wind, can substitute for fossil energy. The microgrid can save 16.2 t of standard coal and 54 t of CO₂ annually. At the same time, the application of PV, fans, inverters and other equipment stimulates the development of related industries.

(3) Economy:

The microgrid can generate 54 MWh/a. It can shift the peak and fill valley load, effectively decreasing installed generation, conductor and transformer capacity. PV and wind generation can also save generation costs, but the cost of batteries is high, so microgrids with energy storage lack a reasonable business model. They cannot be promoted at large-scale, and their economy index is relatively poor.

(4) Practicality:

The microgrid pilot system has already operated safely and stably for three and a half years. The entire system runs well, and the efficiency of power generation meets the expected goal. The completeness and operation of this microgrid has accumulated precious experience of microgrid and energy storage operation, including planning and design, construction, technology assessment, standards establishment, operational control, plus repair and maintenance; therefore, this sub-project has good practicality.

Tianjin Sub-Project 3:

(1) Technology:

Using fiber optics to transmit signals can reduce low voltage cabling, and using advanced application functions, such as sequential control and source maintenance, can reduce intermediate link operation and improve reliability. The primary equipment visualization and auxiliary control system is convenient for management of equipment and prolonging equipment life.

(2) Social:

The construction of an intelligent substation increases the reliability of power supply, reduces operations and maintenance cost, promotes the application of intelligent transformers, intelligent high voltage switching, and other auxiliary intelligent equipment. It is also conducive to the development of related equipment manufacturing.

(3) Economy:

As the equipment is highly integrated and standard components are installed on the spot, intelligent substations have a lower footprint and cause less construction disruption. Its operating and maintenance cost is also lower than a conventional substation. Construction time is 10% less, the substation footprint is reduced by 10.9%. the required construction area is about 11.2% less, the two cables lengths were decreased by 40.4%, and the maintenance workload is decreased by 30%.

(4) Practicality:

The operation of the Hechang Road intelligent substation effectively guarantees power supply in the Eco-city. It also establishes an effective equipment maintenance and management system, operation system operation, and substation control integration. It improves the reliability of power supply, and has provided a successful sample that can be copied for follow-up intelligent substation operation and maintenance.

Tianjin Sub-Project 4:

(1) Technology: Distribution automation has used self-healing, DG access control and other technologies, leading to a 100% score.
(2) Social: The project promotes the secure access to the microgrid by DG, e.g. solar and wind power. It also promotes energy saving and emission reduction, can decrease fuel consumption by 324 t/a, save 1856 t of standard coal, and reduce emissions by 6179 t of CO ₂ . Meanwhile the application of intelligent equipment, like intelligent transformer sand intelligent distribution terminals, promotes the development of equipment manufacturing and IT.
(2) Economy: The implementation of the project can improve the reliability of power supply in the region, reduce the average outage time and line losses; however, if the distribution automation requires a high standard of whole cable double loops, the construction cost is relatively high, so the economy is not ideal at present.
(3) Practicality: The project has been put into use in the Eco-city, and its self-healing function has been proved in the field. It also has established a sound operation management system, encouraged many standards, such as for the distribution automation switching station operation rules, has improved power distribution reliability and has high customer satisfaction, so it has high practicability.

The weight of technical, social, economic, and practical indices determined by the above methods are shown in Table 1 in detail.

Table 1 Smart grid integrated demonstration project evaluation index system (Source: This study)

Tianjin Sub-Project 2					
Technical index (60%)	Advancement	24%	Social index (10%)	Greenhouse-gas reductions	10%
	Security	12%			
	Reliability	6%			
	Interactivity	18%			
Practical index (15%)	Practical level	6%	Economic index (15%)	Economic benefits	10%
	Operation and management level	9%		Cost control	5%
Tianjin Sub-Project 3					
Technical index (60%)	Completeness of basic functionality	30%	Social index (10%)	Save energy	8%
	Advancement	30%		Social impact	2%
Practical index (15%)	Equipment operation management	10%	Economic index (15%)	Economic benefits	10%
	Operation and management system	5%		Cost control	5%
Tianjin Sub-Project 4					
Technical index (58%)	Foundation platform	34%	Social index (12%)	Excellent service	12%
	Advancement	24%			
Practical index (15%)	Management system	10%	Economic index (15%)	Economic benefits	10%
	Talent team	5%		Cost control	5%

b. Benefit Analysis with EPRI Methodology and JRC Methodology (ISGD and Rome)

Both EPRI and JRC approaches define benefit as a monetized value of the impact of a smart grid project to a firm, a household, or society in general. All the benefits must be expressed in monetary terms. For smart grid systems, there are four fundamental categories of benefits, as identified by EPRI:

- Economic – reduced costs, or increased production at the same cost, that result from improved utility system efficiency and asset utilization
- Reliability and Power Quality – reduction in interruptions and power quality events
- Environmental – reduced impacts of climate change and effects on human health and ecosystems due to pollution
- Security and Safety – improved energy security (i.e., reduced oil dependence); increased cyber security; and reductions in injuries, loss of life and property damage

There are multiple stakeholders involved in smart grid development, *consumer*, *utility*, and *society* as a whole. It needs to be noted that different stakeholders might have different focuses and shares of those benefits. The *consumer* and *utility* would share the economic benefits, the *utility* captures most of the reliability benefits, while environmental and security benefits accrue to *society* at large. The benefits analysis in the EPRI method is based on the difference between the benefits and costs associated with a baseline scenario, which represents the system state without the smart grid demonstration project, and a contrasting project scenario.

In general, benefits are reductions in costs and damages (such as deferred capacity investment, reduced electricity purchases, reduced or deferred transmission and distribution (T&D) investment, lower operation and maintenance, reduced transmission congestion, improved power quality, and reduced environmental insults), whether to firms, consumers or to society at large.

The logic of both methods starts from a listing of smart grid assets, then identifies the functions of those assets, and ultimately monetizes project benefits, as shown in Figure 1. In the U.S., this sequence forms the basis of the Department of Energy’s benefits calculator, the smart grid Computational Tool (SGCT). The first step is to list all the smart grid assets deployed in the project for evaluation, for example, *Distribution Automation*, *Smart Appliances and Equipment (Customer)*, etc. Step 2 is to identify the functions of each asset, for example, *Distribution Automation* can provide *Power Flow Control*, *Automated Feeder and Line Switching*, *Automated Islanding and Reconnection*, *Automated Voltage and VAR Control*, and so on. Step 3 is to map the benefits of each of those functions. Step 4, the last step, is to monetize all the benefits. One function might have multiple benefits, therefore, all should be summed up to estimate the project’s total monetized value.

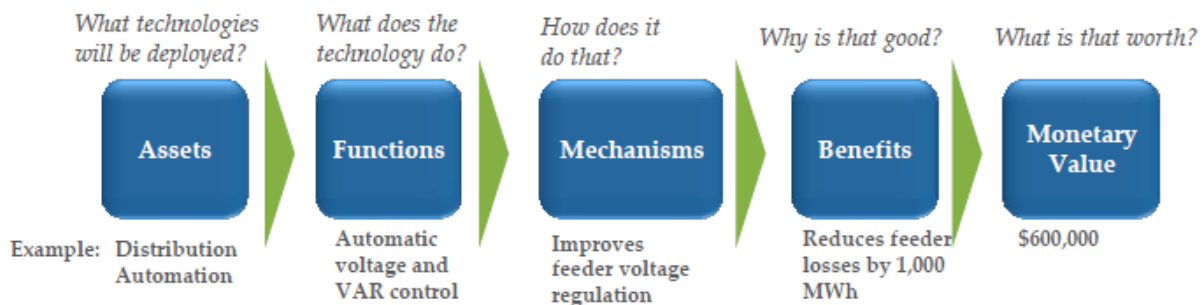



Figure 1 The logic flow of the SGCT (Source: EPRI, 2010)

Smart Grid Assets	Functions													
	Delivery											Use	Other	
	Fault Current Limiting	Wide Area Monitoring, Visualization, and Control	Dynamic Capability Rating	Power Flow Control	Adaptive Protection	Automated Feeder and Line Switching	Automated Islanding and Reconnection	Automated Voltage and VAR Control	Diagnosis & Notification of Equipment Condition	Enhanced Fault Protection	Real-time Load Measurement & Management	Real-time Load Transfer	Customer Electricity Use Optimization	Storing Electricity for Later Use
Advanced Interrupting Switch														
AMI/Smart Meters														
Controllable/regulating Inverter														
Customer EMS/Display/Portal														
Distribution Automation														
Distribution Management System														
Enhanced Fault Detection Technology														
Equipment Health Sensor														
FACTS Device														
Fault Current Limiter														
Loading Monitor														
Microgrid Controller														
Phase Angle Regulating Transformer														
Phasor Measurement Technology														
Smart Appliances and Equipment (Customer)														
Software - Advanced Analysis/Visualization														
Two-way Communications (high bandwidth)														
Vehicle to Grid Charging Station														
Very Low Impedance (High Temperature Superconducting) cables														
Distributed Generator (diesel, PV, wind)														
Electricity Storage device (e.g., battery, flywheel, PEV etc)														

Figure 2 Mapping assets into functionalities in EPRI methodology

In the adapted methodology by JRC, the level of detail of assets, functionalities and benefits are different, in order to take into account the contribution of each single physical asset constituting the project and its impact on the total benefits, as shown in Figure 3 below.



ASSETS	Integrate users with new requirements		Enhancing efficiency in day-to-day grid operation				Ensuring network security, system control and quality of supply					Better planning of future network investment			Improving market functioning and customer service				More direct involvement of consumers in their energy usage																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33		
Energy Box	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
HAN Module																																			
Distribution Transformer Controller (DTC)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
DTC Cell Module				*																															
DTC Wave Quality Module		*	*			*	*	*	*	*								*																	
InovGrid Infrastructure Management	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Meter Data Management (MDM)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Energy Data Management (EDM)							*	*											*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
DSO Webportal	*	*																	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Supervision Module	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Meter Asset Management (MAM)							*	*										*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
Distribution Management System (DMS)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Figure 3: mapping assets into functionalities in JRC methodology

3. Results

In this paper, aspects of the three actual demonstrations are analyzed: (1) ISGD Project in Southern California, (2) the Tianjin Eco-city project in northeastern China, and (3) the Malagrotta project in Rome.

a. Tianjin Eco-city

The overall performance of the Tianjin Sub-Project 2 (i.e., microgrid) is good, but the economy is relatively poor. The overall score is 89, and the scores of technical social economic and practical indices are 98, 75, 58, and 90 as shown in Figure 4.

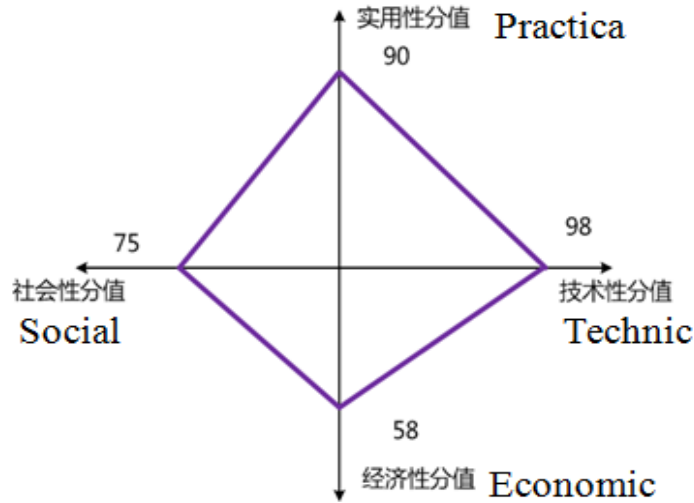


Figure 4 Radar map of overall evaluation of the Tianjin Sub-Project 2

The overall performance of Tianjin Sub-Project 3 (i.e., smart substation) is good, but the economy and sociality index are relatively poor. The overall score is 89, and the scores of technical social economic and practical index are 94, 80, 70, and 96 as shown in Figure 5.

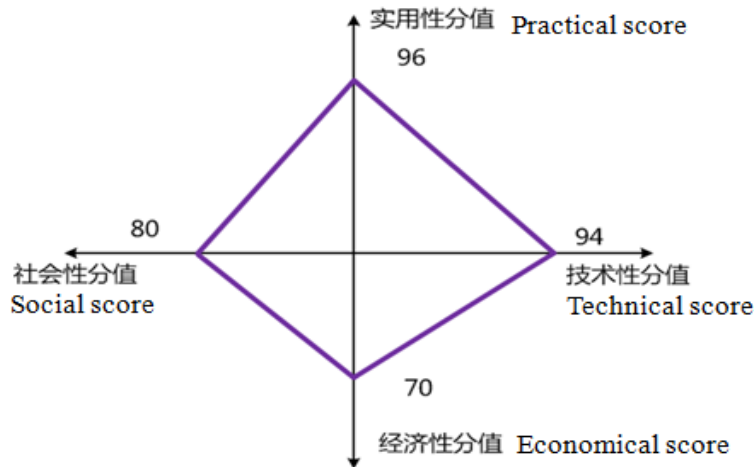


Figure 5 Radar map of overall evaluation of the intelligent substation

The overall performance of the Tianjin Sub-Project 4 (i.e., distribution automation) system is good, but the economy is relatively poor. The overall score is 85, and the scores of technical social economic and practical index are 94, 86, 55, and 92 as shown in Figure 6.

For the economic benefits of a smart project, the evaluation system should consider both the direct economic factors (e.g., return on investment, payback period, and line loss reduction) and the effect of promoting the development of relative industries by encouraging more companies to participate in building smart grid and changing the business direction to the area of advanced technologies. In fact, smart grid has tremendous market potential for manufactures to make considerable profits by producing smart grid equipment, systems, and services; however, smart grid development is still in its early stage, and the promotional benefit is trivial. In the next decade, as the growth of smart grid markets, the effect could be significant and should be considered in a smart grid evaluation approach.

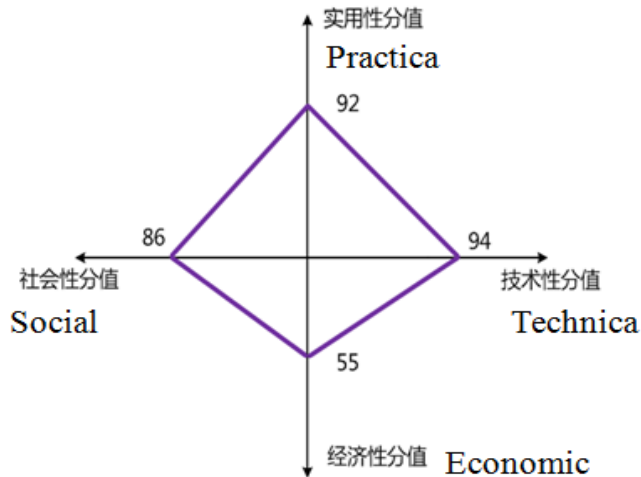


Figure 6 Radar map of overall evaluation of the Tianjin Sub-Project 4

Sensitivity analysis and uncertainty

The aim of sensitivity analysis is to analyze the impact of the change of certain factors (indices) on the Eco-city project evaluation score, and to discover the influence of key indicators on the score. Figure 7 shows the results of changing the outrage rate for the scoring of Tianjin Sub-Project 2. The influence goes from bottom to up to impact the score at each layer by multiply the corresponding weights.

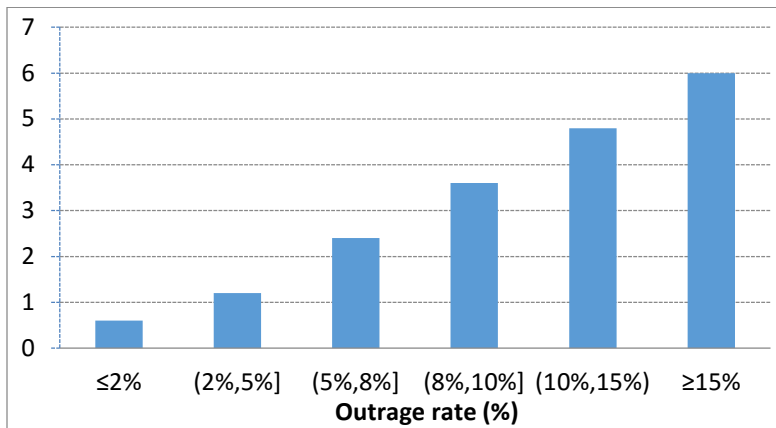


Figure 7 Comparison of outrage rate scoring for Sub-project 2

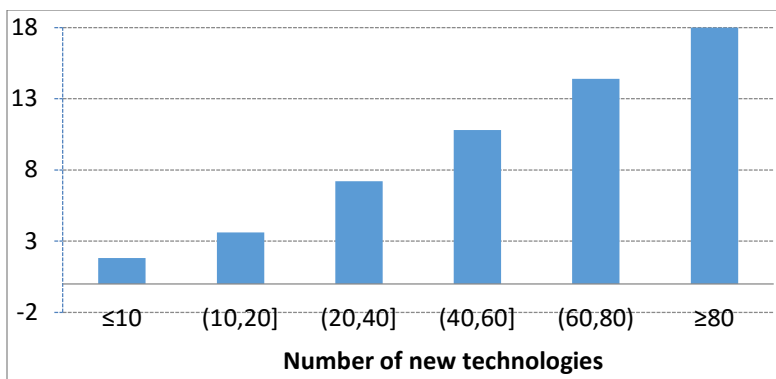


Figure 8 Comparison of number of new technologies for Sub-project 2

b. Irvine smart grid Demonstration

The main structure of the EPRI method declares assets provide a set of functions that can, in turn, generate smart grid benefits to be monetized (EPRI, 2010). The analysis therefore begins by identifying the assets deployed in each of the sub-projects included in this study, and then mapping them to functions that generate benefits.

Figure 9 summarizes the functions to benefits mapping provided by the SGCT for each test case Sub-project. The green cells with *YES* mark the benefits of each sub-project identified through the mapping exercise; however, this second mapping shows that functions to benefits links are not accurate in every case. Some identified functions do not appear to be linked as expected to benefits, and one function is linked to an unexpected benefit. *Optimized Generator Operation* is a benefit not directly realized from the *Distributed Production of Electricity* function in ISGD Sub-Project 1. It is certainly credible that coordination between output from distributed sources and operation of centralized assets might improve overall fuel efficiency, but such coordination implies a detailed level of operational control. In this study, no input was made for this benefit to eliminate it from calculations. Likewise, *Automated Voltage and VAR Control* function in ISGD Sub-Project 4 is only linked to the benefits *Reduced Electricity Losses*, *Reduced CO₂ Emissions*, and *Reduced SO_x, NO_x, and PM-2.5 Emissions*; however, field experiments have shown DVVC produces an average customer energy savings of 2.6 %, ranging between 1.6 % and 3.6 % (Irwin and Yinger, 2015)². These benefits not identified in the tool for DVVC are marked in red (with +*YES*) in Figure 9. To overcome this limitation, a phantom asset was added to generate the missing benefits at no cost.

Consumers are mainly affected through changes in electricity consumption due to efficient and/or smart equipment, feedback on electricity usage, substitution of grid electricity by on-site PV generation, energy storage, and DVVC. The evaluation method for Consumer benefits relies on the decrease in annual total electricity bill. For the 22 project homes, ISGD Sub-Project 1 reduces the total bill by 75 %. For ISGD Sub-Project 4, the 2.6 % energy savings rate demonstrated in these field experiments were applied to the seven circuits, which serve roughly 8300 customers, served from MacArthur substation. Shaving of peak load would postpone, reduce, or even eliminate the need to install expensive generation and T&D capacity. In addition, peak load tends to drive delivery losses more than average load, thus, managing the peak, i.e., reducing maximum demand and flattening the load curve, leads to improvements in electricity delivery efficiency. All sub-projects investigated in this paper help decrease peak load.

² In early October 2014, the SCE research team obtained voltage and energy consumption data for two sets of alternate on-off weeks. For each week, all of the voltage readings from 14 instrumented field capacitors and the substation bus were averaged. The Conservation Voltage Reduction (CVR) factor, which for these two test periods averages 2.6, measures the decrease in energy consumption associated with a 1 % voltage decrease (i.e., % average power reduction/1 % voltage reduction). Normally, the CVR factor is expected to be close to unity, and no explanation for this disparity is known. For more detail, see Irwin and Yinger (2015).

Benefits			Sub-project 1 Functions			Sub-project 3 Functions	Sub-project 4 Functions
			Customer Electricity Use Optimization	Storing Electricity for Later Use	Distributed Production of Electricity	Storing Electricity for Later Use	Automated Voltage and VAR Control
Economic	Improved Asset Utilization	Optimized Generator Operation			YES		
		Deferred Generation Capacity Investments	YES	YES	YES	YES	+YES
		Reduced Ancillary Service Cost	YES	YES	YES	YES	
	T&D Capital Savings	Reduced Congestion Cost	YES	YES	YES	YES	
		Deferred Transmission Capacity Investments	YES	YES	YES	YES	+YES
		Deferred Distribution Capacity Investments	YES	YES	YES	YES	+YES
	T&D O&M Savings	Reduced Equipment Failures					
		Reduced T&D Equipment Maintenance Cost					+YES
		Reduced T&D Operations Cost					
	Theft Reduction	Reduced Meter Reading Cost					
Energy Efficiency	Reduced Electricity Theft						
Electricity Cost Savings	Reduced Electricity Losses		YES	YES	YES	YES	
Reliability	Power Interruptions	Reduced Electricity Cost	YES				+YES
		Reduced Sustained Outages					
		Reduced Major Outages					
	Power Quality	Reduced Restoration Cost					
		Reduced Momentary Outages					
Environmental	Air Emissions	Reduced Sags and Swells					
		Reduced CO2 Emissions	YES	YES	YES	YES	YES
Security	Energy Security	Reduced SOx, NOx, and PM-2.5 Emissions	YES	YES	YES	YES	YES
		Reduced Oil Usage (not monetized)					

Figure 9 Functions to benefit mapping of each case ISGD sub-project (Note: green cells are identified by the SGCT, red cells are additional)

The technologies implemented in ISGD Sub-Project 1 reduces the peak based on efficient appliance usage, demand shift, PV generation, and battery discharge at peak times. The 2 MW battery can be discharged at peak hours in ISGD Sub-Project 3, and optimizing voltage/VAR control in ISGD Sub-Project 4 also reduces the peak demand and the amount of T&D losses. Benefits for the environment relate to CO2 emissions and other pollutants damage costs. Estimation relies on physical quantification of the emissions and subsequently on their conversion to monetary costs, using California carbon and pollutant costs.³ Increased consumer awareness of electricity use and decrease in electricity consumption achieved through improved efficiency of smart appliances reduces both the electricity generation required and the associated emissions. PV panels provide electricity without CO2 emissions, contributing to the reduction of overall CO2 emissions of ISGD Sub-Project 1. Electricity reductions based on improved efficiency and energy conservation voltage reduction in ISGD Sub-Project 4 reduce generation and associated emissions. There is also potential for emissions reductions by decreasing peak, although calculation of emission reductions in the EPRI method is only based on consumption reduction and excludes peak reduction.

The Net Present Values (NPVs) for total costs and benefits of each sub-project are summarized in Table 3. Results appear to be significantly different among the sub-projects analyzed here. The overall B/C (i.e., benefit/cost) ratio of ISGD Sub-Project 1 is 0.1 (with -\$4.3M annual net benefits), while ISGD Sub-Projects 3 and 4 have B/C ratios of 2.5 (with \$1.3M annual net benefits) and 12.9 (with \$6.8M annual net benefits), respectively. Moreover, Figure 10 shows present net benefits cumulatively over time, i.e., the cost of each year is the sum of that year's value plus all previous years. As can be seen, net benefits are far from turning

³ We used \$12/tCO₂ based on the average California carbon price in 2014 (<http://calcarbondash.org/>), \$3000/tNO_x and \$250/tSO_x, based on SGCT default data for Western Electricity Coordinating Council (Navigant, 2011).

positive in the investigation period for ISGD Sub-Project 1, i.e. the blue line is always strongly and increasingly negative, ISGD Sub-Project 3 turns to positive starting from 2019, and ISGD Sub-Project 4 turns positive starting in 2013, i.e. even before project deployment is completed. These SGCT results indicate that ISGD Sub-Project 1 is not economically attractive at current project performance and expenditures. The cost of ISGD Sub-Project 1 needs to be about 94 % lower to achieve a B/C ratio greater than 1, i.e. breakeven. Nonetheless, a low B/C ratio is acceptable for a purely technology demonstration project, as ISGD Sub-Project 1, in which most of the equipment installed is at an emerging stage requiring a steep learning curve. The ZNE Homes are very much a technology demonstration, and was not intended to reach breakeven. Recent announcements of residential battery cost reductions underscore the early vintages of the equipment installed in the 22 homes (Tesla, 2015). Nonetheless, B/C ratio results are still valuable for providing suggestive estimates of the cost-performance gap between current generation technology and breakeven, or viable commercialization. The EPRI method does not include uncertainty on cost reductions over time, which would be a welcome extension of these results.

On the other hand, ISGD Sub-Projects 3 and 4 appear to be economic, the latter strongly so. The result for ISGD Sub-Project 4 parallels SCE’s experience, and the company is already moving to widespread deployment. ISGD Sub-Project 3 results suffer from some methodological limitations. For example, factors like charging-discharging inefficiencies and auxiliary energy use are not available. Importantly, the analysis excludes the energy capacity and only considers storage power. This causes overestimates of utility capacity deferrals from batteries because any storage system may not have sufficient energy capacity to sustain its maximum power level long enough to achieve an equivalent lower the peak.

Table 2 Total costs and benefits of each ISGD sub-project (in NPV)

	ISGD Sub-Project 1	ISGD Sub-Project 3	ISGD Sub-Project 4
NPV (of annual cost)	\$(4.64M)	\$(0.85M)	\$(0.59M)
NPV (of annual benefit)	\$0.30M	\$2.14M	\$7.58M
NPV (of annual net benefit)	\$(4.34M)	\$1.30M	\$6.99M
B/C Ratio	0.1	2.5	12.9

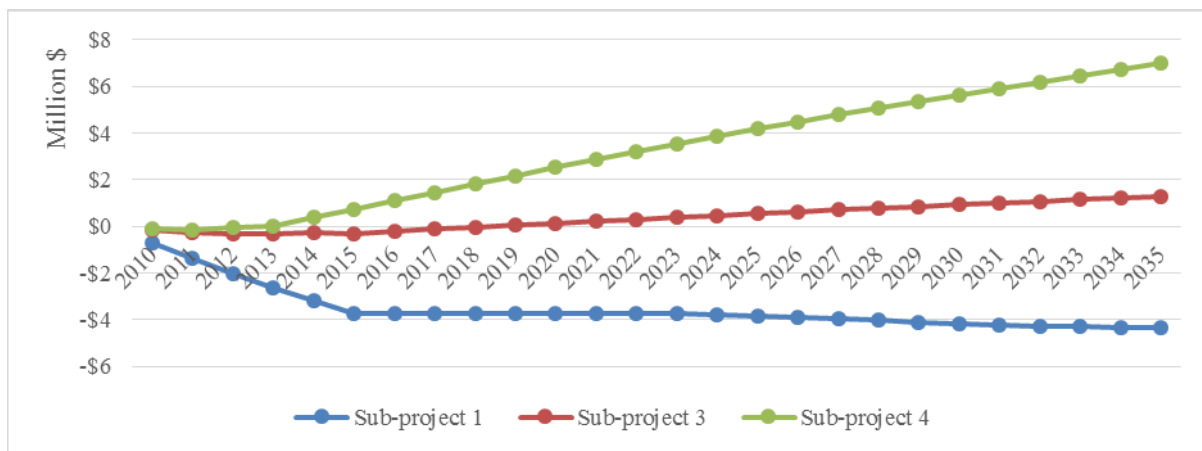


Figure 10 Cumulative net present benefits of each ISGD sub-project

Sensitivity analysis and uncertainty

Figure 11 compares the cumulative net present benefits of Sub-project 1 with and without energy storage technologies and also heat pumps. Heat pump is the second expensive technology in the project, listed after energy storage technologies. As can be seen, net benefits are improved when the energy storage technologies are excluded from the analysis with or without heat pump. However, they are still negative throughout the computation horizon. In addition, the results showed that the B/C ratio increased to 0.2 when only energy storage technologies are excluded, and 0.3 when energy storage technologies and a heat pump are together excluded, which are still very low to be an economically positive demonstration project.

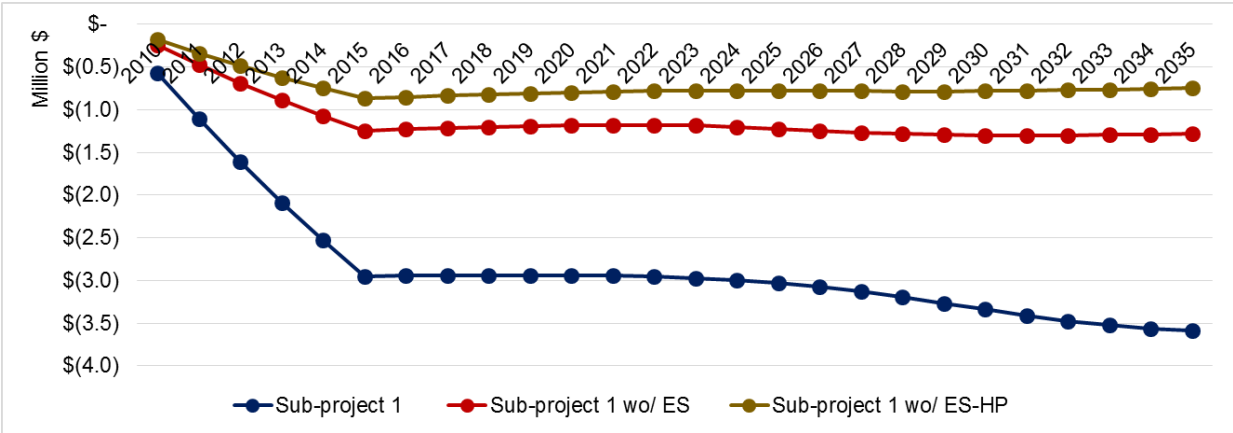


Figure 11 Cumulative net present benefits of ISGD Sub-Project 1 compared to the scenarios ‘without Energy Storage Technologies’ and ‘without Energy Storage Technologies and Heat Pump’

(Note: ISGD Sub-Project 1 wo/ ES represents sensitivity run without including Energy Storage Technologies in the analysis, Sub-Project 1 wo/ ES-HP represents sensitivity run without including Energy Storage Technologies and Heat Pumps in the analysis)

The sensitivity of benefits analysis outcomes to variations in key variables and parameters is critical to any economic analysis involving uncertain variables. The discount rate, for example, typically has a significant impact on the assessment of smart grid projects, since costs are incurred predominantly at the beginning of the scenario while benefits may be sustained over the long-term. Figure 12 and Table 4 illustrate the sensitivity of each case sub-project to discount rate. Naturally, the results show that the higher the discount rate, the lower the NPV. Nonetheless, note that results are fairly robust and all NPVs are negative and all ISGD Sub-Project 1 B/C ratios are close to zero regardless of the discount rate, while ISGD Sub-Projects 3 and 4 always generate positive NPVs and B/C ratios above breakeven.

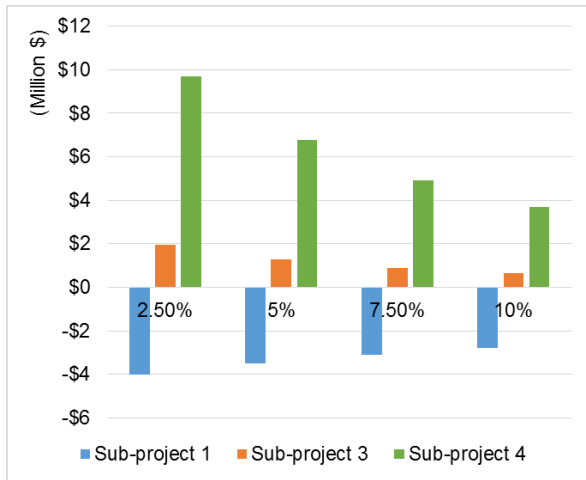


Figure 12 ISGD Sub-Project NPVs with varying discount rates

Table 3 B/C ratios with varying discount rates

	2.5%	5%	7.5%	10%
ISGD Sub-Project	0.11	0.09	0.07	0.06
ISGD Sub-Project	3.07	2.53	2.16	1.92
ISGD Sub-Project	14.42	12.94	11.00	9.61

c. City of Rome

When examining a new project, the key steps of the benefits analysis are the quantification of benefits, as these are usually difficult to attribute to the different stakeholders involved and also hardly quantifiable. The JRC methodology approaches this problem by building a detailed list of assets to be installed/executed within the pilot and then identifying for each single asset the multiple functionalities that are enabled.

Given the high number of lines (~ 15,000) and substations on which ACEA aimed at replicating the project, the DSO internal expertise developed its own *priority indicators* that not only mapped assets into functionalities and then into benefits, but also identified (for each line involved) the contribution of installing the smart grid assets to the functionalities and then their relative benefit in term of SAIDI/SAIFI for each line segment. More in details, such indicators have been built taking into account the number of users connected to each line, the probability of faults on the line (based on historic data) and the cost of installing the smart grid assets. This exercise has been repeated for each of the three sub-projects, resulting in a priority indicator for each line segment for each of the three subprojects.

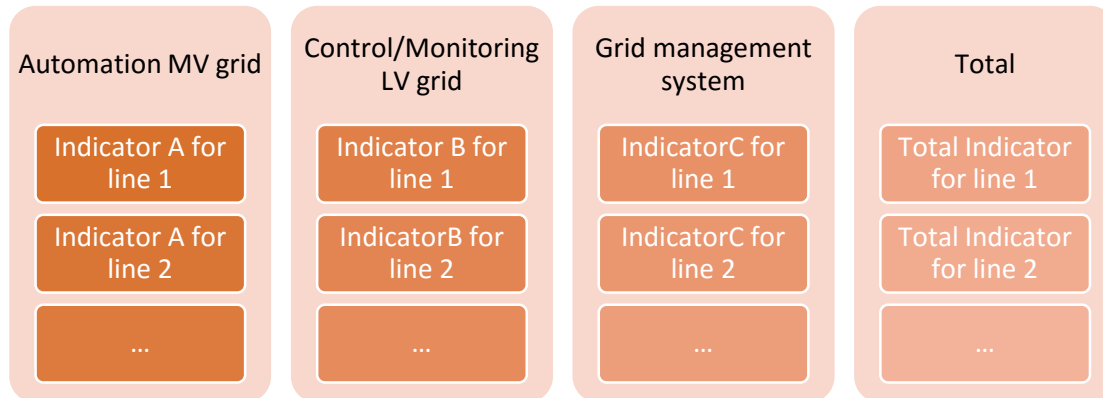


Figure 13 ACEA's per line indicators of benefits stemming from the implementation of the smart grid project

For each year considered, CAPEX and OPEX are calculated per each sub-project. Figure 14 shows the typical trend of any pilot project: CAPEX is concentrated in the very first years, when the installation of infrastructure takes place.

Interestingly, when the same assessment is repeated for the scale-up of the same smart grid solutions to the entire Rome's network, CAPEX shows a slightly different pattern, with virtually no significant CAPEX expense on the New Grid Management Criteria project (as the investment has been already done at the pilot stage) and CAPEX on MV automation and LV remote control and monitoring increasing up to 2020, when the roll-out across the whole grid is expected to be completed.

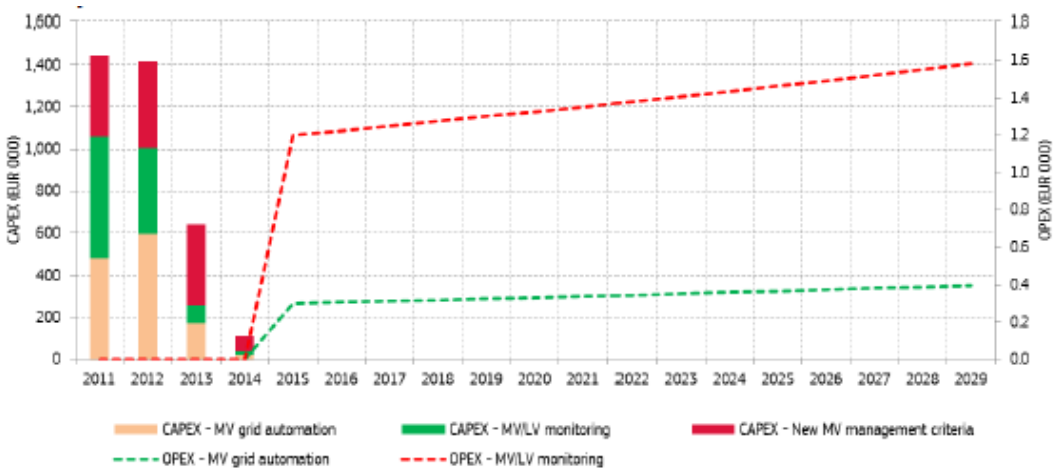


Figure 14 CAPEX and OPEX for Malagrotta project

Benefits for the Malagrotta pilot are also calculated. The sub-project *LV remote control and monitoring* are the most important in monetary terms, as shown in Figure 15.

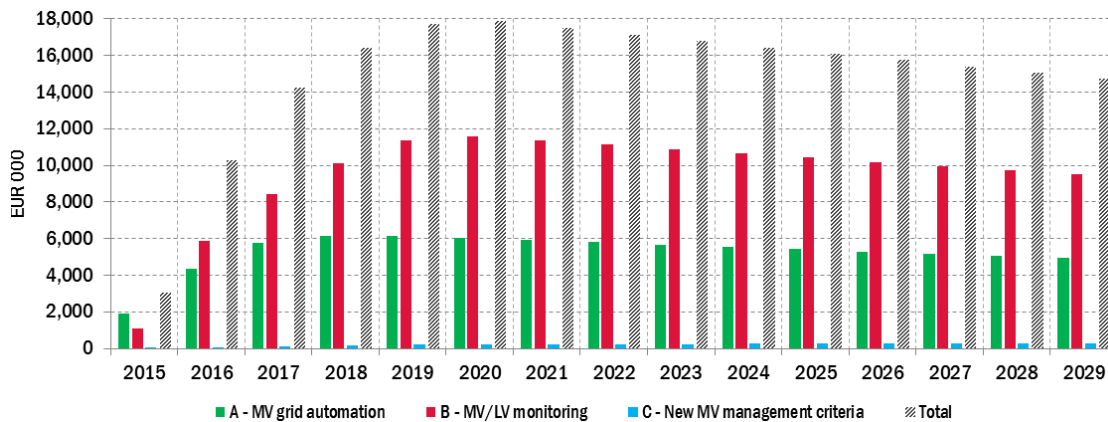


Figure 15 Benefits for Malagrotta project

Summing up, the results of the application of JRC's benefits analysis method to the Malagrotta pilot project are extremely promising. Including cautious adjustments to the assessment, e.g. a yearly rate of benefit decrease, uncertainty of benefits assessment, and an extensive sensitivity analysis on the most important parameters of the model, the outcome of the analysis points to an internal rate of return for Malagrotta of 1.23%, that however becomes 16.60% when scaling up the solutions tested in the pilot to the whole Rome network.

The most promising sub-project, in terms of contribution to total benefits, is clearly the LV monitoring and remote control, as show in Figure 16 below.

Private investor CBA	MALAGROTTA	ROMA
<i>Smart Grid project</i>	<i>(Pilot)</i>	<i>(Scale-up)</i>
NPV (Net Present Value year 2014)	-K€ 1,262	K€ 35,972
IRR (Internal Rate of Return)	1.23%	16.60%
Private investor CBA	MALAGROTTA	ROMA
<i>Automation</i>	<i>(Pilot)</i>	<i>(Scale-up)</i>
NPV (Net Present Value year 2014)	-K€ 374	K€ 10,026
IRR (Internal Rate of Return)	1.86%	12.55%
Private investor CBA	MALAGROTTA	ROMA
<i>MV/LV monitoring</i>	<i>(Pilot)</i>	<i>(Scale-up)</i>
NPV (Net Present Value year 2014)	-K€ 456	K€ 24,608
IRR (Internal Rate of Return)	0.61%	21.17%
Private investor CBA	MALAGROTTA	ROMA
<i>New Management Criteria</i>	<i>(Pilot)</i>	<i>(Scale-up)</i>
NPV (Net Present Value year 2014)	-K€ 432	K€ 1,406
IRR (Internal Rate of Return)	1.13%	12.28%

Figure 16 Results of JRC CBA on Malagrotta pilot project and its scale up to Rome.

Sensitivity analysis and uncertainty

When analyzing the potential economic outcome of a smart grid project, the level of uncertainty is high, due to the long-term period over which the initial CAPEX investment is carried out. To take into account the possible deviations from the initial estimate, JRC includes in its assessment framework a sensitivity analysis on all the major parameters used to build the model estimating costs and benefits for the project. In the Malagrotta case, the sensitivity analysis performed revealed that only few parameters might have a relatively significant impact on the NPV of the project and on the scale-up to the whole Rome network.

The first crucial variable is the financial discount rate. If the discount rate applied changes, NPV can be less than halved. Therefore operating within a solid economic context is crucial to ensure that the investment is recovered and its benefits maximized.

<i>Financial discount rate</i>	0.0%	1.0%	2.0%	3.0%	4.0%	5.0%	6.0%	7.0%	8.0%
Rome	55,449	48,194	41,735	35,972	30,821	26,206	22,065	18,341	14,987
Malagrotta	-259	-617	-950	-1,262	-1,556	-1,834	-2,097	-2,348	-2,588

Figure 17: sensitivity analysis for Malagrotta project – financial discount rate

Another crucial parameter considered is the increase in CAPEX: if significant additional investments in infrastructure are needed each year to enable the functionalities of the smart grid project, clearly the NPV fluctuates and, in the scale-up option, might decrease by about 20%.

Yearly increase in CAPEX costs	0.0%	2.0%	4.0%	6.0%	8.0%	10.0%	12.0%	14.0%	16.0%
Rome	35,972	35,246	34,496	33,719	32,915	32,084	31,225	30,337	29,420

Figure 18: sensitivity analysis for Malagrotta project – yearly increase in CAPEX costs

The last parameter that proves to be crucial when evaluating long-term projects is the social discount rate, representing the time preference of the general public on investment and obtaining benefits from the investment done. The social discount rate can have a significant negative impact on the smart grid project tested. It is therefore of the utmost importance to 1) have a solid business case, that holds even under significant fluctuations of the Social Discount Rate, and 2) carefully estimate the social discount rate when assessing each project.

Social discount rate	0.0%	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%	4.5%	5.0%
Rome	55,887	52,133	48,592	45,252	42,098	39,119	36,303	33,642	31,124	28,741	26,484
Malagrotta	-254	-436	-612	-781	-945	-1,104	-1,258	-1,407	-1,552	-1,693	-1,830

Figure 19 sensitivity analysis for Malagrotta project – Social discount rate

The above figures show that, among the several parameters tested on the sensitivity analysis, only few of them might have a significant impact on the project's financials. It is also crucial to understand that, as shown when analysing Malagrotta project, most of them are not under the direct control of the investor, but are rather linked to the general economic context. Appropriate risk management solutions are therefore required to ensure that the project delivers even in case of deteriorating conditions of the economic environment, as even the most solid business plan for the realisation of a smart grid might be hindered by external factors.

To conclude, the JRC methodology proved appropriate to answer the impelling questions concerning investment in smart grids: is the investment worth? And what are the sources of uncertainty that might affect the economic results of a project? This same analysis can also be used to identify ways to maximize benefits both from both private investor and societal standpoints. However, once the sources of uncertainty are clearly identified, an appropriate risk management system must be put in place to ensure that the positive outcome of any project is eventually delivered.

4. Conclusions

Uncertainties in the estimates from all methods and cases are relatively high, based on the range of estimates provided by the studies drawn upon for this report, and the judgment of the authors. Both methodologies present some difficulties in the evaluation of smart grid benefits. SG-MCA, for instance, is not effectively representing public and private costs, but only their effectiveness in achieving the overall goal. It hardly evaluates the investment cost of smart grid projects. On the other hand, EPRI methodology is not appropriate in managing intangible impacts, such as practicability, which could be more relevant to policies and strategies at this scale for achieving smart grid benefits.

SG-MCA is useful at micro-scale, where all stakeholders are easily accessible and able to express their opinions and priorities. In EPRI method, large-scale evaluation is possible via scaling-up when all costs are assumed stable between small and large scale.

The EPRI method uses only a single criterion, i.e., monetary value, while evaluating the smart grid projects and generate monetary results. SG-MCA, on the other hand, introduces qualitative aspects via multiple criteria and indicators system.

In addition, in order to use EPRI, certain input parameters must be known or, in absence of real data, estimated, while SG-MCA depends solely on the subjective judgments of experts. The two methods do not provide the same information. EPRI's output is not the decision, rather one of the inputs helping to support decision makers when taking decisions. SG-MCA, on the other hand, summarizes the stakeholders priorities and opinions in terms of importance in the decision.

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