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BENEFITS ANALYSIS OF SMART GRID PROJECTS

U.S.–China Climate Change Working Group, Smart Grid

国家能源局
National Energy Administration

WHITE PAPER 2014 – 2016

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White Paper on Benefit Analysis of Smart Grid Projects

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White Paper on Benefit Analysis of Smart Grid Projects

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Executive Summary

Introduction

Smart grids are rolling out internationally, with the United States (U.S.) nearing completion of a significant USD4-plus-billion federal program funded under the American Recovery and Reinvestment Act (ARRA-2009). The emergence of smart grids is widespread across developed countries. Multiple approaches to analyzing the benefits of smart grids have emerged. The goals of this white paper are to review these approaches and analyze examples of each to highlight their differences, advantages, and disadvantages.

This work was conducted under the auspices of a joint U.S.-China research effort, the Climate Change Working Group (CCWG) Implementation Plan, Smart Grid. We present comparative benefits assessments (BAs) of smart grid demonstrations in the U.S. and China along with a BA of a pilot project in Europe. In the U.S., we assess projects at two sites: (1) the University of California, Irvine campus (UCI), which consists of two distinct demonstrations: Southern California Edison's (SCE) Irvine Smart Grid Demonstration Project (ISGD) and the UCI campus itself; and (2) the Navy Yard (TNY) area in Philadelphia, which has been repurposed as a mixed commercial-industrial, and possibly residential, development. In China, we cover several smart-grid aspects of the Sino-Singapore Tianjin Eco-city (TEC) and the Shenzhen Bay Technology and Ecology City (B-TEC). In Europe, we look at a BA of a pilot smart grid project in the Malagrotta area west of Rome, Italy, contributed by the Joint Research Centre (JRC) of the European Commission.

The Irvine sub-project BAs use the U.S. Department of Energy (U.S. DOE) Smart Grid Computational Tool (SGCT), which is built on methods developed by the Electric Power Research Institute (EPRI). The TEC sub-project BAs apply Smart Grid Multi-Criteria Analysis (SG-MCA) developed by the State Grid Corporation of China (SGCC) based on the analytic hierarchy process (AHP) with fuzzy logic. The B-TEC and TNY sub-project BAs are evaluated using new approaches developed by those project teams. JRC has adopted an approach similar to EPRI's but tailored to the Malagrotta distribution grid.

Project Overviews

Irvine Smart Grid Demonstration Project, U.S.

The ISGD project field experiments were designed to evaluate the physical effects of various smart grid technologies and quantify the associated benefits for various stakeholders. SCE operated the ISGD project. Many of the project components were located at or near UCI, which is 60 kilometers (km) southeast of the Los Angeles airport. Three ISGD sub-projects are included in this study:

1. Zero Net Energy (ZNE) Homes: ISGD equipped three test blocks of homes with an assortment of advanced energy technologies to reduce energy use, empower families to control their energy use, improve grid performance, and produce and store energy with photovoltaic arrays (PV) and residential energy storage. The goal of one block of homes was to evaluate strategies and technologies for achieving ZNE; the ZNE homes are one of the ISGD sub-projects examined in this white paper.
2. Distribution Battery Energy Storage System (DBESS): This sub-project involves a 2-megawatt (MW)/0.5-megawatt-hour (MWh) battery that keeps the distribution circuit load within a set limit, mitigating overheating of the substation getaway and reducing peak load.
3. Distribution Volt/Volt ampere reactive (VAR) Control (DVVC): DVVC optimizes consumer voltage profiles, maintaining voltage at consumer connections close to the allowable minimum in an effort to achieve conservation voltage reduction. DVVC

technology significantly improves this capability and can provide VAR support to the transmission system. Field experiments showed an average energy savings of approximately 2.5% from the DVVC project, making this demonstration a major success.

University of California, Irvine, U.S.

The UCI Microgrid is a test bed that (1) is served by SCE through 2×15 mega-volt ampere (MVA) transformers at the UCI substation, which steps down voltage from 66 kilovolts (kV) to 12 kV; (2) encompasses 3×12 kV circuits; (3) includes nearly 3.6 megawatts (MW) of solar power; (4) owns a 19 MW natural-gas-fired, combined-cycle (combined heat and power, CHP) plant with heat recovery; (5) incorporates centralized chilling, including a large thermal energy storage tank; and (6) serves all major campus buildings with district heating and cooling. Four specific technologies from this test bed are covered in this analysis:

1. Central 19 MW CHP plant: The central plant consists of eight electric chillers, a steam turbine chiller, a thermal-energy-storage tank, boilers (used only for backup), a 13.5 MW gas turbine, a heat-recovery steam generator, a duct burner, and a 5.5 MW steam turbine. The plant provides all campus heating and cooling as well as 96% of campus non-cooling electricity, the balance of which is provided by solar resources (3.5%) and utility imports (0.5%).
2. PV arrays totaling 3.6 MW: Twelve UCI buildings and three parking structures have rooftop PV panels totaling 3.6 MW, and, in 2012, an additional 113 kW of concentrating photovoltaics (CPV) with dual-axis tracking was installed. Although campus solar resources are still at a low penetration (3.5%), they are enabling the gas turbine to be turned down at times of low electricity demand and high solar irradiation.
3. Microgrid controller (MgC): The generic MgC is envisioned as a set of modules including a master microgrid controller that contains the control algorithm and functions as a single point of communication with the larger grid, a load controller, a generation controller, a storage controller, and a breaker controller.
4. Lithium-ion battery: The recently installed 2 MW-0.5 MWh lithium-ion iron phosphate battery consists of battery, auxiliary, and 12 kV interconnection skids. The battery system will be utilized to reduce electricity imports and as a balancing resource during islanding. In both applications, the battery system will buffer small transient mismatches between load and generation.

Sino-Singapore Tianjin Eco-City, China

TEC is the first comprehensive integrated smart grid demonstration project in China. The ultimate aim of this demonstration project is to boost eco-city development. TEC is located in the 30-square km (km^2) national development strategic area, 45 km from Tianjin city center. Project implementation focuses on the pilot ecological city zone, which is a 4 km^2 area located south of TEC. Initial construction in the Cheong Road area included a 110 kV intelligent substation and a total of 123 planned distribution sites. Three sub-projects from TEC are included in this analysis:

1. Microgrid with storage (MgS): The 380-V MgS is composed of a 30 kW PV array, 6 kW of wind turbines, and 15 kW × 4 h of lithium-ion batteries. The total load is 15 kW, consisting of 5-10 kW of lighting plus electric-vehicle (EV) charging. Control is by an economic microgrid energy management system that includes distributed power, an energy storage inverter, microgrid intelligent terminals, an MgC, the server host, and an operator station.
2. Smart substation (SS): The Cheong 110 kV SS includes electronic transformers, primary equipment on-line monitoring and other intelligent devices, a network of secondary

equipment, 110 kV line protection and monitoring arrangements, three layers of two networks, direct data-mining network control, a unified messaging platform technology, and access to the distributed power sources.

3. Distribution automation (DA): The construction of an intelligent DA system relies on a strong distribution network, a power distribution master station with electronic stations, distribution terminals, and communication channels. Regional planning began with construction of the 110 kV Cheong Road substation together with 10 kV and 36 feeders.

Shenzhen Bay Technology and Ecology City, China

Currently occupying 0.2 km^2 of a total construction area of more than 1.2 km^2, B-TEC is the pilot technology demonstration for the huge Qianhai smart power grid. B-TEC includes optimal scheduling, smart metering with advanced energy services, and distribution network asset life-cycle operations and maintenance (O&M) minimization based on big data. Five B-TEC sub-projects included in this study are:

1. Distribution grid optimal operation and fault self-recovery system (OOFSS): B-TEC demonstrates electrical monitoring, state monitoring, and comprehensive environmental monitoring of distribution rooms that depend on smart distribution integration terminals and distribution automation and protection functions.
2. Distributed energy coordination and scheduling (DECS): B-TEC consists of one mixed commercial-residential building microgrid system and three commercial-office-building microgrids. It has access to a 142 kW PV array and 90 kWh of energy storage and each building is equipped with one set of background microgrid monitoring systems, allowing for easy O&M.
3. Advanced metering infrastructure (AMI) system: B-TEC remote communication uses optical fiber network facilities. Node communication access is realized by means of special networks.
4. Distribution operational state sensory module (OSSM): Using a smart distribution grid operations control strategy support system, B-TEC coordinates, optimizes, and dispatches all resources and schedules O&M to optimize grid asset life as well as advanced energy utilization services that are based on smart measurement, big data, and cloud computing technologies.
5. Load center energy storage station (ESS): Baoqing ESS, with a total capacity of 6 MW/18 MWh, is the world's first MW-scale lithium-battery peak regulation and frequency modulation power storage station.

The Philadelphia Navy Yard, U.S.

TNY was a longtime military base that came under the jurisdiction of the City of Philadelphia in 2000. TNY is now being repurposed as a mixed commercial-industrial, and possibly residential, development. TNY's electricity distribution network is served by PECO (formerly Philadelphia Electric Company) through the two TNY-owned and -operated substations that step voltage down from 33 kV to 13.2 kV. TNY has established a microgrid network operation center that will support following key functions:

1. Integrated smart metering and communication functions
2. Supervisory control and data acquisition (SCADA) and distribution grid monitoring functions
3. Substation data automation and monitoring
4. Operation interface with third-party-owned assets
5. Operation interface with PECO

6. Operation interface with PJM (formerly Pennsylvania-New Jersey-Maryland Interconnection) and/or third-party PJM aggregators
7. Platform for the microgrid control system being developed as part of U.S. DOE MgC project

ACEA, Europe

ACEA, the third-largest distribution system operator in Italy, tested smart grid solutions in a pilot project in Malagrotta near Rome. The project installed new technologies on six feeders that total about 69.5 km of medium-voltage (20 kV) and low-voltage (8.4 kV) underground and aerial lines. The smart grid characteristics include management of different voltage levels (from two primary substations to 76 secondary substations), four distributed-generation (DG) plants directly connected at medium-voltage (one PV and three biomass sources totaling about 20 MW of installed capacity), seven users directly connected to the medium-voltage grid, and EVs and storage solutions. The project is made up of three main, additive components:

1. Medium-voltage grid automation: This component enables automatic selection of fault line segments and allows remote distributed generator management on the basis of actual grid conditions.
2. Remote monitoring and control: At both medium and low voltages, 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.
3. New grid management algorithm: At the central level, a new grid management algorithm will enable capture of additional benefits of the first two sub-projects, such as management of load flow management, optimization of load profile, and minimization of technical losses.

Methods

EPRI-U.S. DOE

The EPRI/U.S. DOE BA method, as embodied in the SGCT, defines a benefit as the monetized impact of a smart grid project. All benefits must be expressed in monetary terms, accrue to one or more of three stakeholders (consumers, utility, or society as a whole), and fall into the following four benefit categories:

- Economic: reduced costs or increased production at the same cost
- Reliability and power quality: reduction in interruptions and power-quality events
- Environmental: reduced greenhouse gas emissions and other pollution
- Security and safety: improved energy security; increased cybersecurity; and reduced injuries, loss of life, and property damage

The benefits estimate is based on the difference between the monetary values associated with a baseline scenario, which represents the system state without the project, and a contrasting project scenario. In general, benefits are reductions in costs and damages, such as deferred capacity investment, improved power quality, or reduced environmental harm, whether to utilities, consumers, or society at large.

SGCT logic starts from a listing of smart grid assets, then identifies asset functions, and ultimately monetizes benefits. Because one function might have multiple benefits, all benefits are summed to estimate the project's total monetized benefit.

SG-MCA

The SG-MCA method includes four dimensions: practicality, technological, economic, and social. It includes both qualitative and quantitative indicators and employs a combined AHP and fuzzy evaluation method. The basic principle of AHP is to divide the various elements of the program evaluation into an orderly multi-level hierarchy and then compare elements of each level with those of previous levels to obtain weights for each element. This comprehensive weight set determines the optimal solution, defined as the maximum weight. Fuzzy comprehensive evaluation jointly evaluates attributes measured by different indicators using the characteristics of fuzzy relation composition. The first level of the comprehensive fuzzy evaluation initially determines evaluation indices, e.g., practical, technical, economic, and social. The second level is based on the first and can be applied to multi-dimensional assessment; i.e., a total evaluation synthetically considers the four-attribute index. By combining these two evaluation methods, the method can find a composite index score that reflects all attributes.

Qianhai Project Approach

In the Qianhai Project Approach (QPA) BA, achievable and potential benefits of smart grid projects are analyzed from two perspectives; (1) stakeholder (e.g., consumers, the power supply bureau, the utility) and (2) investor. QPA evaluation principles are as follows:

- Comprehensiveness: A comprehensive BA should reflect the benefits of the smart grid for different perspectives and categories.
- Consistency: The BA contents should be consistent with evaluation targets, e.g., incremental benefits should correspond to incremental assets.
- Measurability: BA indices should be measurable, and data easy to collect and in standard form.

To assess smart grid benefits, assets are classified first, then their functions are matched, and a cost-benefit analysis is performed for the internal operational mechanisms of system modules and external markets. Finally, economic benefits are evaluated.

The Navy Yard (TNY) Method

TNY BA method is based on computing a set of project benefits and costs for a given operational scenario compared to a baseline. Figure ES-1 shows TNY's benefit analysis framework. Four cost-benefit analysis categories (CBACs) are defined: (i) financial / economic, (ii) operational reliability and efficiency, (iii) environmental, and (iv) innovation and economic growth.

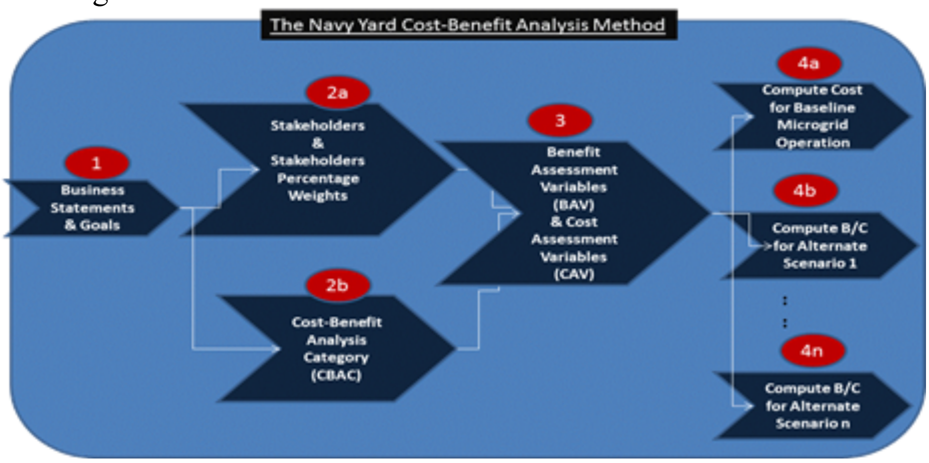

Figure ES-1. TNY benefit analysis step-by-step process

Results

ISGD, U.S.

The ISGD project is evaluated using the EPRI-U.S. DOE tool. The SGCT results shown in Table ES-1 indicate that ZNE homes are far from being economically attractive based on current project performance and expenditures. The equipment cost, about USD146 k/home, would need to be about 94% lower to break even, i.e., a benefit/cost (B/C) ratio greater than 1. The ISGD ZNE homes demonstrated multiple early-stage technologies that are expected to become more economic over time. In contrast, DBESS and DVVC appear to be economic, the latter strongly so.

Table ES-1
Benefits, costs, and B/C ratios for ISGD sub-projects based on analysis with SGCT tool

	ZNE	DBESS	DVVC
Cost	USD(4.64M)	USD(0.85M)	USD(0.59M)
Benefit	USD0.30M	USD2.14M	USD7.58M
Net benefit	USD(4.34)M	USD1.30M	USD6.99M
B/C ratio	0.1	2.5	12.9

Note: Costs and benefits are represented as net present value (NPV).

For both ZNE and DVVC, more than 80% of the benefits are from reduced electricity cost, which is a consumer benefit. For DBESS, almost 70% of the benefits come from deferral of generating capacity investments, and 25% derive from reduction in losses, with deferral of transmission and distribution (T&D) expansion providing the remaining benefit. The utility is the only stakeholder that benefits from this sub-project.

UCI, U.S.

Table ES-2 shows the results from the EPRI-U.S. DOE tool for each sub-project analyzed at UCI. The MgC project exhibits an extremely high value, driven by its highly valued reliability improvement. It was assumed that outages caused by the SCE system would be solved by islanding, yielding a decrease in system average interruption duration index (SAIDI) from 1.17 to 0.17 h/a. The CHP plant also shows significant value, largely because of the economic benefit associated with optimized generator operation and current low gas prices. The net benefit of installing PV is much lower than the value of the CHP plant and MgC projects because of the high investment cost for PV; solar installation costs would need to drop for PV to compete with CHP. The lithium battery case also shows a high B/C ratio compared to the ratios for the other projects although the absolute value of the battery net benefit is much smaller than for the other projects.

Table ES-2
Benefits, costs, and B/C ratios for UCI sub-projects analyzed using SGCT tool

	CHP	PV	MgC	LiB*
Cost	USD(30.6 M)	USD(13.7 M)	USD(1.14 M)	USD(0.51 M)
Benefits	USD124 M	USD43.2 M	USD242 M	USD3.47 M
Net benefit	USD93.1 M	USD29.5 M	USD241 M	USD2.96 M
B/C ratio	4.0	3.2	212	6.8

Note: Costs and benefits are represented as NPV. * LiB – lithium-ion battery

Sino-Singapore TEC, China

The overall performance of the eco-city project as determined using the SG-MCA method is good with a score of 87 out of 100, but the economic value is relatively poor with a score of 64. Results by category are: (1) Practical: The TEC project has supported local business development and promoted energy conservation. (2) Technological: Power-supply reliability is greater than 99.999 %, and the power-quality rate has been increased to 100 %. All renewable-energy resources are controllable including wind turbine and PV, with a utilization rate of more than 20 %. (3) Economic: The TEC project can reduce the annual investment of CNY11.7M in land costs, line losses, power supply reliability, operations, and maintenance. However, many software and hardware capabilities were developed for the project without solid policy support or appropriate business models, so the project's economic performance is worse than expected. (4) Social: DG, microgrid, and EV charging facilities reduce about 1,074.32 tons (t) of fuel consumption, 5,929.7 t of standard coal, and 18,488 t of carbon dioxide (CO_2) emissions per year. These projects also have the potential to stimulate technology upgrades and development of equipment manufacturing, electronic information, petrochemicals, new energy, and new materials that would have significant social benefits. Table ES-3 shows the SG-MCA analysis results for the TEC project.

Table ES-3
Results for the overall TEC project and three sub-projects analyzed using the SG-MCA approach

	TEC project	DA sub-project	Microgrid sub-project	SS sub-project
Practical	80	92	90	96
Technological	96	94	98	94
Economic	64	55	58	70
Social	93	86	75	80

Note: The values in the table are the scores in the specified area, out of a maximum of 100 points.

B-TEC, China

Table ES-4 shows QPA benefits analysis results for each B-TEC subsystem. The cost of investment in fixed assets includes equipment purchase costs, software costs, installation fees, etc. The OOFSS and DECS sub-project analyses consider social benefits in addition to power supply bureau benefits; the bureau is the main beneficiary of the AMI, OSSM, and ESS sub-projects.

Table ES-4
Benefit analysis results for B-TEC sub-projects using QPA approach

	OOFSS	DECS	AMI	OSSM	ESS
IRR* (%)	17.3%	-17.2%	11.9%	5.9%	7%
NPV (CNY)	1.05M	(1.75M)	1.16M	(0.11M)	
Payback (year)	6	Cannot be paid back	8	10	9

* IRR – internal rate of return

TNY, U.S.

The analysis of TNY's microgrid uses TNY's BA tool, developed during the joint research effort for this white paper to study the following scenarios:

- Scenario 1: MgC integrated with a 6 MW internal combustion generator set (IC-genset). Substation 93 is currently at or near capacity at certain times of the year; the 6 MW unit will delay the need to expand the substation and will thus avoid significant capital expense. In addition, the unit will provide resiliency and financial benefits through participation in PJM markets.

- Scenario 2: MgC with 2 MW of solar PV and 2.5 MW of battery storage. Daily solar PV output would coincide with typical peak-load periods, and the solar-storage asset would result in multiple potential benefits including delaying the need to expand the substation, reducing peak loads, and providing financial benefits through participation in PJM markets.
- Scenario 3: MgC with 6 MW IC-genset, 2 MW solar PV, and 2.5 MW battery storage would be interconnected to substation 93 in TNY's industrial zone and would be operated to shave peak demand, participate in energy markets to earn revenue, and provide resilience to consumers served by the area substation.

A summary of TNY analysis results is shown in Table ES-5.

Table ES-5
Comparison summary of TNY scenario results

Scenario Results	Scenario 1	Scenario 2	Scenario 3
Cost	USD(2.41) M	USD(2.03) M	USD(3.18) M
Benefit	USD3.61 M	USD3.63 M	USD6.82 M
Weighted B/C	2.79	4.05	3.87
Non-weighted B/C	1.5	1.79	2.14

ACEA, Europe

Applying JRC's BA method to the Malagrotta pilot project produced extremely promising results including an IRR for Malagrotta of 1.23 %; however, that figure becomes 16.6 % when the solutions tested are scaled up from the pilot to the whole Rome grid. The most promising sub-project, in terms of contribution to total benefits, is clearly the low-voltage monitoring and remote control, as shown in Table ES-6.

Table ES-6
JRC BA results for Malagrotta pilot project (private investor BA)

	Smart grid project	Automation	Medium-/low-voltage monitoring	New management criteria
NPV (2014)	€(1.26) M	€(0.37) M	€(0.46) M	€(0.43) M
IRR	1.23%	1.86%	0.61%	1.13%

Conclusion

The CCWG collaboration is not intended to result in a rigorous, consistent BA but instead to demonstrate and compare methods of evaluating the performance of smart grid demonstrations. This white paper comparatively analyzes five BA methods applied to five different smart grid demonstration projects: two in the U.S., two in China, and one in Italy. Originating from different methodological backgrounds, all approaches contribute to our understanding of smart grid demonstration project performance. The outcomes of the QPA, EPRI-U.S. DOE, TNY, and JRC approaches are NPV or B/C ratio whereas the SG-MCA provides a total benefit score based on expert judgment. The best method to use for a given smart grid project would depend on the characteristics of the project and the nature of the analysis outcome that would best serve the goals of the analysis. The QPA and EPRI-U.S. DOE methods might be more useful for decisions that require monetary results. The EPRI-U.S. DOE method facilitates analysis by providing a documented, generic setup. The SG-MCA method might be a better choice for projects aiming to achieve non-monetary benefits such as practicality. Users who want qualitative analysis in addition to monetized benefits might prefer the JRC method. Projects requiring a detailed, sound financial picture to justify investment might benefit from the business perspective that informs the TNY method.

Review and comparison of methods provides useful insights and should continue. Exchange of results and cross-fertilization of ideas and technologies could be fostered by development of universal open-source software based on the EPRI-U.S. DOE method but applicable internationally. The basis would most likely be EPRI-U.S. DOE because the EPRI work completed in the early days of the ARRA program provides a solid basis of definitions and formulas for the basic financial indicators which are widely accepted.

Contents

Table of Figures

Table of Tables

Acronyms and Abbreviations

ACEA	the third distribution system operator in Italy
AEEGSI	Autorita per l'energia elettrica, il gas e i servizi idrici (National Regulatory Authority for gas and electricity, Italy)
AHP	analytic hierarchy process
AMI	advanced metering infrastructure
APEP	Advanced Power and Energy Program (UCI)
ARRA	American Recovery and Reinvestment Act
ASC	assessment standard category
AUD	Australian dollar
AWV	Assessment Weight Values
BA	benefit assessment
BACW	benefit assessment composite weight
BAV	benefit assessment variable(s)
BAU	business-as-usual
B/C	benefit-cost ratio
B-TEC	Technology and Ecology City (Shenzhen Bay)
CA	California
CACW	cost assessment composite weight
C&I	commercial and industrial
CAPEX	capital expenditure
CAV	cost assessment variables
CBA	cost-benefit analysis
CBAC	cost-benefit analysis categories
CCWG	Climate Change Working Group
CEC	California Energy Commission
CER	Irish Commission for Energy Regulation
CES	community energy storage
CHP	combined heat and power
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
CPV	concentrating photovoltaic
CVR	conservation voltage reduction
DA	distribution automation
DBESS	distribution-level battery energy storage system
DECC	Department of Energy and Climate Change, United Kingdom
DECS	distributed energy coordination and scheduling
DER	distributed energy resources
DER-CAM	Distributed Energy Resource – Customer Adoption Model
DG	distributed generation
DMGCS	distributed microgrid control system
DVVC	Distribution Volt/VAR Control
EEGI	European Electricity Grid Initiative
EMS	Energy Management System
ENI	Energy Needs Ireland
EPRI	Electric Power Research Institute
ESS	Energy Storage Station
EU	European Union
EV	electric vehicle

GIS	geographic information system
GJ	gigajoule
GridSTAR	a smart grid education and research center of Pennsylvania State University that is conducting work at TNY
GPRS	general packet radio service
HRSG	heat recovery steam generator
ICA	integration capacity analysis
ICE	interruption cost estimate
IC-genset	internal combustion engine generator set
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IRR	internal rate of return
ISGAN	International Smart Grid Action Network
ISGD	Irvine Smart Grid Demonstration
JRC	Joint Research Centre of the European Commission
kg	kilogram
KPI	key performance indicator
km	kilometer
kV	kilovolt
kW	kilowatt
kWh	kilowatt-hour(s)
LED	light-emitting diode
LNBA	locational net benefit analysis
MAIFI	momentary average interruption frequency index
MAISY	Agent-Based End-Use Model Developed By Duke Energy
MgC	microgrid controller
MgS	microgrid with storage
MVA	mega-volt ampere
MW	megawatts
MWh	megawatt-hour(s)
NaS	sodium sulfur
NOx	nitrogen oxide
NPV	net present value
NYEMP	The Navy Yard Energy Master Plan
O&M	operations and maintenance
OFGEM	Office of Gas and Electricity Markets, United Kingdom
OOFSS	optimal operation and fault self-recovery system
OOP	object oriented programming
OPEX	operational expenditure
OSSM	operational state sensory module
PAID	Philadelphia Authority for Industrial Development
PECO	current name of electric utility serving The Navy Yard (formerly Philadelphia Electric Company)
PIDC	Philadelphia Industrial Development Corp.
PJM	regional transmission operator in Northeast and Central U.S. Interconnection (Formerly Known As Pennsylvania-New Jersey-Maryland Interconnection)
PLC	power line carrier
PM-2.5	2.5-micron particulate matter
PPA	power purchase agreement

PPP	public-private partnership
Pt	payback period
PV	photovoltaic
QPA	Qianhai Project Approach
R&D	research and development
RESU	residential energy storage unit (Battery)
RoR	rate of return
CNY	Renminbi (Official Chinese Currency, also Written Yuan or ¥)
ROI	return on investment
SAIDI	system average interruption duration index
SAIFI	system average interruption rrequency index
SCADA	supervisory control and data acquisition
SCE	Southern California Edison
SCW	stakeholders' composite weight
SGCC	State Grid Corporation of China
SGCT	Smart Grid Computational Tool
SGIM	Smart Grid Investment Model
SG-MCA	Smart Grid – Multi-Criteria Analysis
SGRC	Smart Grid Research Consortium
SMART	specific, measurable, attainable, relevant, and trackable
SOA	service-oriented architecture
Sox	sulfur oxide
SPW	stakeholder percentage weight
SS	smart substation
SS93	substation No. 93
SS602	substation No. 602
SS664	substation No. 664
SV	sample value
SWV	stakeholders' weight values
t	ton(s)
T&D	transmission and distribution
TEC	(Sino-Singapore) Tianjin Eco-City
TNY	The Navy Yard (Philadelphia)
TNYEU	The Navy Yard Electric Utility
U.K.	United Kingdom
U.S.	United States
U.S. DOE	United States Department of Energy
UCI	University of California, Irvine
V	volt
VAR	volt ampere reactive
WACC	weighted average cost of capital
ZNE	zero net energy

Forward

This White Paper on Benefits Analysis of Smart Grid Projects represents a noteworthy collaboration between researchers from the United States, China and European Union aimed at moving toward global standardized analytical methods to evaluate the cost and benefits of smart grid investments. The U.S. Department of Energy recognized the importance of standardizing analytical methods to evaluate the smart grid investments made in its 140 smart grid demonstration and deployment projects funded through the 2009 American Reinvestment and Recovery Act (ARRA). As a result, DOE and the Electric Power Research Institute collaborated to develop a method for conducting cost and benefits analysis. This method was used by DOE to create the smart grid computational tool to assist in cost and benefit analysis of the smart grid investments made in the ARRA projects.

The challenges in creating global standardized analytical methods to evaluate smart grid investments are many. Differences in ownership of the electric power system (e.g., government and private sector); valuation of assets; valuation of benefits; allocation of cost and benefits; regulatory and policy climate; motivations; and customer base are among the many factors that impact analysis of these investments. There are also differences in the amount and type of experience with smart grid investments with wide variations between countries on progress made in moving toward modern power systems. As more experience is gained, confidence will grow in making smart grid investments and realizing their benefits.

Despite these challenges, it is important that we continue to collaborate and focus on creating standardized methods to evaluate smart grid investments. These methods can be applied to assist in making smart grid investment decisions and to evaluate existing investments using field data. Evaluation of existing investments using field data can be used to improve the standard methods and ultimately, investment decisions.

This White Paper contributes substantially to the growing body-of-work on methods to evaluate smart grid investments. Progress in creating global standardized methods for smart grid investments will be made incrementally and continued collaboration and white papers, such as this one, and other research papers will create the necessary momentum to achieve standard methods for smart grid investments that can be confidently applied in any country.

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1. Introduction

Smart grid technology is rolling out around the world, with the United States (U.S.) nearing completion of a particularly significant USD4-plus-billion federal program funded under the American Recovery and Reinvestment Act (ARRA) – 2009. The emergence of smart grid is an international phenomenon with policies adopted to accelerate deployment in many developed countries (Brown and Zhou, 2012). Multiple approaches to benefits analysis (BA) have accompanied projects around the world. There is a clear need for an understanding of the differences among these approaches and for movement toward a common approach. At least one international team is developing a common open-source benefits tool (ISGAN, 2015). A coherent basis for international evaluation of smart-grid project performance will facilitate comparison and transfer of results and will ultimately accelerate smart grid deployment.

The work described in this white paper was conducted under the auspices of a joint U.S.-China research effort, the Climate Change Working Group (CCWG) Implementation Plan, Smart Grid. Sharing of U.S. and China smart-grid research capabilities and results is an overarching objective of this activity. Early discussions in 2014 between the research teams identified two areas of focus: the analysis of smart-grid demonstration project benefits, which is the exclusive topic of this white paper, and advanced technology. The Advanced Technology Subgroup progressed along different lines, focusing on information exchange and will not produce a formal report. Researchers in both the U.S. and China have developed formal BA methods, which are explained and demonstrated in this document by means of example analyses. We present comparative analyses of smart grid benefits for four case studies, two in the U.S. and two in China, along with an additional BA of a smart grid project from Italy; this BA for the Italian project was done by the Joint Research Centre (JRC) of the European Commission, which has adopted a similar approach to that developed by the Electric Power Research Institute (EPRI) and U.S. Department of Energy (U.S. DOE) but adapted to the European energy system.

The first demonstration project we discuss comes from China and encompasses several smart-grid aspects of the Sino-Singapore Tianjin Eco-City (TEC). This project is evaluated using the analytic hierarchy process (AHP) together with fuzzy logic, in a method developed by the State Grid Corporation of China (SGCC).

The second demonstration project we discuss is the Shenzhen Bay Technology and Ecology City (B-TEC) project, also from China. B-TEC is a pilot component of the huge Qianhai Shenzhen-Hong Kong Modern Service Industry Cooperation Zone development (Qianhai Project).

The third demonstration project consists of two distinct projects in Irvine, California in the U.S. The first is an ARRA project from the Southern California Edison (SCE) Irvine Smart Grid Demonstration Project (ISGD). We analyze three of ISGD's sub-projects using the U.S. DOE Smart Grid Computational Tool (SGCT), which is based on the BA approach of the Electric Power Research Institute (EPRI). The second project is the University of California, Irvine (UCI) campus itself where distributed energy resource (DER) development has been in progress for many years, and extensions currently under way will convert the campus to a true microgrid.

The fourth smart grid project is at The Philadelphia Navy Yard (TNY) in Philadelphia, Pennsylvania in the U.S. This site was a longtime military base that came under jurisdiction of the City of Philadelphia in 2000 and is being repurposed as a mixed commercial-industrial, and possibly residential, development.

The final demonstration project we discuss is a smart grid demonstration by the Italian distribution company ACEA in the Malagrotta area near Rome. A key feature of this study is the treatment of technology scale-up to the entire Rome distribution grid.

For all projects, our analysis focuses on the methods used to account for benefits generated by smart grid technologies.

The remainder of this paper is organized as follows:

- Chapter 2 describes the different approaches to benefits analysis.
- Chapter 3 presents a broad overview of the case studies from China, the U.S., and Italy.
- Chapters 4 and 5 give the details and results of the in-depth analysis for the demonstrations in China and the U.S., respectively.
- Chapter 6 describes the outcomes of the in-depth JRC analysis for the project in Italy.
- Chapter 7 reveals the key limitations of methods discussed in this report through the case studies.
- Chapter 8 presents our conclusions and recommendations.

2. General Methods of Benefit Analysis Application to Smart Grid Projects

2.1. Nomenclature

Variable	***Variable Definition***
B_net	difference between the net benefits of the baseline scenario and the project scenario in the EPRI/U.S. DOE method
C_baseline	net benefits in the baseline scenario of EPRI/U.S. DOE method
C_project	net benefits in the project scenario of EPRI/U.S. DOE method
NPV	net present value
U	factor set of SG-MCA method
Ui	ith factor of a factor set (multi-layer evaluation) of SG-MCA method
Uij	factor of SG-MCA method
C	decision matrix of SG-MCA method
Cij	an element of decision matrix C of SG-MCA method
μM (x)	triangular membership function of SG-MCA method
l	lower bound of a fuzzy number of SG-MCA method
u	upper bound of a fuzzy number of SG-MCA method
wi	fuzzy weight of factor i of SG-MCA method
λ	number of levels of SG-MCA method
V	evaluation level set of SG-MCA method
Ri	single-factor decision matrix of Ui of SG-MCA method
Ci	decision value of Ui of SG-MCA method
CI	cash inflow of QPA method
CO	cash outflow of QPA method
n	calculation period of QPA method
Ic	specified discount rate of QPA method
IRR	internal rate of return of QPA method
Pt	static investment payback period of QPA method

2.2. Objectives and Principles

Demonstration and deployment of smart grid technologies and related practices are often evaluated and justified on an economic basis. The challenge for decision makers – utilities, policy makers, and others – is to use accurate, well-defined, consistent methods to evaluate smart grid proposals rigorously and objectively before an investment is realized. In addition, post-investment analysis using field data ensures that the capital has been invested wisely and that a balance among economic, social, and environmental targets is struck. Estimating the benefits of smart grid demonstration projects in this regard is challenging because social and environmental aspects are not easy to incorporate into such an analysis. Literature on BA of smart grid projects is fairly new, having emerged mainly in response to the need to evaluate the U.S. ARRA projects. There has been considerable worldwide activity in smart grid BA since 2010, and multiple BA approaches and embellishments have been developed. The primary objective of this chapter is to summarize existing BA methods and provide some detail about the methods examined in this white paper.

2.3. Overview of Benefits Analysis Methods

The subsections below briefly describe BA methods that have been developed to date, to the best of CCWG's knowledge. Using BA to assess smart grid projects is a relatively recent practice; the first method was published in 2011. Therefore, several of the methods mentioned here are being continuously improved as insights and data are gathered from their application to smart grid projects implemented in different contexts and electricity system settings.

2.3.1. Benefits Analysis with EPRI/U.S. DOE Method, U.S.

EPRI adjusts standard cost-benefit analysis (CBA) to apply to smart grid demonstration projects. CBA is the most-used evaluation technique for assessing infrastructure investments. The EPRI/U.S. DOE method is based on monetization and discount. Money is the common unit used to translate all costs and benefits associated with an investment or policy. EPRI's study concentrates on aspects of smart grid performance such as efficiency, environmental impact, reliability, power quality, safety, security, and cost reduction (Personal et al., 2014).

EPRI published its first BA report on a "future grid" in 2004 (EPRI, 2004). In collaboration with U.S. DOE, EPRI then developed the first comprehensive BA method in 2010 (EPRI, 2010). This method has been revised and refined with updates in 2011, 2012, and 2015 (EPRI, 2011, 2012, 2015a).

EPRI's BA method is also the basis for their work on the costs and benefits of integrating DER into the grid (EPRI, 2015b). The version of the EPRI method that focuses on DER develops specific scenarios of DER penetration or other exogenous factors (e.g., fuel cost, DER adoption cost) to consider what changes are needed in the grid to accommodate DER (in addition to regular maintenance-related upgrades that would be carried out anyway) and in regard to smart grids focuses only on DER-related smart grid benefits and costs.

The EPRI/U.S. DOE BA method method defines benefit as a monetized value of the impact of a smart grid project to a firm, a household, or society in general. Benefits are usually aggregated from multiple variables such as deferred capacity investment, reduced electricity purchases, reduced or deferred transmission and distribution (T&D) investment, reduced operations and maintenance (O&M), reduced transmission congestion, improved power quality, reduced environmental impacts, and so on. Once all relevant effects of a smart grid investment are quantified, a social discount rate is applied to translate future costs and benefits to the present day.

In addition, EPRI/U.S. DOE's work has been used by U.S. DOE as a basis for developing a tool, SGCT, to evaluate monetary benefits of smart grid projects funded by ARRA. This U.S. DOE tool was developed by Navigant Research (U.S. DOE 2011) and is still in use.

EPRI has published a guidebook based on EPRI/U.S. DOE work to facilitate implementation of smart grid pilot programs and experiments (EPRI, 2015a).

2.3.2. Benefits Analysis with Smart Grid Investment Model, U.S.

Within the U.S., the Smart Grid Research Consortium (SGRC) developed a Smart Grid Investment Model (SGIM™) (SGRC, 2012) that aims to evaluate the financial impact of smart grids on utilities, mainly by assessing the load profile of consumers served. This approach therefore emphasizes an investor perspective and does not appear to address customer benefits or societal or environmental impacts. This model examines a standard reference period of 20 years.

2.3.3. Benefits Analysis with Frontier Economics Method, European Union (EU)

In Europe, two main approaches to smart grid benefits quantification have appeared. One focuses on real options and one on social BA.

In 2011, Frontier Economics prepared a first evaluation report (Frontier Economics, 2011a) adopting a real options approach, which was consolidated in 2012 (Frontier Economics, 2012) with an application to the United Kingdom (U.K.). Real-options-based analysis provides a platform to choose the best strategy when there is uncertainty. This method defines scenarios to consider changing future circumstances resulting from new information about the utility of smart grids. Frontier Economics acted as contractor for the U.K. Smart Grid Forum, which is a working group set up to advise the U.K. electricity and gas regulatory authority (Office of Gas and Electricity Markets [OFGEM] and the U.K. Department of Energy and Climate Change (DECC) on how to deploy smart grids.

Frontier carried out a similar evaluation of smart metering deployment in Germany (Frontier Economics, 2011b). In that evaluation, the methodological approach was much simpler: each German household was assigned to a specific category depending on factors such as consumption behavior, size, and so on. Costs and benefits were calculated for each category and summed up. The result of this estimation suggested that only about 15% of German households would benefit from installing smart meters.

2.3.4. Benefits Analysis with JRC Method, EU

Another approach developed on the basis of EPRI's work was tailored to the European context by the JRC of the European Commission in 2012 (European Commission, JRC, 2012a). This method has since also been applied several times to support specific policy-making processes within the EU and in particular has been modified to evaluate projects that focus only on smart metering (European Commission, JRC, 2012b). In comparison to the EPRI method, JRC adopts a different approach to benefits monetization and suggests mapping new assets related to smart grid project installations to specific functionalities and calculating the benefits of each of functionality.

As in the EPRI method, JRC goes beyond the definitions that would be used in a simple CBA, including sensitivity analysis and other analytic tools tailored to specific evaluations. JRC’s assessments of smart grid projects are therefore often considered to be “multi-criteria" analyses. Some examples of applications of the JRC method are:

- Evaluation of EU Projects of Common Interest (trans-national projects involving more than one European Country) in the field of smart grids (European Commission, JRC, 2013, 2014a, 2016)
- Benchmarking the smart metering roll-out across the EU (European Commission, JRC, 2014a, 2014b, 2014c)
- Evaluation of the scalability from pilot to the whole grid of the city of Rome
- Evaluation of Ente nazionale per l'energia elettrica’s Isernia project (forthcoming)

2.3.5. Benefits Analysis with McKinsey Method, EU

The consulting firm McKinsey developed a tool to calculate smart grid benefits (ISGAN, 2015). The tool takes into account four groups of smart grid functionalities and four smart grid benefits. The functionalities are: advanced metering infrastructure (AMI), customer applications, grid automation, and integration of DER and electric vehicles (EVs). The four smart grid benefits are: demand shift and savings, longer life of assets, operational improvements, and reliability improvements. The tool calculates the difference between a baseline and a reference scenario. This tool is not available to the public and is provided as a commercial package without much detail on its analysis.

2.3.6. Benefits Analysis using Other Methods

Several other studies have targeted the quantification of benefits resulting from smart grid implementation. However, some studies are not included in this analysis because of the difficulty in accessing data and details about their methods. Examples of these studies are:

- A Czech study on BA (estimation of NPV) for a typical Czech household (Adamek et al., 2011).

- The European Electricity Grid Initiative (EEGI) (GridPlus, 2010). This is a European Industrial initiative under the Strategic Technology Plan launched by the European Commission "to accelerate the development and deployment of low-carbon technologies" (European Commission, 2006). EEGI focuses on complementing BA methods with a set of specific key performance Indicators (KPIs) to assess each project's consistency with the defined policy objectives.
- The Smartness Barometer (Eurelectric, 2012) tool. This tool, developed in close collaboration with JRC, focuses on building KPIs to evaluate the impact of smart grid projects, particularly their contribution to EU policy goals.
- A study on social BA conducted by the Netherlands Committee for Environment in Delft (CE Delft, 2012). Unfortunately, only a summary of this study is available in English, so no further analysis of the method adopted has been carried out.
- The California Public Utilities Commission (CPUC) 2013 distribution resources plan (CPUC, 2015). This plan allows California utilities to present their DER plans to the commission for approval. The method uses locational net benefit analysis (LNBA) to determine the optimal location of DER with the aim of optimizing generation. This method compares NPVs resulting from different scenarios. First, simulations of DER integration in a specific line segment are run, and distribution margin costs are calculated with and without DER. Various scenarios are generated comparing the optimal amount and location of DER in terms of cost-effectiveness and dispatch. This method complements the existing Integration Capacity Analysis (ICA) method and exhibits several characteristics of a traditional CBA. However, a detailed study would be needed to integrate LNBA features into a more general BA method.
- Duke Energy's agent-based end-use model, MAISY, developed to analyze benefits of smart grid programs (Jackson, 2009). Agent-based models enable evaluation of each individual agent or customer in a statistically representative sample rather than an aggregate customer segment. MAISY is a detailed model in which individual utility customers are reflected as separate agents. Benefits are all economic, calculated as avoided costs of installing new generation and T&D assets. There is no consideration of environmental/social, security, and reliability-related benefits. The report discussing the case application of the model on a representative sample of 1,350 residential customers of Duke Energy in Indiana points to a likely significant NPV associated with DER implementation. However, no numeric value is reported.
- BA estimation of smart grid development for the Russian power system (Fedor and Fedosova, 2015). This study defines the technical options for each component of the system, then combines these into a "Smart Power System" scenario in which all of the possible options for generation, transmission, distribution, and consumption are pooled into a technically viable complete electricity system. The resulting system is then optimized under different scenarios, and the results are compared to a business-as-usual (BAU) scenario. This method relies on a combination of techniques (expert assessment of technologies in phase 1, various mathematical models in phases 2 and 3) to identify how the Russian power system would look under selected scenarios. Finally, this approach uses financial models to evaluate the effects of smart grid installations in terms of capital expenditure (CAPEX) and operational expenditure (OPEX) for each additional generation facility or T&D line/substation/retrofitting investment.
- The "Smart Grids, Smart City" program, which focused on deploying and testing smart grid technologies with Australian grid operators Ausgrid, and EnergyAustralia between 2010 and 2013. The program assessed costs and benefits of additional DER and distributed storage and ran trials on peak-shaving opportunities involving about 17,000 electricity customers (Arup, 2014). The report suggests a potential economic benefit of 28

billion Australian dollars (AUD) over a period of 20 years, starting in 2014, if smart grids are deployed in the country. The study calculates the benefits of smart grids stemming from eight technology types (smart grid assets) on the entire Australian electricity system. The study uses an approach similar to that used in the EPRI and JRC methods, identifying in a step-by-step manner the impacts and associated benefits of smart grid technologies and products. The calculation of each impact and benefit has been validated by data collected from customer trials. The impacts are replicated at the national level by defining customer and network types as well as three different macroeconomic states for Australia. The authors identify a BAU scenario, run a preliminary BA, and then build a smart grid scenario from the most promising technologies and perform a final BA on this scenario.

- Ernst & Young (2012) report analyzing the potential benefits for the British economy if smart grids are fully developed in the U.K. The main finding of the report is that pursuing effective deployment of smart grids could save £19 billion (NPV) compared to a scenario in which only typical grid reinforcement is carried out. The Ernst & Young approach does not explicitly quantify benefits but instead estimates net benefits, i.e., additional benefits compared to the base scenario of only typical grid reinforcement. Important features that distinguish this approach from EPRI's include that the quality of electricity supply (i.e., reliability) is constant – i.e., it does not improve in the smart grid scenario – so this important source of benefits is not quantified. At the same time, this study includes benefits that are often neglected, such as the impact of smart grid deployment along the supply chain and the positive effect on job creation and on British exports if the U.K. becomes a leading actor in smart grids worldwide. In addition, the impact of full-scale deployment of EVs is seen as a positive output of smart grid diffusion.
- International Smart Grid Action Network (ISGAN) "Benefit – Cost Analyses and Toolkits." ISGAN is an implementing agreement set up by the International Energy Agency in 2010 with participation of 25 countries from all over the world (ISGAN, 2010). ISGAN's "Benefit – Cost Analyses and Toolkits" activity aims to help policy makers at all levels make choices about smart grid deployment. Although the tool itself has not been completed, the description of the work to be undertaken by the consortium expresses that the aim is to combine several tools into a system that will concentrate on few characteristics of a smart grid system but will be highly flexible and therefore produce results that are easily comparable among the 25 partner countries. Inputs will be provided by project promoters in the form of Excel files, and calculations will be performed through object-oriented programming (OOP) (ISGAN, 2014).
- The Irish Commission for Energy Regulation (CER) BA. CER approached the issue of smart grid roll-out in 2010 with a first consultation paper and subsequent smart metering customer behavioral trials and technology trials. Their first BA (CER, 2011) focuses only on smart metering and societal impacts without quantifying costs and benefits that accrue only to selected parties. The main options considered are the type of technology used – power line carrier (PLC) or general packet radio service (GPRS) or combinations of the two – and the frequency of billing (monthly or bi-monthly). The societal NPV is generally positive (eight out of 12 option combinations). In 2013, the Energy Needs Ireland (ENI) initiative was launched as a research and education program based at the Electricity Research Centre of University College of Dublin. ENI, following up on CER's smart metering BA, completed a BA of full deployment of smart grids. The approach is an accounting one: different cost and benefit items are quantified on the basis of previous studies, e.g., costs of upgrading the grid infrastructure are taken from the national transmission system operator, and a best-case and worst-case scenario are selected. Several non-quantifiable costs and benefits are described as well, and a non-quantitative risk analysis is performed. The outcome shows huge variability in costs and benefits

depending on scenarios, and the conclusion is that full smart grid deployment should be deferred to the future when more precise data about smart grid uptake are available.

2.1. Details of Benefits Analysis Methods Studied in this Report

The following subsections briefly describe the BA methods that CCWG used or developed for evaluating benefits of the smart grid projects described in this white paper.

2.4.1. Benefits Analysis with the SG-MCA Method (applied to Sino-Singapore TEC Project)

SG-MCA combines AHP and fuzzy logic to assess the benefits of smart grid projects. Multi-objective decision making is well known field that is a branch of operation research models. This approach can handle significant social, economic, and environmental impacts. Its inclusion of multiple stakeholders in the decision-making process is widely acknowledged.

AHP was first introduced by Saaty (1980) and has been used extensively as a tool in single- and multi-objective decision-making problems. AHP is constructed as a hierarchy that breaks down a decision top to bottom in a three-stage method: (1) building the hierarchy, (2) weighting the indicators by a pair-wise comparison, and (3) calculating the final value for the alternatives. The goal is at the top level, criteria and sub-criteria are in the middle levels, and the alternatives are at the bottom of the hierarchy. Public and private stakeholders might take part in constructing this hierarchy (Beria et al., 2012). The best alternative can be selected by its rank among alternatives. The method uses a subjective assessment of relative importance converted to a set of overall scores (i.e., weights), which structures the problem as a hierarchy (Barin et al., 2009).

However, use of AHP as single decision-support tool may be problematic largely because, in many decision-making situations, it is difficult to obtain exact numerical values for criteria or attributes (Li et al., 2010). Evaluations of many parameters are not accurate, and conversion of subjective criteria to weights, which are usually expressed as qualitative descriptors by the decision maker and thus reflect his/her biases, are also often problematic. Fuzzy logic, introduced by University of California, Berkeley mathematician Lotfi A. Zadeh (1988), was employed to expand the AHP decision-making methodology (Yager, 1981) by using partially ordered sets of fuzzy ratings in the decision process rather than cardinal numbers. Fuzzy logic theory admits the uncertainty of truth in an explicit way; it can also easily incorporate qualitative information (Shang and Hossen, 2013).

Some decision-making research has applied AHP and fuzzy logic theory to energy and electricity planning. Luo et al. (2014) used a method based on AHP and fuzzy logic to evaluate the energy efficiency of EV charging stations. Le et al. (2016) proposed the Fuzzy Analytic Hierarchy Process algorithm (Fuzzy-AHP) approach to determine the weight of the load nodes of a system and select the control strategy when the system operates at various load levels. Barin et al. (2011) applied both AHP and the fuzzy logic to evaluate the operation of energy storage such as pumped hydro, compressed air energy, hydrogen, flywheels, super-capacitors, and lithium-ion or sodium sulfur (NaS) advanced batteries, and vanadium redox flow batteries. The main objective of their study is to find the most appropriate energy storage technology consistent with power quality. Thengane et al. (2014) performed a BA using classical AHP and the fuzzy AHP to compare eight different hydrogen production technologies. They plotted the results obtained for benefits against the normalized equivalent annual costs of each technology. Results showed that the fossil-fuel-based processes appear to have fewer beneficial qualities (including greater environmental impacts) but are more cost effective. The renewable-energy-based processes appear to have more benefits but hydrogen production is more expensive than fossil-fuel production.

The SG-MCA method is used for the TEC BA to evaluate practical, technical, economic, and social factors with qualitative and quantitative indicators. A combined AHP and fuzzy evaluation method was chosen. As explained previously, the basic principle of AHP is to divide the various elements of the program evaluation system into several levels to form an orderly hierarchical model and to make comparative judgments among the elements of each level and between each level and the previous levels to obtain weights for each element. This comprehensive weight set is used to determine the optimal solution, which is defined as the maximum weight.

The fuzzy comprehensive evaluation method jointly evaluates the attributes measured by different indicators using the characteristics of fuzzy relation composition. The mathematical model can be divided into a model and a multi-level model. Fuzzy judgment is the basis for multi-level fuzzy, which can lead to a multi-stage model. For the smart grid pilot project evaluation, the first level of the fuzzy comprehensive evaluation is initially used for the individual dimensions of the evaluation, such as the practical, technological, economic, and social; the second level of fuzzy evaluation is based on the first level and can be applied to multi-dimensional assessment. That is to say, a total evaluation is formed by synthetically considering the four attribute dimensions. By combining these two evaluation methods, a composite index score can be determined that reflects all attributes.

This method defines a decision matrix to represent expert opinion in a reasonable way without requiring conciseness and thereby allowing for the vagueness of expert judgment. Compared to conventional methods, this approach combines both AHP and fuzzy set theory by using triangular fuzzy numbers instead of integer values, i.e., 1 to 9. The evaluation routine can be formulated as follows;

(1) Hierarchy model

For a given factor set $U = \{U_1, U_2, \cdots, U_n\}$, where the i^{th} factor is U_i, U_i should satisfy $U_i \cap U_j = \emptyset\ (i \neq j)$

(2) Fuzzy *decision matrix*

C_{ij} is a element in the decision matrix that represents the relative priorities of the i^{th} element in respect to j^{th} element, with a larger value indicating that the i^{th} element is more important than the j^{th}. The decision matrix is written as follows,

$$C = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ C_{n1} & C_{n2} & \cdots & C_{nn} \end{bmatrix} \tag{1}$$

Table 2.1
Scale expression of a decision matrix

Number	Definition	C_{ij}
1	equally important	1
2	moderately important	3
3	very important	5
4	significantly important	7
5	extremely important	9

In a decision matrix, a triangular function is determined by three numbers. . The membership function (Xiaoting and Shijan, 2011) $\mu_M(x)$ is expressed as shown in Eq. 2:

$$\mu_M(x) = \begin{cases} \frac{1}{m-x}x - \frac{l}{m-l}, x \in [l,m] \\ \frac{1}{m-u}x - \frac{u}{m-u}, x \in [m,u] \\ 0\,, otherwise \end{cases} \tag{2}$$

where, l and u are the lower and upper bounds of a fuzzy number; i.e., $l \leq m \leq u$ and m is the intermediate value. Therefore, a fuzzy number can be expressed as (l, m, u) by convention.

(3) Fuzzy weights

The fuzzy weights, w_i, can be calculated by

$$w_i = \sum_{j=1}^{n} C_{ij} \div \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}\,, i = 1,2,\cdots,n \tag{3}$$

(4) Evaluation set

An evaluation set maps the evaluation values to λ levels to reflect the expert judgments, i.e., $V = [V_1, V_2, \cdots, V_\lambda]^T$.

(5) Multilayer *fuzzy comprehensive evaluation*

A single-factor fuzzy evaluation is applied to the factor set $U_i(i = 1,2,\cdots,n)$. Based on expert judgments, the membership values for each $U_{ij}(j = 1,2,\cdots,m)$, which is a sub-factor, e.g., $U_i = \{U_{i1}, U_{i2}, \ldots, U_{im}\}$, can be obtained for each layer. Hence, R_i is the fuzzy evaluation transformation matrix of U_i , where

$$R_i = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1\lambda} \\ r_{21} & r_{22} & \cdots & r_{2\lambda} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \ldots & r_{m\lambda} \end{bmatrix}_{m\times\lambda} \tag{4}$$

The weight vector w_i of U_i can be calculated by using the triangular-fuzzy AHP method, where $w_i = [w_{i1}, w_{i2}, \cdots, w_{in}]^T$. For each layer, the membership value of U_i can be calculated by

$$C_i = w_i * R_i = \left(C_{ij}\right)_{1\times\lambda} \tag{5}$$

where C_i is the fuzzy integration operator.

2.4.2. Benefits Analysis with the Qianhai Project Approach (Applied to B-TEC Project)

(1) Comprehensive benefit evaluation approach for the project

Similar to CBA of engineering projects, the CSG-Qianhai approach analyzes the benefits of smart grid technologies applied in the Qianhai project, and the cost of each technology is analyzed as well. The evaluation indices (for example, NPV, IRR, or PT) reflect the benefit of the project. In the analysis process, costs and benefits are calculated for all stakeholders, and a correspondence table is developed that includes smart grid subsystems, functions, and benefits, based on interests of stakeholders. China is currently engaged in structural reform of the power system, so the BA classifies both achievable profits under the current market mechanism and future potential achievable benefits. In the comprehensive benefit evaluation, achievable and potential benefits are analyzed for stakeholders and investors. The evaluation approach is objective and considers all aspects. Uncertainties are subjected to sensitivity and risk analysis after the comprehensive benefit evaluation.

(2) Evaluation principles of the Qianhai Project Approach

The principles underlying the QPA are:

- Comprehensiveness: A comprehensive benefit evaluation should be completed for the smart power grid to reflect its benefits from different perspectives and in different categories.
- Consistency: The contents of the benefit evaluation should be consistent with evaluation targets to ensure the rationality of the evaluation; e.g., incremental benefits should correspond to incremental assets.
- Measurability: The quantification of benefit indices should be well defined. Indices should be calculable or measurable, and data should be easy to collect and in standard form.

(3) Qianhai Project Approach evaluation system

For the QPA smart power grid BA, equipment assets are classified first, then their functions are matched, then a BA is performed consistent with the internal operation mechanisms of system modules and external markets, and, finally, an economic benefit evaluation approach is adopted. Figure 2.1 shows the evaluation logic.

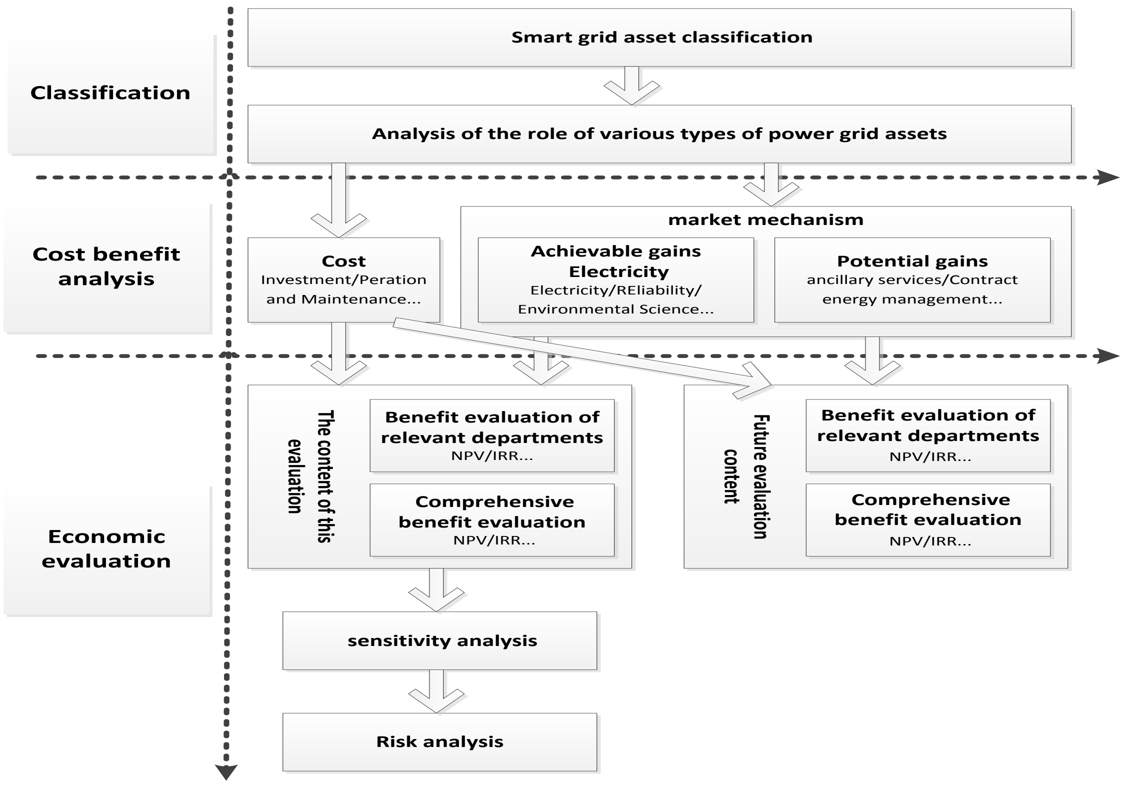

Figure 2.1. Smart power grid evaluation system construction logic in QPA Method

(4) Benefit calculation

Compared with traditional power grids, the smart power grid extends all or some of the following system modules: 1) for grid structures, the module of optimal operation and the fault self-recovery system, which is intended to facilitate optimal operation of the network; 2) for distributed generation (DG), the DG coordination and dispatch system module that aims to optimize economic operation of power sources; 3) for users, the AMI system for precise measurement and demand-side response; 4) for equipment, the distribution grid operation state sensor system (Sun et al., 2011) for improving equipment and system operation reliability; and 5) the energy storage station system in the load center.

(5) Sensitivity analysis and risk analysis

Factors of high uncertainty among costs and benefits are analyzed, the impact on the benefits of the project is analyzed quantitatively, and sensitive factors are identified to enable control and avoidance of risks. Multi-factor sensitivity analysis is carried out as required. The risks of not realizing the project's benefits are determined according to the sensitivity analysis.

(6) Evaluation method

The quantitative method outlined above enables analysis of the comprehensive benefits of the smart grid investment as well as specific benefits for stakeholders, e.g., consumers, the power supply bureau, and the utility. The primary evaluation indices are NPV, IRR, and payback period. Other evaluation indices that may be used, as relevant to actual conditions, include investment interest rate, investment profit-tax rate, and capital interest rate. When evaluating stakeholder benefits, costs and income are calculated separately.

- IRR refers to the discount rate when the following are zero: the accumulated current value of the actual annual net cash flow before the evaluation time and each annual net cash flow during the estimated life cycle after the evaluation time. IRR is a major dynamic index that reflects the actual profitability of the project.
- Financial NPV is the sum of current values of net cash flows in the project's life cycle for discount rate calculation based on benchmark yield as a discount rate. Financial NPV is a dynamic index that reflects the actual profitability of the project.
- Investment payback period (Pt) is the period of balancing net profits and all construction expenses. It is a significant index for reflecting the project's investment return capacity. Payback period can be broken down into dynamic and static. To simplify the calculation, the static investment payback period is adopted for the calculations for the smart grid project.

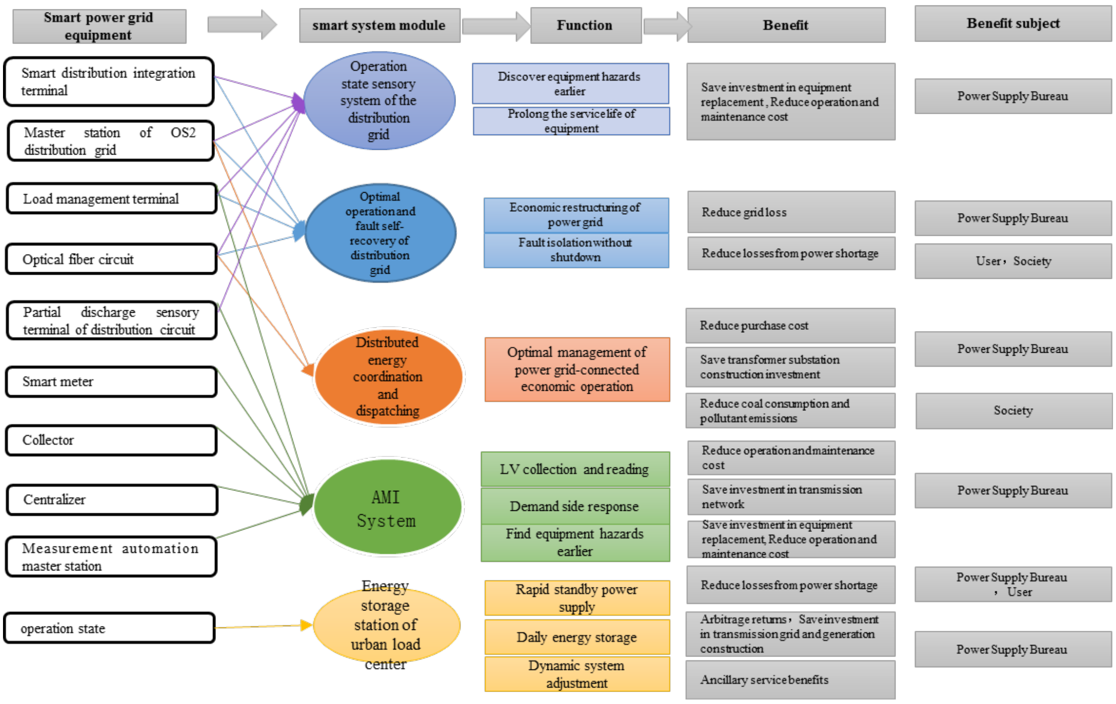

Figure 2.2. Analysis of smart distribution network equipment benefit

Table 2.2
QPA method evaluation index calculation methods and evaluation standards

Index	Calculation method	Evaluation standard
NPV	$NPV = \sum_{t=1}^{n} (CI - CO)_t (1 + i_c)^{-t}$ CI: cash inflow; CO: cash outflow; n: calculation period; ic: specified discount rate (benchmark yield)	If NPV is ≥0, the project achieves its expected benefits.
IRR	$\sum_{t=1}^{n} (CI - CO)_t (1 + IRR)^{-t} = 0$ CI: cash inflow; CO: cash outflow; (CI-CO)t: net cash flow of the tth year; n: calculation period; IRR: internal rate of return	If IRR is > benchmark yield, the project achieves its expected benefits.
Pt	(The year in which the accumulated net cash flow becomes a positive value – 1) + the absolute value of the accumulated net cash flow of the previous year / the net cash flow of the current year	If Pt is > benchmark yield, the project achieves its expected benefits.

2.4.3. Benefits Analysis with the EPRI/U.S. DOE Method (applied to ISGD & UCI Campus Projects)

The EPRI/U.S. DOE method defines *benefit* as a monetized value of the impact of a smart grid project to a firm, household, or society in general. All benefits must be expressed in monetary terms. For smart grid systems, there are four fundamental categories of benefits:

- Economic – reduced costs, or increased production at the same cost, that result from improved utility system efficiency and asset utilization
- Reliability and Power Quality – reduced number, duration, and extent of 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

Multiple stakeholders are involved in smart grid development, including *consumers*, the *utility*, and *society* as a whole. Different stakeholders might have different areas of focus and shares of benefits. The *consumer* and *utility* would share the economic benefits, the *utility* captures most of the reliability benefits, and *society* at large enjoys the environmental and security benefits.

The EPRI/U.S. DOE BA method is based on the difference between the net benefits associated with a baseline scenario, which represents the system state without the smart grid demonstration project, and a contrasting project scenario.

$$B_{net} = NPV\{C_{project} - C_{baseline}\} \quad (6)$$

In general, benefits are reductions in costs and damage (e.g., deferred capacity investment, reduced electricity purchases, reduced or deferred T&D investment, reduced O&M, reduced transmission congestion, improved power quality, and reduced environmental insults), whether to firms, consumers, or society at large. U.S. DOE's SGCT, which is based on the EPRI/ U.S. DOE BA approach, starts with a listing of smart grid assets, identifies the functions of those assets, and ultimately monetizes project benefits, as shown in Figure 2.3. The first step is to list all the smart grid assets deployed in the project to be evaluated, for example, *Distribution Automation*, *Smart Appliances and Equipment*, 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 final 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.

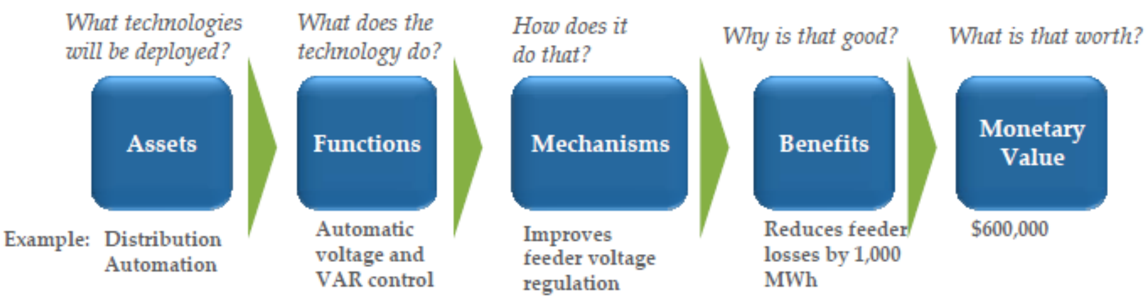

Figure 2.3. SGCT logic flow. *Source*: EPRI, 2010.

Table 2.3, adapted from EPRI (2010), summarizes the way in which the framework defines the categories of benefits of smart grid projects, the sources of the benefits, and the data needed
to estimate the benefits.

Table 2.3
Summary of benefits, sources of benefits, and data that project-funding recipients can expect in EPRI/U.S. DOE method

Benefit Category	Benefit	Source of Benefit	Information Reported by Project, with and without Smart Grid Deployment
Economic	- Electricity cost savings - Lower electricity cost to consumers	- Flatter load curve (from load shifted to off-peak periods, e.g., from consumer behavior and smart appliances that can respond to price signals) - Dynamic pricing and/or lower electricity rates (reflecting reduced generation costs with flatter load curve) - Lower total electricity consumption	- Hourly load data, by customer - Monthly electricity cost, by customer - Tariff description, by customer - Demographic and other information affecting demand - For firms, square footage and standard industrial classification code - Types of smart appliances in use
	- Reduced generation costs from improved asset utilization	- Flatter load curve (from load shifted to off-peak periods, e.g., from consumer behavior and smart appliances that can respond to price signals) - Dynamic pricing and/or lower electricity rates (reflecting reduced generation costs with flatter load curve) - Lower total electricity consumption	- Generation costs (that reflect optimized generator operation) - Deferred generation capacity investments - Reduced ancillary service cost
	- T&D capital savings	- Deferred T&D capacity investments - Reduced equipment failures	- Deferred T&D capital investments
	- T&D O&M savings	- Reduced O&M operations costs - Reduced meter-reading cost	- Activity-based O&M costs Equipment failure incidents
	- Reduced transmission congestion costs	- Increased transmission transfer capability without building additional transmission capacity	- Actual real-time capability of key transmission lines
	- Reduced T&D losses	- Optimized T&D network efficiency - Generation closer to load [from DG]	- T&D system losses (megawatt-hours [MWh]) - % of MWh served by DG

	- Theft reduction	- Reduced electricity theft	- Estimated T&D system losses from theft (MWh)
Reliability and Power Quality	- Reduced cost of power interruptions	- Fewer sustained outages Shorter outages (reduced duration) - Fewer major outages	- System Average Interruption Frequency Index (SAIFI) - System Average Interruption Index Duration Index (SAIDI) or Customer Average Interruption Duration Index (CAIDI)
	- Reduced costs from better power quality	- Fewer momentary outages - Fewer severe sags and swells - Lower harmonic distortion	- Momentary Average Interruption Frequency Index (MAIFI)
Energy Security	- Greater energy security from reduced oil consumption	- Electricity substituting for oil by “smart-grid-enabled” EVs	- MWh of electricity consumed by EVs
	- Reduced widespread damage from wide-scale blackouts	- Reduced wide-scale blackouts	- Number of wide-scale blackouts
Environmental	- Reduced damage as a result of lower greenhouse gas/carbon emissions - Reduced damages as a result of lower sulfur oxide (SOx), nitrogen oxide (NOx), and particulate matter (PM) emissions	- Lower electricity consumption from: o Smart appliances - Lower T&D losses from: o Optimized T&D network o Generation closer to load (DG) - Lower emissions from generation from: o Combined heat and power (CHP) o Renewable energy (RE) o Operating generators more efficiently o Avoiding additional generator dispatch with demand response	- Reduced CO_2 emissions Reduced SOx, NOx, and PM emissions from: o Hourly consumption by fuel type, compared to baseline/control group o % of MWh served by DG o T&D system losses (MWh) o Megawatts (MW) of CHP installed o % of MWh served by RE o % of feeder peak load served by RE o Average heat rate of supply (or similar information)

Source: EPRI, 2010. Note: Sustained outages are those > 5 min, excluding major outages and wide-scale blackouts. Major outages are defined using the beta method, per Institute of Electrical and Electronics Engineers (IEEE) standard 1366-2003. Wide-scale blackouts are rare, extensive blackouts that cover a wide region.

2.4.4. Benefits Analysis with TNY Method (applied to TNY Project)

The TNY BA framework is based on computing a set of project benefits and costs for a given project operation scenario compared to a baseline operation scenario. Figure 2.4 shows TNY's BA framework.

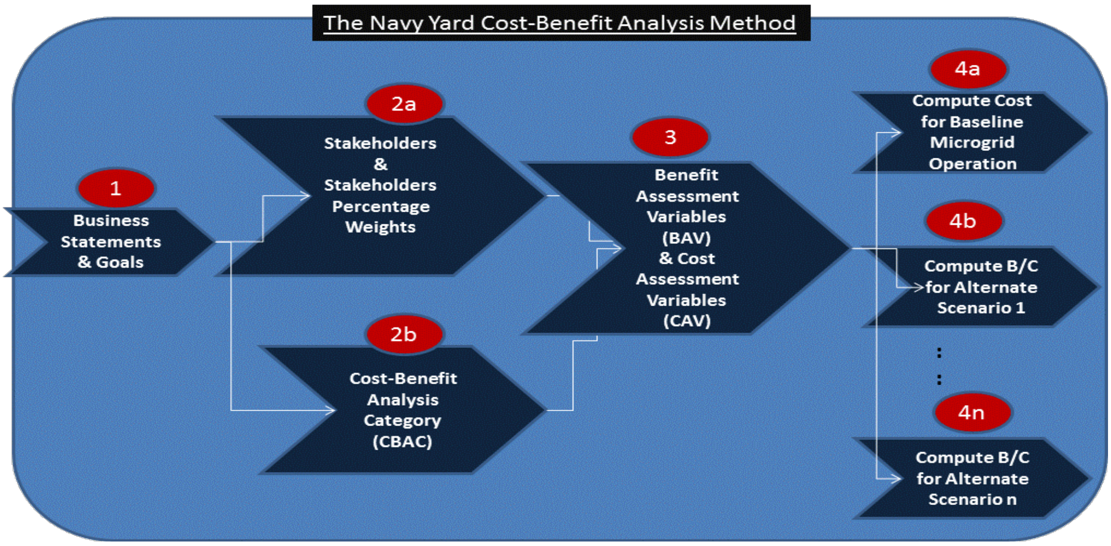

Figure 2.4. Step-by-Step process used by TNY BA Method

A summary of all of TNY BA steps is as follows:

Step 1: Establish a business context driven by the Business Problem Statement and Goals.

Step 2a: Define stakeholders; each stakeholder is assigned a percent weight, called the stakeholder percentage weight (SPW)

Step 2b: Functional grouping of benefit assessments are called cost-benefit analysis categories (CBAC).

Step 3: Define a set of benefit assessment variables (BAVs) and cost assessment variables (CAVs) by CBAC together with the following:

- Assessment weight values (AWVs) are assigned to each of the BAVs and CAVs
- Stakeholders' weight values (SWVs) are assigned to BAVs and CAVs by stakeholder.
- Stakeholders' composite weight (SCW) is calculated as weighted product of SWVs/ SPWs
- Benefit assessment composite weight (BACW) and cost assessment composite weight (CACW) are established by calculating the product of SCWs and AWVs

Step 4: Project benefits and costs are computed for baseline scenarios and the other operational scenarios being considered as follows:

- Different BAVs and CAVs are calculated utilizing the designated tool and methodology.
- BACWs and CACWs are applied to the participating BAVs and CAVs when calculating project benefits and costs as defined in the Appendices.
- A single composite benefit-cost (B/C) ratio is calculated.

(1) Establish Business Problem Statement and Goals

The business problem that needs to be addressed by the Navy Yard Electric Utility (TNYEU) is to determine the most cost-effective means for adding significant electricity capacity – both in terms of the quantity of electricity required, and in terms of installing new distribution infrastructure where it does not presently exist – and to keep customer electricity costs as low as possible. In parallel, efforts must support the overall economic development agenda at The Navy Yard.

(2) Identify Stakeholders and Establish CBAC

Table 2.4
Primary Stakeholders at the Navy Yard

No.	Stakeholder Name	Stakeholder Description
a	Philadelphia Industrial Development Corp. (PIDC)	PIDC established TNYEU as a separate owner and operator of the electricity distribution grid providing services to TNY's 70 electric customers, referred to as "Tenants" and classified into two categories.
b	Tenant A (Tenant - Category A)	Stakeholder Tenant A represents the nine largest electricity customers who consume approximately 90% of all electricity. This stakeholder group has a significant impact on key parameters such as peak demand.
c	Tenant B (Tenant – Category B)	Stakeholder Tenant B represents roughly 60 of the 70 smaller users, most of whom are very concerned with cost per kilowatt-hour (kWh).
d	Detroit Edison Energy	Detroit Edison Energy maintains and operates TNYEU on behalf of PIDC. This stakeholder's mission is to ensure safe, effective operations. Detroit Edison Energy is less focused on financial performance of the alternatives being considered.
e	Philadelphia Electric Company (PECO)	As the regulated public utility supplying most of the electricity to TNY, PECO is concerned with the interconnection and reliability of on-site DER.
f	The "Pennsylvania-Jersey-Maryland" Market (PJM)	PJM, the regional transmission operator, is interested in the operational, security, optimization, and resiliency characteristics.
g	Public Private Partnership (PPP)	Private investment in the form of power purchase agreements (PPAs) or PPPs is to fund energy projects at TNY.

The following four CBACs are defined for TNY benefit analysis computations: (i) financial / economic, (ii) operational reliability and efficiency (iii) environmental, and (iv) innovation and economic growth.

(3) Establish Assessment Variables and Composite Weight Values

BAVs and CAVs corresponding to each of the CBACs are defined. The objective is to evaluate benefits and costs by each assessment standard category (ASC) as shown in Figure 2.5.

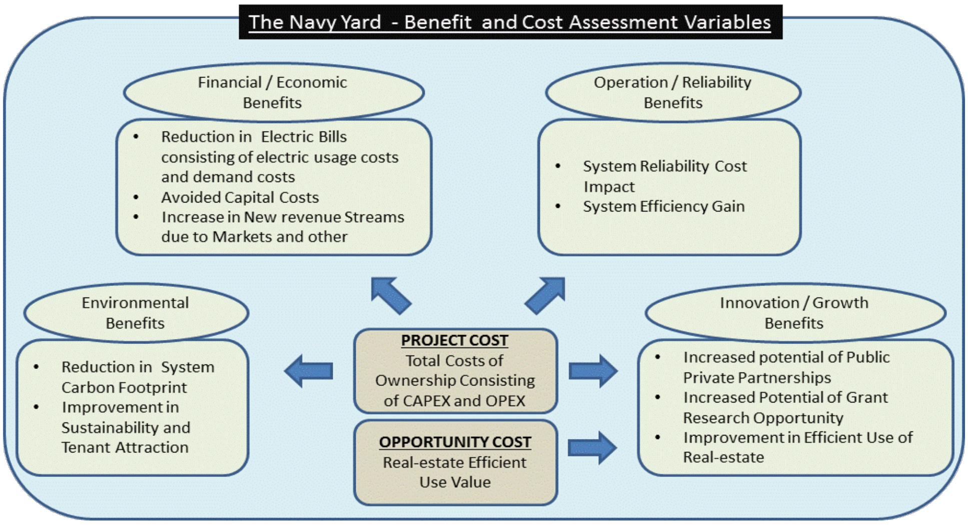

Figure 2.5. Benefit – Cost Correspondence by Assessment Category

(4) Project Benefit and Cost Calculations

Different methodologies and tools are used to perform calculations for different BAVs and CAVs as described in Table 2.5.

Table 2.5

Calculation of BAV and CAV data in TNY Method – Tools & Methodology

Methodology	Tool
Operational planning optimization	DER-CAM (Sullivan et al., 2015): The Distributed Energy Resource – Customer Adoption Model developed by Lawrence Berkeley National Laboratory, U.S.
Project finance calculations	PIDC Financial Model-Computation Spreadsheet Tool : TNY Business Case Analysis Tool developed internally by PIDC as part of The Navy Yard Energy Master Plan Project (Agate, 2013) to analyze its own financial-model computation in order to perform project financing calculations.
IEEE system reliability standards – SAIDI. SAIFI, & CAIDI*	Interruption Cost Estimate (ICE) Computation Tool[1]: ICE developed by Nexant / Lawrence Berkeley National Laboratory, U.S.
System loss calculation methodology	PJM and PECO Loss Coefficient: PJM and PECO publish the transmission loss factor and distribution loss factors that are used to estimate power delivery losses on the electricity transmission and distribution grids, respectively. TNY project computes the reduction in system losses using the T&D loss factors.
PIDC heuristic Methods	PIDC Tools & Heuristic Methods: PIDC uses internal tools and heuristic methods to compute a subset of ASVs.

* SAIDI – system average interruption duration index; SAIFI – system average interruption frequency index; CAIDI – customer average interruption duration index

[1] (http://icecalculator.com/)
[2] http://www.iec.ch/smartgrid/standards/
[3] Sampled value network is a widely used communication network which was designed to support data (like voltage and current value) transmission between terminal device and protection control device in a

3. Overview of Smart Grid Project Case Studies

3.1. Sino-Singapore (TEC) Project

(1) Project Background

On November 18, 2007, the leaders of China and Singapore signed an agreement to cooperate on building TEC. The eco-city theme is "environmental protection, energy conservation, and green building," and its philosophy is strong, self-healing, flexible, economic, compatible, integrated smart grid construction providing reliable, cost-effective, clean and environmentally friendly, transparent and open, friendly and interactive service. The shared objectives of the two governments are to address global climate change, strengthen environmental protection, and encourage resource conservation.

In recent years, the SGCC has expressed its commitment to social responsibility by actively committing to promote innovation through development of grid technology and transformation of energy use patterns. The Tianjin Power Company is implementing the national energy strategy, serving the economic and social development of Tianjin, and relying on TEC as the first comprehensive study of all aspects of smart grid technology, with its integrated smart grid demonstration projects designed to boost eco-city development and provide a model and reference for construction in other similar areas of the world.

Figure 3.1. Animation park at TEC

TEC is located in the 30 km^2 national development strategic area, 45 km from Tianjin city center and 150 km from Beijing. TEC is within the Tianjin Binhai New Area about 15 km from its core. TEC construction focuses on renewable energy utilization and ecological protection, resource conservation, environmental friendliness, economic prosperity, and social harmony. The implementation of key projects is focused in the pilot ecological city zone, a 4 km^2 area located south of the TEC. Initial construction in the Cheong Road area included building a 110 kV smart substation and a total of 123 planned distribution sites.

TEC projects subsequent to those in the pilot area are intended to "replicate, implement, and promote" general concepts including power flow, information flow, business flow, and unified convergence. The projects aim to perform in-depth study of key smart grid technologies and their engineering applications.

(2) Current Project Status

The pilot area smart grid focuses on generation, transmission, substation automation, electricity efficiency, scheduling, and the communication-information platform. The overall demonstration project will be divided into 12 sub-projects encompassing power supply, grid, and end uses (see Fig. 3.2). This analysis covers only three of the 12 projects, indicated in *italics* below:

1. DG integration
2. *Distribution automation (DA) and control*
3. *Microgrid and energy storage system*
4. *Smart substation (SS)*
5. Integrated equipment monitoring system
6. Power quality monitoring system
7. Visualization platform
8. AMI
9. Smart community building
10. EV charging infrastructure
11. Smart business hall
12. Advanced communication and security system

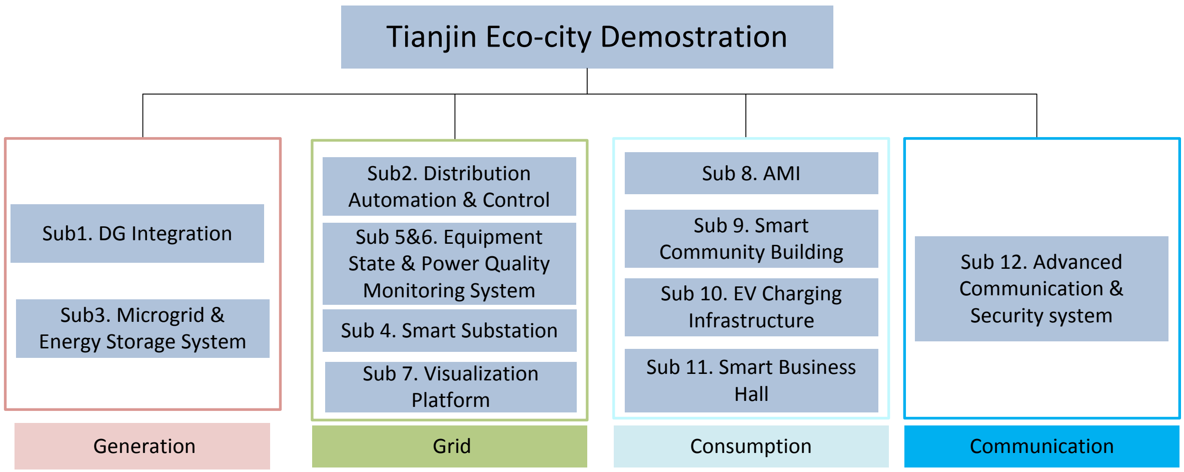

Figure 3.2. TEC Demonstration project overall structure

a. Sub-project 2: Distribution Automation and Control

TEC includes a smart DA system: a distribution network, power distribution master station with electronic stations, distribution terminals, and communications channels. The complete distribution network includes SCADA functions, control functions, and self-healing features, such as smart analysis, flexible operation modes. It also allows for clean energy access. The information exchange bus permits information exchange with superior dispatching automation, production management, geographic information systems (GIS), marketing and management, and other business systems to support operations of modern power-intensive business processes.

The DA pilot area distribution network uses a ring network power supply, an open-loop operation mode, and provides mutual interconnection capability to meet N-1 requirements; important individual lines and loads meet N-2 line break points and provide reasonable focal points for a clear, reliable network structure, with each load spread evenly among the lines to meet the N-1 criterion. The current network serves the approximately 4 km^2 TEC project pilot area, which is primarily a residential, commercial finance, and an eco-industrial zone. Regional planning started with construction of the 110 kV Cheong Road substation with 36 feeders. The distribution site planning region has a total of 123 nodes, including 52 distribution stations, 15 switching stations, and 56 front ring network devices (multiple power supply). TEC is a new city, so construction of the distribution network backbone has to be coordinated with the region's development.

b. Sub-project 3: Microgrid and Energy Storage System

The microgrid and energy storage system is composed of 30 kW of PV panels, 6 kW of wind turbines, and 15 kW × 4 h of lithium-ion batteries. The microgrid load totals 15 kW: 5 - 10 kW for lighting plus additional load for EV charging. This load is served by a microgrid energy management system (EMS) that operates economically using smart controls. The demonstration includes distributed power systems, a battery bank, EMSs, distribution systems, harmonics control, as well as reactive power compensation, load control, and micro-network protection. The microgrid EMS includes distributed power, an energy storage inverter, microgrid smart terminals, an MgC, the server host, and an operator station. The SCADA EMS platform, based on the latest microgrid control and energy management technology developments, is designed for optimal control of distributed power, economic dispatch, renewable energy output forecasting, reactive power optimization and voltage control, demand response, plug and play interconnection, and network and application silo conversion functions to remedy the current high cost of distributed power interconnection and control challenges, provide optimal microgrid scheduling, and meet security and stability requirements.

The microgrid is rated at 380 V and has single-conductor wiring with one incoming line and eight outgoing lines. PV panels and the system fan are installed on a smart business hall roof, the microgrid EMS and batteries are located in a fourth-floor operating room, 10 kW of smart operating room lighting is located in a third-floor office area, and the 5 kW EV charging pole is located in the compound area.

Figure 3.3. EV charging stations at TEC microgrid

Figure 3.4. Translucent PV at TEC

c. Sup-project 4: Smart Substation

The SS is a smart grid technology that enables energy efficiency and control. This core platform is an important part of the smart grid and supports grid access for new energy sources such as wind and solar. The SS allows smart grid power generation, transmission, substation automation, DA, end-use efficiency, and scheduling (the six aspects of convergence).

The Cheong Road 110 kV smart substation uses electronic transformers, primary equipment on-line monitoring, and other smart devices; a network of secondary equipment; 110 kV line protection and monitoring arrangements; three layers of the two networks; direct data mining network control using the International Electrotechnical Commission (IEC)-61850 standard[2]; a unified messaging platform technology; and access to the distributed power sources. The SS equipment includes two 50 MVA transformers and two 110 kV lines. The SS rating is 110/10 kV. The 110 kV side of the building has two independent buses, each one with inflow and outflow, and the 10 kV side has three groups of single bus bars with 36 back outlets. The smart substation architecture complies with the "Smart Substation Technology Guideline" requirements. Stratified, distributed, open network systems connect the entire architecture into a "three-two network" structure.

Three process-layer devices have spacer layers and station-level equipment. A process layer device is a smart process interface with spacer layer protection and control and any other secondary equipment, such as station-level equipment, monitoring systems, and other back-end devices. The two networks are the station control and process layers. The substation control layer network uses a single-star topology, and its data model follows the IEC-61850 standard for substation monitoring, control, data recording, and other functions. The layered network processes data by peer-to-peer networking and dual-network configurations, a sample value (SV) network[3], a generic substation event network, an IEEE1588 network for triple play, and a total operations network. Direct mining and data collection are protected. Double sets of main transformer protection provide independent dual-network access as well as access to single-wire line protection.

3.2. B-TEC Project

(1) Project Background

Covering an area of 0.203 km^2 within a total construction area of more than 1.2 km^2, B-TEC is the pilot technological demonstration for the Qianhai smart power grid. Based on equipment including intelligent integrated distribution terminals and smart meters, and infrastructure including optical fiber communication networks, it performs functions such as optimal scheduling of all resources, smart metering and advanced energy services based on a cloud platform, as well as distribution network asset life-cycle O&M based on big data. It also supports a user-side smart microgrid that can promote coordinated supplementation and optimized configuration of various energy resources, improve demand-side management performance, and firm distributed renewable power (See Figure 3.5).

[2] http://www.iec.ch/smartgrid/standards/

[3] Sampled value network is a widely used communication network which was designed to support data (like voltage and current value) transmission between terminal device and protection control device in a substation.

Figure 3.5. Location of Qianhai smart power grid and B-TEC pilot project

(2) Current Project Status

a. Sub-project 1: Distribution grid optimal operation and fault self-recovery system

Smart distribution integration terminals meet the requirements for integration equipment, modular combination and sustainable expansion, integrating distribution automation terminals, environmental measurement and control terminals, equipment protection, and voltage and power quality monitoring terminals among others. Moreover, expansion of functional modules enables the terminal equipment to continuously satisfy demands for data collection, transmission, and monitoring control of various application scenarios.

Using smart distribution integration terminals and distribution automation and protection functions, the B-TEC smart distribution grid provides electrical monitoring, state monitoring, and comprehensive environmental monitoring of distribution rooms. This project involves four out of a total of 13 distribution rooms.

b. Sub-project 2: Distributed energy coordination and scheduling

The B-TEC smart distribution grid consists of one commercial-residential building microgrid system and three commercial-office-building microgrids, including the top floors of the 9A apartment building, No. 6 Research and Development (R&D) office building, 7B R&D office building, and 9B R&D office building. The microgrid has access to a 142 kW PV array and a 90 kWh battery bank. One set of background systems monitors the microgrid system in each building and allows for easy O&M by monitoring equipment condition while also monitoring and controlling the microgrid in each building.

c. Sub-project 3: AMI system

Optical fiber network facilities enable remote communication of the B-TEC smart distribution grid. Node communication is realized via a special network. Because power loads are heavy and centralized in the new high-rise living quarters of the Qianhai Cooperation Zone, EPON+RS485 communication is used for local communication.

d. Sub-project 4: Operation state sensory module of the distribution grid subsystem

The B-TEC smart distribution grid operation control strategy coordinates, optimizes, and dispatches all resources and supports O&M of the distribution grid asset life cycle and advanced energy utilization services based on smart measurement, big data, and cloud computing technologies. The control strategy support system can also monitor the microgrid on the user side.

The full-view monitoring and display center is B-TEC's real-time operation-state monitoring system. It executes abstract service-oriented service interconnection via its mature, flexible service-oriented architecture (SOA) and dynamically displays more than 200 local-grid operations data points through 34 application modules and 43 mutual interaction demands.

e. Sub-project 5: Load center energy storage station

The Baoqing ESS has a total capacity of 6 MW/18 MWh and is the world's first MW-scale peak regulation and frequency modulation lithium-battery power storage station. The first phase of construction, of 4MW, began in September 2010, and the first 1 MW energy storage subsystem was grid-connected and put into operation in January 2011. A total of 4 MW/16 MWh have been put into operation since November 2011. In June 2014, the second phase of construction began and was grid-connected and put into operation in October, 2014. The second phase encompasses a large-capacity ESS with supervision and protection technology (as part of the "energy storage subject" of the national "863 Program").

3.3. ISGD & UCI Campus

3.3.1. ISGD

(1) Project Background

SCE operates the ISGD project primarily in the city of Irvine in California's Orange County. Many of the project components are located on or near the UCI campus, which is 60 km southeast of the Los Angeles airport. Key project participants include UCI, General Electric Energy, SunPower Corporation, LG Chem, Space-Time Insight, and EPRI. ISGD's evaluation approach includes four types of testing: simulations, laboratory tests, commissioning tests, and field experiments. Simulations and laboratory testing validate a technology's performance capabilities prior to field installation. The field experiments evaluate the physical impacts of the various technologies on the electricity grid and quantify the associated benefits for different stakeholders.

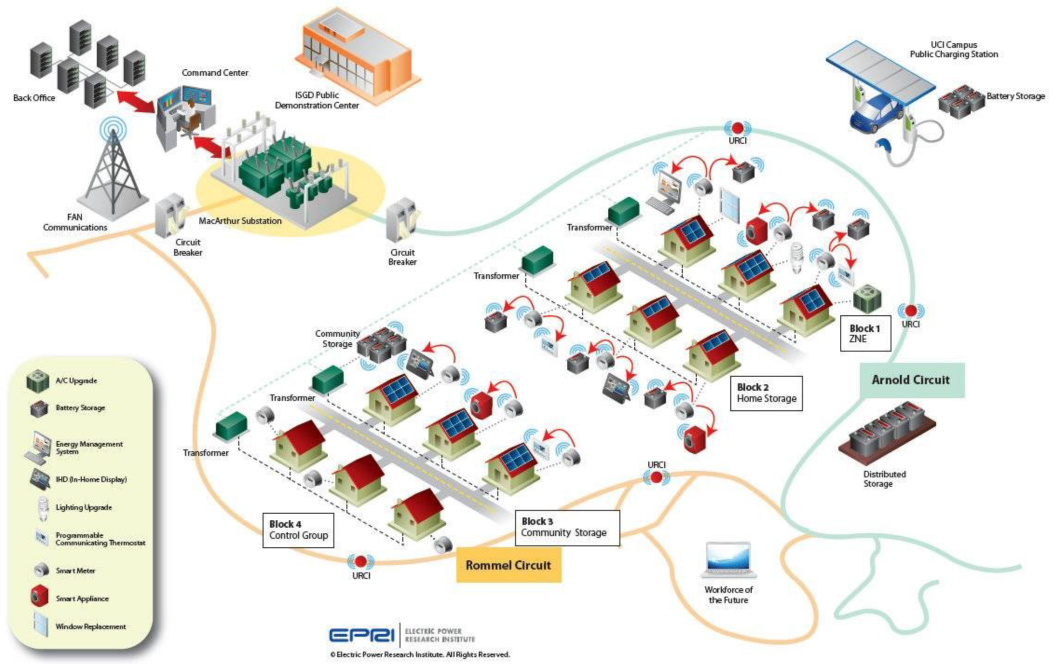

Figure 3.6. ISGD project

(2) Current Project Status

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 three of which, shown in *italics* below, are included in this analysis:

- Smart energy customer solutions (sub-projects 1 & 2)
  - *Sub-project 1: ZNE homes*
  - 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*
  - 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)

a. Sub-project 1: ZNE Homes

Customers are modifying how they consume and, increasingly, how they generate electricity. The ZNE project uses one block of nine homes to evaluate strategies and technologies for achieving ZNE buildings. 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, which will take effect in 2017 (CEC & CPUC, 2015). The project also seeks to understand the impact of ZNE homes on electricity grid performance.

ZNE homes include 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 three blocks of homes used for faculty housing on the UCI campus.[4] ISGD has equipped three blocks of homes with an assortment of advanced energy components, including smart devices capable of demand response (see Table 3.1), energy-efficiency upgrades (see Table 3.2), energy storage, and rooftop solar PV arrays. Three levels of home retrofits are as follows:

1. 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 unit (RESU) block (6 homes)
    a) Demand-response devices
    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)
    a) Demand-response devices
    b) Community energy storage unit (25 kW/50 kWh)
    c) Solar PV arrays (3.2-3.6 kW)

ISGD is evaluating two types of residential-scale batteries in this neighborhood, and a utility-scale battery was demonstrated in sub-project 3, as described in more detail below. All batteries used in ISGD are lithium-ion, from three separate vendors. Individual residential energy storage units have been installed in 15 homes as mentioned above and are being evaluated using a variety of control modes. In addition, seven 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. The batteries underwent extensive testing prior to commissioning. Initial field experiments have been performed, including a demand-response event and a series of load-shifting tests.

Energy simulations determined the energy-efficiency measures for each home. Smart appliances and other home area network devices were lab tested prior to field deployment. Field experiments have been performed on smart appliances and heating and cooling systems. To enable evaluation of the ZNE technology and strategies, detailed energy usage information has been archived via multiple home circuits.

Table 3.1
Demand-response devices deployed in ISGD sub-project 1

Demand-response devices
ENERGY STAR smart refrigerator
ENERGY STAR smart clothes washer
ENERGY STAR smart dishwasher
Programmable communicating thermostat
EV charging station
Home energy management system (EMS)
In-home display

[4] A total of 22 homes in four blocks participated in sub-project 1: 9 of 9 homes in the ZNE block, 6 of 8 homes in the RESU block, 7 of 9 homes in the CES block.

Table 3.2
Energy-efficiency upgrades deployed in ISGD sub-project 1

Energy-efficiency upgrades
Central air conditioning replacement (heat pump)
Light-emitting diode (LED) lighting upgrades
Insulation
Efficient hot water heater
Domestic solar hot water and storage tank
Solar panels for water heaters
Low-flow shower heads
Plug load timers

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

The electricity grid is evolving into an increasingly dynamic system with new types of distributed and variable generation resources and changing customer demands. This project includes DBESS to help prevent a distribution circuit load from exceeding a set limit, mitigate overheating of the substation getaway, and reduce peak load on the circuit. DBESS has a rating of 2 MW of real power and 500 kWh of energy storage and is connected to the Arnold 12 kV distribution circuit, which receives power from MacArthur Substation and is the same circuit where the sub-project 1 test homes are located.

DBESS is also being used along with phasor measurement technology installed within the substation and at a transmission-level substation upstream to detect changes in distribution circuit load resulting from DER such as demand-response resources or energy storage.

c. Sub-project 4: Distribution Volt/VAR Control

DVVC is also included in this study. DVVC optimizes customer voltage profiles in pursuit of conservation voltage reduction. A 1% voltage reduction potentially yields an approximately 1% reduction in customer energy consumption in most cases. This often-proposed measure is required in California where voltage is to be maintained as close as possible to a minimum acceptable level (nominal voltage minus 5%) and at nominal level, 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 this capability and can also provide VAR support to the transmission system; i.e., it can 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 system wide; however, the technology may not be applicable to all distribution networks depending on pre-existing equipment.

3.3.2. UCI Campus

(1) Project Background

The UCI campus includes a portfolio of energy technologies described below. We describe all of the technologies deployed on the UCI campus although only the 19 MW CHP plant, the 3.6 MW PV, an MgC under development, and the 2 MW/0.5 MWh battery are assessed in this study.

UCI was established in 1965 on undeveloped land, so the campus could be methodically and systematically designed from scratch with a large, circular central park encircled by a 1.5 km underground utility tunnel loop connected to the central energy and information infrastructure. The evolving UCI Microgrid (which is expected to have islanding capability in late 2016) is integral to this modern design along with a modern district heating and cooling system. Today, the UCI Microgrid serves a daytime community of more than 30,000 and a wide array of building types (residential, office, research, classroom, etc.), transportation options (automobiles, buses, shared cars, bicycles), and DER. Through an array of prior and current research programs, the UCI Advanced Power and Energy Program (APEP) has teamed and worked with the UCI Administration and Facilities Management to integrate key hardware, software, and simulation assets into the UCI Microgrid.

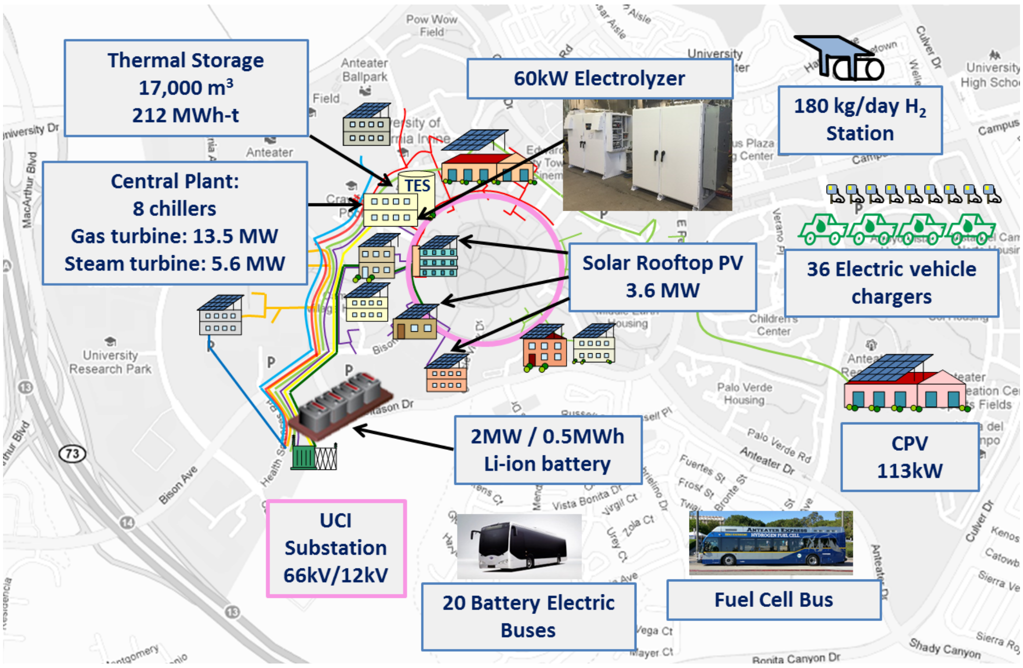

Figure 3.7. UCI Microgrid

As shown in Figure 3.7, the UCI Microgrid is a test bed that (1) is served by SCE through the UCI substation, which steps down voltage from 66 kV to 12 kV using two 15 MVA transformers; (2) encompasses ten 12 kV circuits; (3) includes nearly 4 MW of solar power; (4) is served by a 19 MW, natural-gas-fired, combined-cycle plant; (5) incorporates centralized chilling including a large thermal energy storage tank (17,000 m^3 /212 MWh thermal); and (6) serves all major buildings with district heating and cooling. The UCI Microgrid also contains a unique set of DER including: (1) EV charging at multiple parking locations, (2) 60 kW electrolyzer for producing hydrogen for pipeline injection; (3) hydrogen for fuel-cell vehicles; (4) two-axis tracking CPV systems; (5) advanced building energy-efficiency measures; and (6) advanced building monitoring and control.

(2) Current Project Status

The UCI campus and the entire UC system have a goal of net-zero carbon by 2025 while providing increased reliability and reducing operating costs to the extent possible without increasing carbon emissions. In pursuit of this goal, UCI first deployed deep energy-efficiency programs that reduced energy use by 10% despite adding 93,000 m^2 of building space over the past 4 years. UCI is also participating in the U.S. DOE Better Buildings

Challenge with a goal of reducing energy consumption by 20% by 2020. UCI has also deployed nearly 4 MW of solar, a fuel-cell bus, 20 battery electric buses, 36 EV chargers, a hydrogen fueling station, and a 60 kW electrolyzer in an effort to investigate different pathways for reducing carbon emissions. The development of an MgC is the most recent deployment, including a 2 MW/0.5 MWh battery. The MgC (complete by 2017) will enable islanding from the utility system as well as improve operations and alleviate current challenges such as manual operation, no export to utility (for economic, not technical/regulatory reasons), and an 8 MW minimum output required to remain in emissions compliance.

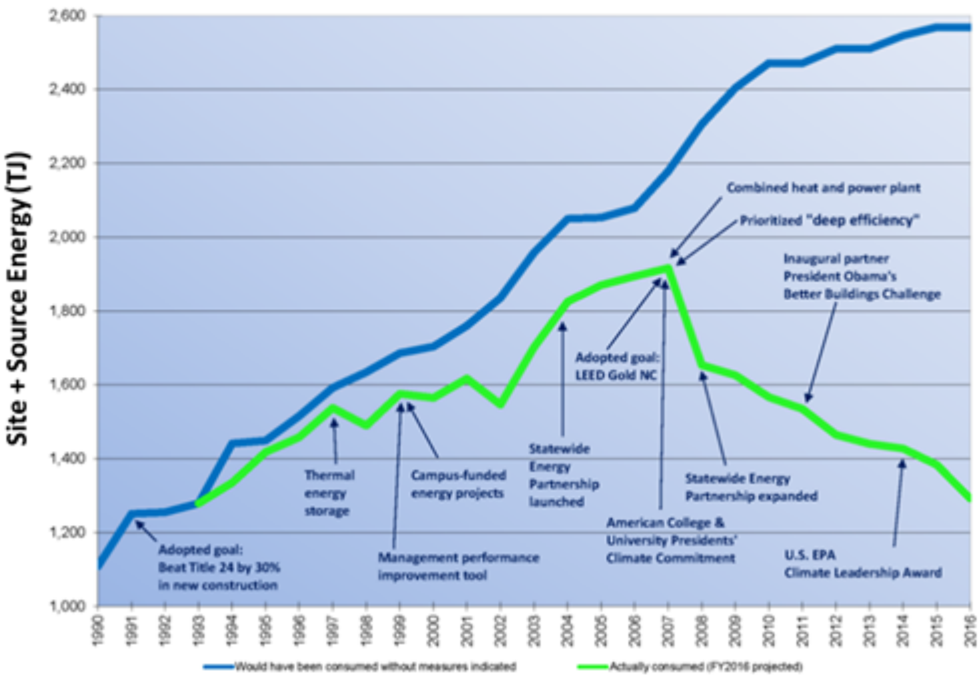

Figure 3.8. UCI energy-use-reduction history and future forecast

UCI has also been performing scenario analyses to understand the level at which severe over-generation (requiring curtailment of generation) would occur for different renewable-energy deployment scenarios. These analyses have been conducted using dispatch models for the UCI Microgrid and include detailed models of the renewable resources and the existing resources on the UCI Microgrid (for further details see Samuelsen et al., 2013 and Shaffer et al., 2014). Figure 3.9 shows the results of these analyses. The major conclusion is that achieving a renewable penetration greater than 50% without any additional complementary technology (e.g., energy storage, increased gas turbine flexibility, etc.) will be impossible. Although there will be some benefit from deploying different renewables, the curves cannot simply be added together because there will be interaction among the renewable sources when deployed together (Samuelsen et al., 2013).

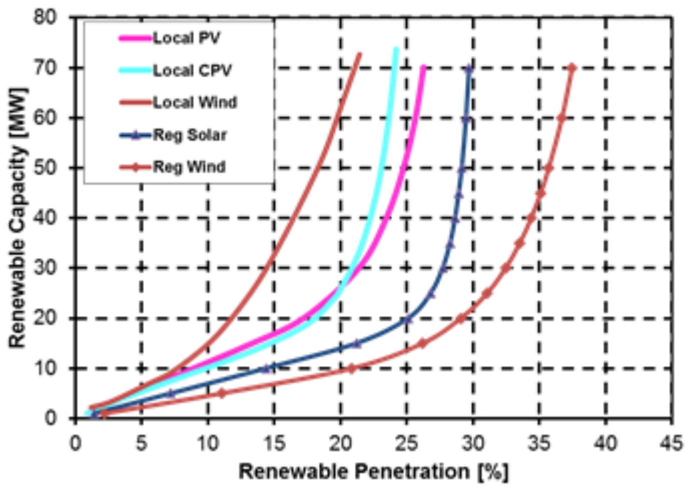

Figure 3.9. UCI Microgrid scenario analyses. *Source:* Shaffer et al., 2014 and Samuelsen et al., 2013.

The following subsections present additional details of the sub-projects selected for BA using the SGCT.

a. Sub-project 1: 19 MW CHP Plant (currently installed)

The CHP plant consists of a 13.5 MW gas turbine, a heat-recovery steam generator (HRSG), a duct burner, and a 5.5 MW steam turbine. The heat recovered with the HRSG supplies 99% of campus heating loads through the district heating system. Additional steam is used to drive the steam turbine. The gas and steam turbines supply about 96% of campus electrical needs with the balance being served by solar resources (3.5%) and utility imports (0.5%).

b. Sub-project 2: 3.6 MW Solar PV (currently installed)

UCI has 893 kW of fixed-panel PV installed on the rooftops of 12 buildings and an additional 2.6 MW installed on three parking structures. These systems are owned and operated by third parties with which UC has power-purchase agreements for the electricity. The capacity factor for the rooftop panels, in operation since 2008, was 0.187 in 2012, which is reasonable for the local climate. There is potential for 22 MW of dual-axis tracking CPV and 15 MW of fixed-panel PV based on GIS studies (Samuelsen, 2013). Although the campus solar resources are still at a low penetration (3.5%), they are already enabling the gas turbine to be turned down at times of low electricity demand and high solar irradiation. The extent of turndown is affected by a minimum turndown requirement that allows the turbine to remain in emissions compliance and the inability of the UCI Microgrid to export to the utility.

c. Sub-project 3: MgC (to be installed Fall 2016)

A major challenge for the UCI Microgrid is continued manual operation for most processes. Several research contracts have furthered efforts to automate microgrid controls. These include awards from the California Energy Commission and U.S. DOE with partners including Siemens, ETAP, and Melrok. The U.S. DOE award (FOA DE-FOA-0000997) will move the UCI Microgrid further toward full automation through development of an MgC in partnership with SCE and ETAP. The MgC will be generic to enable deployment at a wide array of different microgrid types and will provide (1) seamless islanding and reconnection of the microgrid; (2) efficient, reliable, and resilient operation of the microgrid with the required power quality, whether islanded or grid-connected; (3) the ability to offer existing and future ancillary services to the larger grid; (4) microgrid capability to serve resiliency needs of participating communities; (5) communication with the electricity grid utility allowing the microgrid to be a single controllable entity; and (6) increased reliability and efficiency and reduced emissions. The generic MgC is envisioned as a set of generic modules including a master microgrid controller that contains the control algorithm and acts as a single point of communication with the larger grid, a load controller, a generation controller, a storage controller, and a breaker controller.

d. Sub-project 4: 2 MW Battery (currently installed)

The battery system consists of A123 lithium-ion iron phosphate battery cells (3 amp hours) with a total power rating of 2 MW and an energy capacity of 0.5 MWh. The battery system will be utilized to reduce electricity imports from the utility and as an important resource during islanding events. In both applications, the battery system will buffer small, transient mismatches between load and generation. The application of interest for our benefit study is reducing utility electricity imports. The operators are skilled at following load with the CHP plant with a typical margin of error ± 100-200 kW. This requires that electricity be imported from the utility at a certain level to ensure that no electricity is exported, which would result in tripping the CHP plant. Utility electricity import is currently set at a comfortable level of 500 kW to ensure that no export occurs. The battery system will buffer the operators' margin of error (+/- 100-200 kW) to allow a lower import set point of 300 kW. Simulations were performed using historical data and simple feedback control (see Figure 3.10) to ensure feasibility of an import of 300 kW and no export while accounting for the battery's energy and power capacity. The results of these simulations demonstrated the feasibility of this setup and a potential savings of USD140,000 per year. The control design is currently under way.

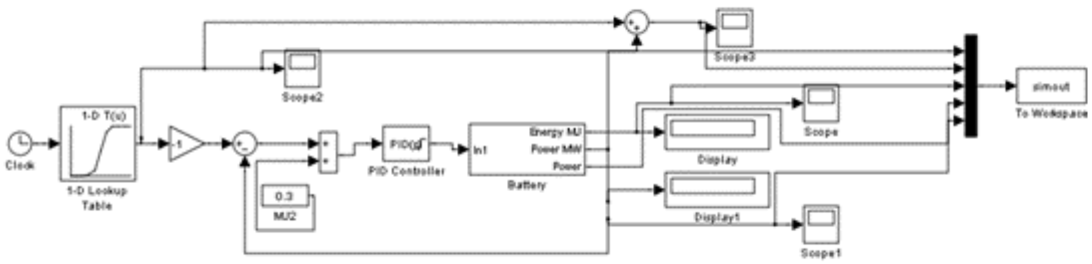

Figure 3.10. Simulink feedback control model

3.4. TNY

(1) Project Background

In March 2000, as a result of the U.S. Base Realignment and Closure Commission process, the U.S. Navy conveyed approximately 1,000 of the total 1,200 acres of the former Philadelphia Navy Yard to the Philadelphia Authority for Industrial Development (PAID) while retaining ownership of and operations on roughly 200 acres. PIDC, on behalf of PAID and the City of Philadelphia, is overseeing redevelopment and management of TNY. A comprehensive real-estate master plan was developed in 2004 to turn the former industrial yard into a vibrant, mixed-use campus.

Over the past decade, TNY redevelopment has been a remarkable success, attracting many new businesses and research opportunities. TNY is currently home to more than 120 businesses and 12,000 employees. These companies range from industrial to service, office, and R&D organizations. PIDC plans for these numbers to nearly double over the next 10 years.

As shown in Figure 3.11., TNY's distribution microgrid is served by PECO through the two Navy Yard-owned and operated substations: Substation No. 93, (SS93) and Substation No. 664, (SS664)[5], which step down voltage from 33 kV to 13.2 kV. In addition to SS93 and SS664, two more substations exist, SS602 and 26th Street, as shown in Figure 3.11.

Figure 3.11. TNY Distribution grid overview with substations

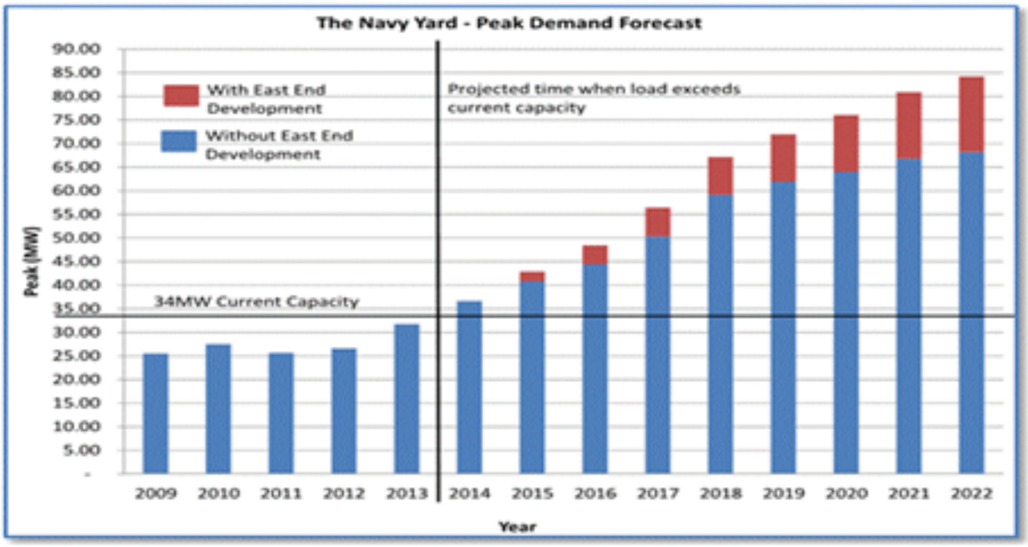

Figure 3.12. TNY Distribution Grid Load Growth Profile

[5] The Navy has historically identified each Navy Yard building by a number assigned based on when the building was commissioned. For example, Building 1 refers to the first building ever built within TNY (which still exists and is used for offices). Thus, the building numbers 93 and 664 simply signify when the substation buildings were built.

Key recommendation of the NYEMP analysis are shown in the Figure 3.13.

In February 2013, PIDC released The Navy Yard Energy Master Plan (NYEMP), which was developed to comprehensively tackle the need to nearly double electricity capacity from 30 MW to more than 70 MW by the year 2022, based on projected real-estate growth as shown in Figure 3.12.

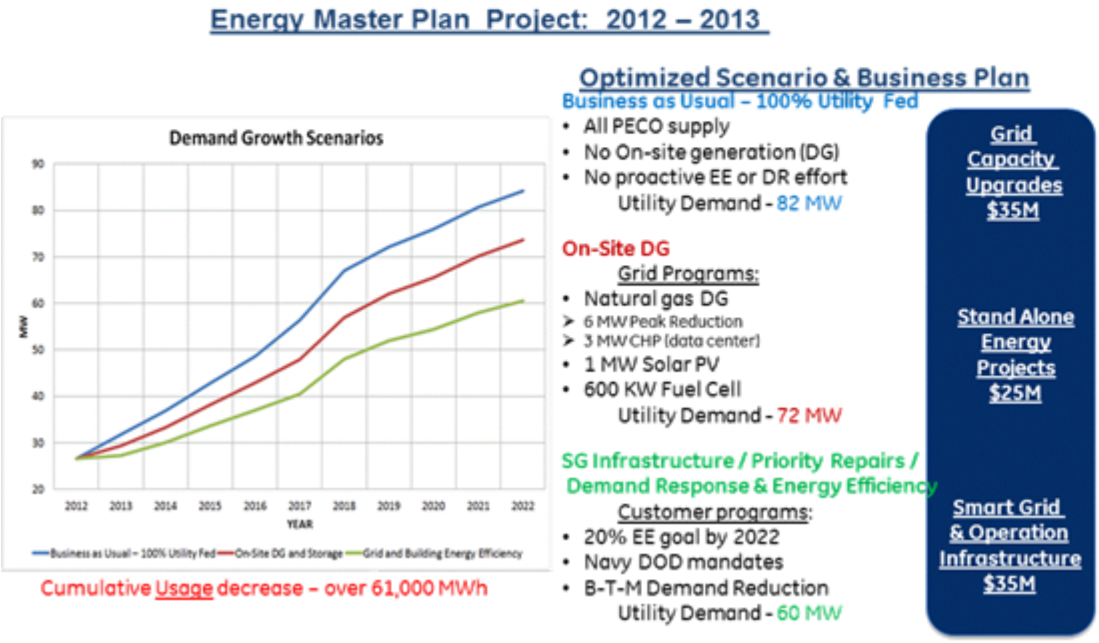

Figure 3.13. NYEMP results and recommendations

(2) Current Project Status

TNY project current status can be characterized by a list of critical loads and DER as shown in Table 3.3 and Table 3.4.

Table 3.3
TNY Current Project Status – Microgrid Critical Load

Microgrid Assets & Load	Microgrid System	Average Demand Load (kW)	Controllable Load (kW)
ZNE House	GridStar	4	2
EV Charging	GridStar	10	10
Building 101	GridStar	150	75
Building 100	GridStar	160	80
Chapel	GridStar	16	
Aker Shipbuilding	SS602	3,000	1,000
Naval Research	SS 602	6,000	
TastyKake Bakeries	SS 602	1,300	400
Rhode Industries	SS 602	800	200
Central Fire Pump Station	SS 602	100	
Urban Outfitters	SS 602	1,500	500
TOTAL		13,040	2,267

Table 3.4
TNY Current Project Status –DER

Microgrid Assets & Load	Microgrid System	Solar PV (kW)	Storage (kW)	NG Generator (kW)	Fuel Cell (kW)	TOTAL (kW)
ZNE House	GridStar	5	10.4			15.4
EV Charging	GridStar					
Solar Grid Storage	GridStar		250			250
Solar Training Center	GridStar	5				5
Building 101	GridStar					
Building 100	GridStar					
Chapel	GridStar					
Natural Gas Generator	*SS 602*			*6,000*		*6,000*
Substation Storage	*SS 602*		*2,000*			*2,000*
Community Solar	**SS 602**	**750**	**250**			**1,000**
Aker Shipbuilding	SS602					
Naval Research	SS 602					
TastyKake Bakeries	SS 602					
Rhode Industries	SS 602					
Central Fire Pump Station	SS 602					
Urban Outfitters	SS 602			800	800	1,600
TOTAL		760	2,510.4	6,800	800	10,870.4

Note: Italics = in planning, bold = in construction

As of June 2016, TNY established a Microgrid Network Operation Center which will support the following key functions:

- Integrated smart metering and communication
- SCADA and distribution grid monitoring
- SS data automation and monitoring
- Operation interface with 3rd-party-owned assets
- Operation interface with PECO
- Operation interface with PJM and/or 3rd-party PJM aggregator
- Platform for microgrid control system being developed in U.S. DOE microgrid controller project

Figure 3.14 shows an overview of TNY microgrid system design and the microgrid network operation center.

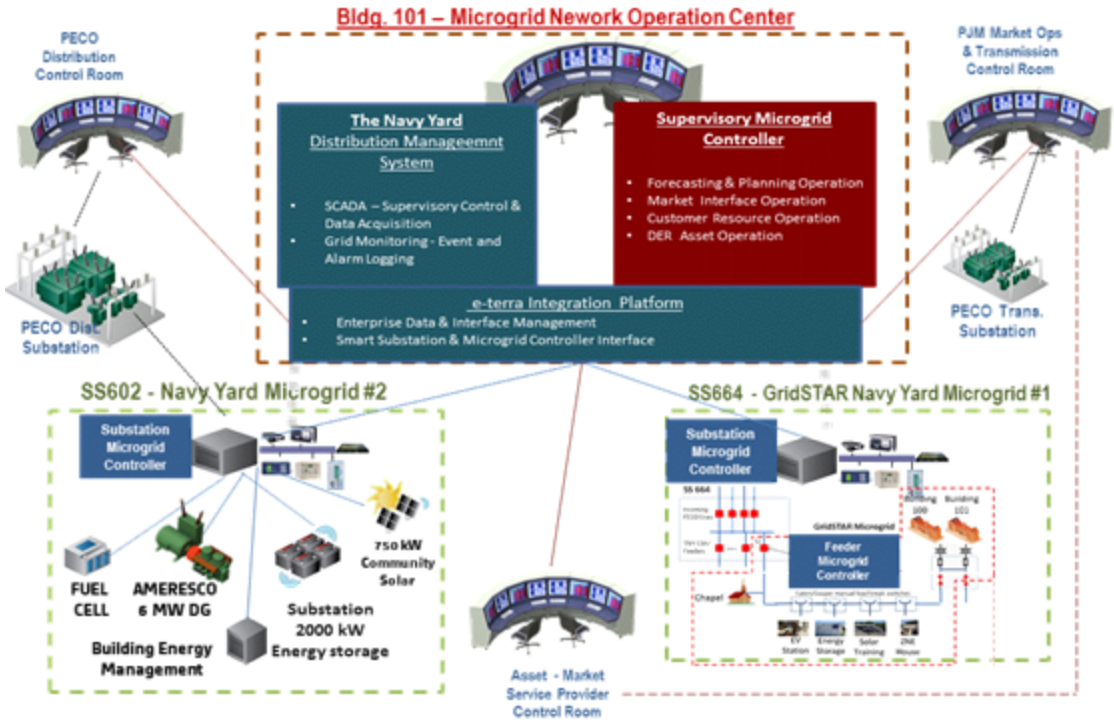

Figure 3.14. TNY Microgrid Architecture

The objective of the parallel U.S. DOE MgC project is microgrid automation though a distributed microgrid control system (DMGCS). TNY's Microgrid DMGCS is being designed to support a distributed hierarchal architecture. This philosophy of distributed hierarchal control is achieved in the most efficient and effective manner as follows:

1. *First Level – Supervisory MgC* (implemented using existing Alstom /GE **e-terra***distribution* platform integrated with L&G smart metering and AT&T communication system) will be configured for entire TNY 13.2 kV power system.
2. *Second Level - Substation MgC* (implemented using existing Alstom /GE **DAP***Server* platform) will be configured for each of the substations (SS664 and SS602)
3. *Third Level - Feeder MgC* (also implemented using existing Alstom /GE **DAP***Server* platform) will be configured for feeder 1392 making up the GridSTAR microgrid system (a Smart Grid Education and Research Center of Pennsylvania State University Conducting Work at TNY).
4. *Fourth Level – Device MgC* (implemented using existing Alstom C264 platform wherever appropriate) will be configured for the point of common coupling control and other device controls as necessary.

Key functions of the DMGCS are classified into four categories:

1. Monitoring and mode management - manage mode of operations, evaluate microgrid conditions, and perform status checks
2. Control functions - ensure reliable, efficient, autonomous operation of the islanded microgrid and provide support functions to the supervisory controller for grid-connected mode
3. Power operation mix management functions - perform or support power mix dispatch together with integrated PJM market operation and PECO utility operation
4. Protection and resilience functions - perform adaptive/dynamic protection coordination functions

Detailed functions for each category are described in Table 3.5.

Table 3.5
TNY distributed microgrid control functions

Class	Top-Level Function	Description
Monitoring and mode management	F1. System Status	Establish connectivity state - interconnected or islanded
	F2. System Monitoring	Real-time tracking of local load and DER
Control functions and resiliency	F3. Mode Transitions	Manage mode transition processes
	F4. Device Control	Provide coordinated control signals for local DER and switches in the microgrid control
	F5. Load Management	Real-time management, prioritization, and command of available microgrid controllable loads
Power mix management	F6. Operation Strategy	Define operating DER set points according to microgrid operating targets in various operating modes
Protection	F7. Protection	Adapt protection relay settings to microgrid operating state

4. Benefit Analysis of Smart Grid Projects in China

4.1. Benefit Analysis of Sino-Singapore TEC Project (using SG-MCA Method)

The TEC smart grid demonstration project is China's first project substantive construction and operation of an integrated smart grid. This project provides a good template for future similar projects.

4.1.1. Sino-Singapore TEC Project

(1) General Assumptions

This TEC project BA focuses on three sub-projects – the distribution automation sub-project, microgrid sub-project, and smart SS sub-project). The SG-MCA evaluation method is used to convert project / sub-project properties to multiple indices in a bottom-up fashion.

Because of the diversity of each sub-project, a hierarchical structure is needed to demonstrate the characteristics and evaluate performance of each. In each hierarchy, all of the indices should be assigned a weight determined by SG-MCA. Each project / sub-project is evaluated in four different domains: technological, economic, social, and practical. Ultimately, a score is given to each project/sub-project to qualify performance in the four aspects and overall. Three years worth of operational data are used to examine the impact of smart grid-related technologies. Table 4.1 shows key data associated with the TEC project evaluation.

All of the index weights are obtained through by SG-MCA calculations. The resulting values can be found in Table 4.2.

Table 4.1
Key data for TEC demonstration project evaluation

TEC Data	2012	2013	2014
Average Outage Time	8mins	5mins	4mins
N-1Passing Rate	100%	100%	100%
Number of Standardized Software	65	68	75
Number of Software Systems	12	13	15
Monitored Large Electricity Customers	29	60	115
Number of AMI Installed Customers	6553	2277	8668
First-invented Technologies	9	12	18
Line Loss	5.16%	4.85%	3.88%
Microgrid Operating Profit	USD17,538	USD8,000	USD8,461

Note: Average Outage Time = $\sum(\textbf{outrage time for each event} * \textbf{number of affected customers})$ /total number of customers in Eco-city.

a. Technological index

The technological index represents reliability, security, automation, interaction, software systems, and technical levels, as follows:

- Reliability: probability of stable operation of equipment and grid within a certain time period, in accordance with technology performance requirements
- Security: robustness and security of grid structure as well as security of automation system devices, i.e., the security of power supply and system information
- Automation: automation level in entire smart grid including load control, DA, and distribution network self-healing

- Advanced technologies: advanced performance of demonstration technologies, including system integration capabilities, system technical scheme, application of advanced technologies, and other similar technology characteristics
- Interaction: information interactional ability of DA system and AMI as reflected in contribution of demonstration project to friendly interaction and coordination among power generation, grid, and users
- Software systems: software systems in overall smart grid including information security, availability of informational system, and deployment rate of informational system

b. Economic index

The economic index refers to the project's return on investment (ROI). ROI is the ratio of the benefits of system reliability improvement to utility investment for grid modernization.

c. Social index

The social index represents environmental impacts and social benefits. The environmental impacts include energy savings, emissions reduction, and environmental protection promotion. The social benefits include improvements in social sustainability, enhancement of public image, promotion of technology, and other similar issues

d. Practical index

This index is mainly used evaluate the pilot project's completeness, effectiveness, and quality. It focuses on public service support, O&M improvement, customer satisfaction, and other similar characteristics and outcomes.

Table 4.2
TEC demonstration project indices and corresponding weights

Technological index (60%)	Reliability level	12%
	Security level	12%
	Automation level	23%
	Technology level	6%
	Interaction level	27%
	IT software systems level	20%
Social index (20%)	Environmental impact	40%
	Social benefit	60%
Practical Index (10%)	Undertaking public service business	20%
	O&M improvement	30%
	Customer satisfaction	30%
	Achievements	20%
Economic index (10%)	Construction investment saving	20%
	Improving reliability	20%
	Reduced maintenance cost	20%
	Reduced line loss	20%
	Business benefits	20%

(2) Benefit Analysis

The overall eco-city project performance is good with a score of 87 of 100, but the economic performance is relatively poor with a score of 64 (see Table 4.3).

Practicality: The TEC project has been operating safely and reliably for three and half years since commissioning, supporting local business development and promoting energy conservation. However, an appropriate market model is needed for improving practicality.

Technological: The TEC project is China's first with a distribution network power supply model and a multi-objective planning method with multiple energy resources and flexible load integration. It is also the first project in China to integrate power distribution system information flow, business flow, and energy flow using complex data and different communication protocols. An optimal power dispatch method and a fast fault-recovery method were also devised for this project, and a combined community energy management system for power distribution and business utilization was developed to ensure distribution network security and economical operation with high penetration of DER. The power supply reliability is greater than 99.9%, and the power quality has been increased to 100%. All of the renewable energy resources are controllable including wind turbine and PV. The renewable energy utilization rate is more than 20%.

Economic: The TEC project can save CNY11.7 M annually in land costs, line losses, power supply reliability costs, O&M costs, etc. However, the economic performance is worse than expected because much of the hardware and software were developed for this project without policy support or an appropriate business model.

Social: The project's DG, microgrid, and EV charging facilities save significant energy and emissions: about 1,074.32 t of fuel consumption, 5,929.7 t of standard coal, and 18,488 t of CO_2 emissions per year. These elements of the project can stimulate technology upgrades and development of equipment manufacturing, electronic information, the petrochemical industry, and new energy and materials with significant social benefits.

4.1.2. Sub-project 2: Distribution Automation

(1) General Assumptions

All of the indices are separated into the below four categories – technological, social, economic, practical. All of the index weights are obtained through calculation in SG-MCA. The corresponding values can be found in the Appendices.

a. Technological index

The technological index consists of basic platform and technology advancement indices.

- Basic platform index: This index reflects system safety, reliability, information exchange capabilities, automation, and the level of information related to DA equipment including distribution SCADA, DA master station information exchange levels, DA deployment rate, DA system equipment, automatic load-shifting rate in the primary system, and the communications and security systems.
- Technology advancement index: This index reflects the technology development level including distribution network analytical applications, feeder fault handling, equipment malfunction diagnosis, outage maintenance management, and DG and battery bank integration and application in the microgrid.

b. Economic index

The economic index consists of benefits and cost control indices.

- Benefits index: This index mainly reflects changes in ROI in static investment after the smart updating of DA system and the benefits of improving system reliability and reducing line losses.
- Cost control index: This index mainly reflects the difference between the budget and expenditures by including a savings-investment balance.

c. Social index

The social index focuses mainly on service, including improvement of power supply reliability and voltage quality after smart upgrading of the DA system.

d. Practicality index

The practicality index consists of regulation and talent team indices.

- Regulation index: This index represents DA equipment management including DA equipment maintenance and a distribution dispatch and control policy.
- Talent team index: This index reflects the level of team training and regulation.

(2) Benefit Analysis

The overall performance (95/100) of the DA system is good, but, as noted earlier, the economic performance is relatively poor (55/100) (see Table 4.3). The DA system consists of a master station, slave station, terminal, and communication channel in a robust primary distribution structure, which has a complete distribution SCADA function including self-healing and smart analysis.

Practical: This sub-project has been extended to the whole eco-city, and its self-healing capability has been tested in real-world situations.

Technological: This sub-project integrates several technologies, including self-healing and DG, and has achieved a 100% voltage quality rate, N-1 passing rate,[6] and terminal on-line rate.

Economic: The requirements of the DA double-loop network and distribution station "three remotes" are relatively high. Therefore, the economic performance is worse than expected.

Social: This project promotes secure microgrid and DG access for solar, wind, and other renewable energy sources as well as saving energy savings and reducing emissions. Savings include 1,856 t of standard coal and 6,179 tCO_2. Meanwhile, the application of smart equipment, such as smart transformers and distribution terminals, can contribute to the development of the equipment manufacturing and information communication industries.

4.1.3. Sub-project 3: Microgrid Sub-project

(1) General Assumptions

All the index weights are obtained through calculation in SG-MCA. The corresponding values can be found in the Appendices.

a. Technological index

The technological index consists of the technology level, security, reliability, and interaction indices.

- Technical advancement index: This index reflects the technology design, integration ability, and application of advanced technologies related to power quality, device condition monitoring, active power regulation, power factor adjustment, microgrid configuration optimization, DG forecasting, and load forecasting as well as the completeness of information collected.

[6] N-1 passing rate represents the ability of a substation to shift load between each outgoing line when one of line is switched off under the maximum-load operation.

- Security index: This index represents system robustness and security, including battery safety, fire protection, system protection, and network communication security.
- Reliability index: This index reflects the availability of equipment, which indicates the microgrid's potential for stable, reliable operation relative to the system design.
- Interactive indicator: This indicator reflects the microgrid's capability to interface with information exchange systems such as control coordination and standardized communication protocols and network silos related to conversion capability and scheduling.

b. *Economic index*

The economic index consists of economic and cost control indices:

- Economic index: This index reflects ROI, the economic benefits and static investment resulting from incorporating the microgrid into the larger grid
- . Cost control index: This index reflects the difference between budgeted and actual expenditures and indicates the rate of investment change.

c. *Social index*

This index primarily reflects greenhouse gas emissions reductions after integration of the microgrid.

d. *Practicality index*

This index consists of practicality level and operational management level indices.

- Practicality level index: This index reflects the microgrid's practicality, including field application feasibility and annual operating hours.
- Operation and management level index: This index reflects O&M activities during microgrid operation, such as maintenance staffing and maintenance log engineering data.

(2) Benefit Analysis

The overall performance (89/100) of the DA system is good, but the economic (58/100) and social (75/100) performance are relatively poor (see Table 4.3).

The microgrid plus batteries consists of: DG (30 kW PV, 6 kW wind turbine), (15 kW × 4 h lithium battery), and the microgrid load (a total of 15 kW made up of 10 kW for lighting and 5 kW for EV charging). The microgrid EMS enables smart control and economic operation.

Practicality: This microgrid sub-project has been operating safely for three and half years. The commissioning of the microgrid sub-project provided valuable insight for planning, construction, R&D, standardization, operation, and control of such systems.

Technological: The EMS with smart power dispatching and an embedded smart controller was developed for this sub-project. The EMS is equipped with a power quality monitoring system that monitors system conditions and provides automatic control.

Economic: This microgrid has the capability to perform load shifting, which allows for a reduction in installed capacities of generation units and distribution transformers. This system can generate 54,000 kWh over 1,500 h annually. However, the batteries are very costly, so this microgrid plus battery cannot currently be deployed on a large scale unless a reasonable business model is developed to remedy the current poor economic performance.

Social: This microgrid is geographically close to loads, so losses during power delivery are relatively small. Integration of renewable energy (solar, wind) reduces fossil fuel consumption and can 16.2 t of standard coal and 54 tCO_2 per year.

4.1.4. Sub-project 4: Smart Substation

(1) General Assumptions

All the index weights are obtained through calculation in SG-MCA. The corresponding values can be found in the Appendices.

a. Technological index

The technological index consists of the completeness of basic functionality and technical advancement indices.

- Completeness of basic functionality: This index reflects the capabilities of the SS infrastructure: integration of station layer information, integrated generation system (including communication power source), smart transformer, smart high-voltage switch over 110 kV, and other 35 kV auxiliary smart equipment (e.g., switchgear, arrester， reactive compensator).
- Technological advancement: This index reflects the degree of technological advancement of substation maintenance capabilities and technology design, including the application of advanced technologies such as substation operation sequencing, device status visualization, smart alarms, and economic operation and optimal control technologies.

b. Economic index

The economic index consists of economic and cost control indices:

- Economic index: This index reflects ROI, the economic benefits and static investment resulting from reduced construction and maintenance costs.
- Cost control index: This index reflects the difference between budgeted and actual expenditures and indicates the rate of investment change.

c. Social index

The substation social evaluation index includes resources conservation and social impact indices.

- Resource conservation index: This index reflects resource conservation resulting from optimization of the substation's footprint and associated conservation of land, optimization of construction activities, and reduction in energy consumption.
- Social impact index: This index reflects social benefits, after the commissioning of the substation, including increased power supply reliability.

d. Practicality index

The substation practicality index consists of equipment operation management and O&M regulation indices.

- Equipment operation management index: This index reflects the practicality of substation management, including equipment O&M, management activities, and substation operation.
- Operation and management level index: This index indicates whether a universal management regulation has taken place during substation maintenance.

(2) Benefit Analysis

The overall performance (89/100) of the substation sub-project is good, but the economic (70/100) and social performance (80/100) are relatively poor (see Table 4.3).

The He Chang Road 110 kV substation employs a number of pieces of smart equipment such as an electronic transformer, on-line primary equipment monitoring devices, and secondary equipment, such as 110 kV protection and control, a tree layered and direct mining and forwarding network structure using the IEC-61850 standard[7], and a universal information platform technology for integrating DG.

Practicality: The He Chang Road substation can provide reliable power supply for TEC. Power supply reliability has been improved through regulations of equipment maintenance and management, substation operation, and universal substation management.

Technological: The substation's reliance on smart equipment allows for optimal configuration, including fiber communications that reduce use of low-voltage cable compared to what is required in conventional substations.

Economic: The substation's highly integrated equipment and on-site installable smart components result in smaller land-use and building areas compared to a conventional substation as well as reduced annual maintenance costs. Reductions are estimated to be 10% in construction time, 10.9% in land area, 11.2% in building area, 40.4% in secondary system network cables, and 30% in maintenance.

Social: This substation can produce more reliable power with reduced O&M costs compared to a conventional substation. It promotes the application of smart technology, including the transformer, smart high-voltage switch, and secondary and other auxiliary smart equipment.

Table 4.3
Evaluation results for TEC project and three sub-projects

	TEC project	DA sub-project	Microgrid sub-project	Substation sub-project
Practicality	80	92	90	96
Technological	96	94	98	94
Economic	64	55	58	70
Social	93	86	75	80

Note: A number in the table stands for the score of a project or sub-project in a specific domain out of a maximum of 100 points.

[7] http://www.iec.ch/smartgrid/standards/ 61850 equipment is an aggregate term which generally refers to all the smart substation embedded equipment or devices like transformer protection device, line protection device, and substation automation devices, etc.

4.1.5. Sino-Singapore TEC Project Sensitivity Analysis

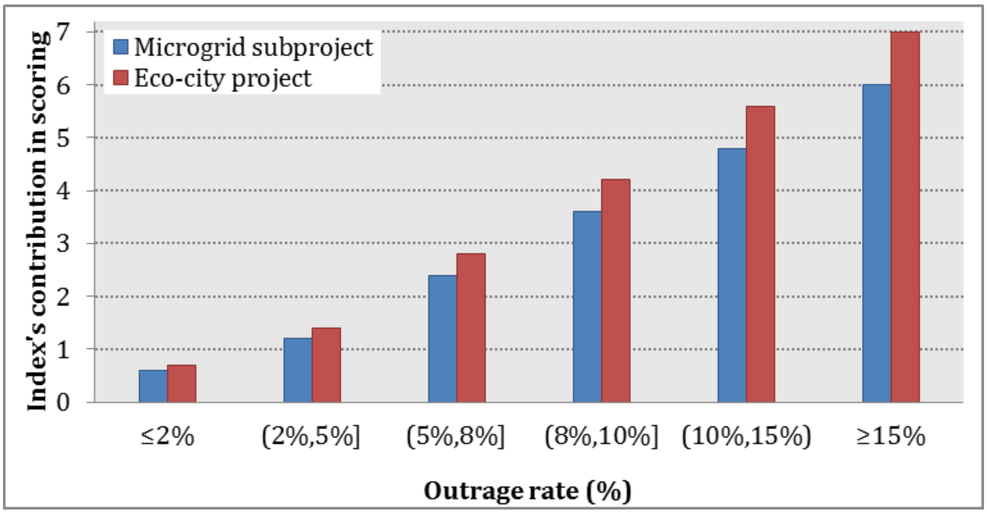

Figure 4.1. Comparison of outage rate for microgrid sub-project and TEC project

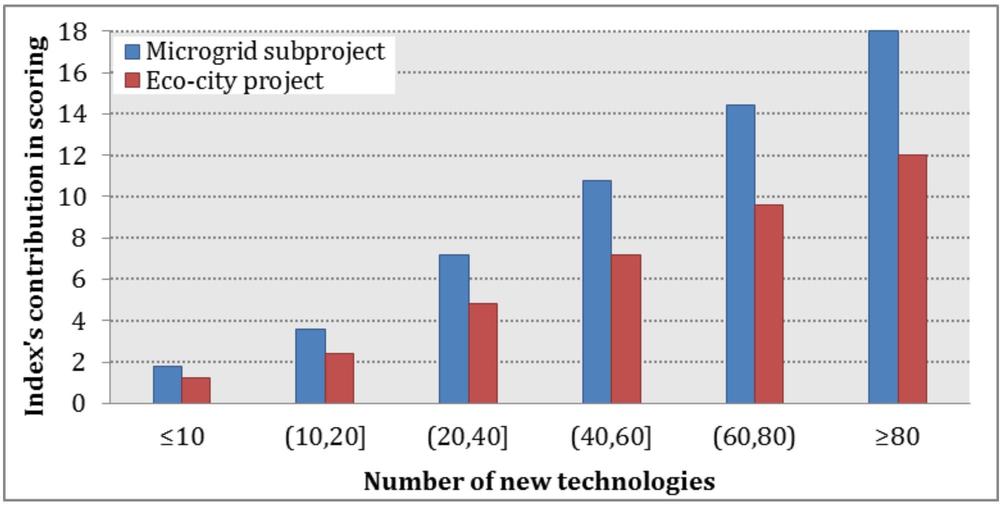

Figure 4.2. Comparison of number of new technologies for microgrid sub-project and TEC project

The aim of sensitivity analysis is to determine the impact of a change in certain factors (indices) on the eco-city's evaluation scores and to discover the key indicators contributing to the scores. Figure 4.1 shows the results of changing the outage rate in scoring the microgrid sub-project and eco-city project. The influence goes from bottom layer to top layer in the hierarchy, impacting the score at each layer by multiplying the corresponding weights. In general, as outage rate increases, the evaluation score increases for both projects. The difference is determined by the weights of the corresponding indices, e.g., technological index, reliability index. In Figure 4.2, the weight of technological index in the microgrid sub-project is much larger than in the eco-city project; therefore, the technological indicator contributes more to the evaluation score in the microgrid sub-project.

4.2. *Benefit Analysis of B-TEC Project (using QPA Method)*

(1) General Assumptions

- The life cycles of the smart power grid and the ESS are calculated at 10 years and 15 years, respectively.
- The construction period for the smart power grid is assumed to be two years, and the profits are calculated from the year after construction is completed. The construction period for the ESS is considered to be one year, and the profits are calculated from the year after construction is completed.
- The capitalization ratio of fixed assets is 95%, and the residual ratio is 5%.
- The O&M costs account for 2% of the original value of fixed assets.
- The benchmark interest rate is 7%.

(2) Benefit Analysis

The BS of each B-TEC subsystem, using data from the B-TEC project feasibility analysis report, is shown in Table 4.4. The cost of investment represents fixed assets, including equipment purchase, software, installation, etc. The BA outputs include IRR, NPV, static investment P_t for different stakeholders, and classification of assets, functions, and benefits.

Table 4.4
Table of economic benefit calculation for each B-TEC project subsystem

Sub-system	Benefit	Beneficiary	Value	Fixed asset investment cost (2014)	Financial index (2015)		Comprehensive benefit	PSB benefit
Sub-project 1	Benefits from grid loss reduction	Power supply bureau (PSB)	287.5	16,500	0	IRR	17.3%	7.7%
						NPV	1.05M	0.06M
	Reduction of power grid failure losses	PSB	0.9			Pt	6	9
		Users	160.9					
Sub-project 2	Reduction of power purchase cost	PSB	73.9			IRR	-17.2%	-18.9%
	Saving of investment for transformer substation construction	PSB	0	12,500	10,000	NPV	(1.75M)	(1.82M)
	Reduction of coal consumption and pollutant emissions	Society	10.9			Pt	Cannot be paid back	Cannot be paid back

Sub-project 3	O&M expense reduction	PSB	12.4					
	Saving of investment for transformer substation construction	PSB	900			IRR	——	11.9%
				28,000	16,900			
	Saving of investment for equipment replacement	PSB	15.3			NPV	——	1.16M
	O&M expense reduction	PSB	1.3			Pt	——	8
Sub-project 4	Saving of investment for equipment replacement	PSB	318.4	12,500	8,000	IRR	——	5.9%
	O&M expense reduction	PSB	1.3			NPV	——	0.11M
						Pt	——	10
Sub-project 5	Arbitrage returns	PSB	3,000					
	Saving of investment for transformer substation construction	PSB	20,000			IRR	6.7%	-9%
	Saving of generation construction investment	Power producer	25,000	93,680	8,000	NPV	3500	(0.05M)
	Ancillary service benefits	PSB	1,000					
						Pt	9	Cannot be paid back
	Reduction of power grid failure losses	Users	2,000					

Note: Value and Fixed asset investment cost are in ‘000 CNY. NPV is in CNY. Pt is in years. PSB represents Power Supply Bureau.

a. Sub-project 1: Distribution grid optimal operation and fault self-recovery module

Comprehensively considering social benefits from reduced power failure losses, the IRR of the overall project investment is 17.3%, the NPV is CNY[8]1.05M , and the static investment payback period is 6 years, so the benchmark yield is very high. If the power supply bureau is considered the evaluation subject, the IRR of the project, excluding social benefits, is 7.7%; the NPV is CNY0.06M; and the payback period is 9 years, so the benchmark yield is achieved.

b. Sub-project 2: Distributed energy coordination and dispatching

Comprehensively considering social benefits from the reduction in coal consumption and pollutant emissions, the IRR of the overall project investment is -17.2%, and the NPV is CNY(1.75M), which means that the project investment cannot be paid back. If the power supply bureau is considered the evaluation subject, the IRR of the project, excluding social benefits, is -18.9%, the NPV is CNY(1.82M), so the project investment cannot be paid back.

c. Sub-project 3: AMI System

The power supply bureau is the main beneficiary of the AMI system and therefore is the evaluation subject. The IRR of the project is 11.9%, the NPV is CNY1.16M, and the payback period is 8 years, so the economic efficiency of the project is high.

d. Sub-project 4: Distribution grid operation state sensory system

The power supply bureau is the main beneficiary of the distribution grid operation state sensory module and therefore is the evaluation subject. The IRR of the project is 5.9%, the NPV is CNY0.11M, and the payback period is 10 years. The economic efficiency of the project is normal, and the benchmark yield is not achieved.

e. Sub-project 5: Load center energy storage station

Comprehensively considering the benefits of the load center ESS to the power supply bureau, power generation companies, and users, the IRR of the project is 6.7 %, which does not meet the project benchmark yield. The payback period is 9 years.

(3) Sensitivity analysis

Many factors affect the project's comprehensive benefits. The sensitivity analysis estimates the impact of uncertainties (power purchase price, load, investment, PV power, equipment prices, unit capacity investment, peak and off-peak price differences, ancillary service benefits, generation capacity benefits and transmission and distribution capacity benefits) changing by ±20%, ±15%, ±10%, and ±5% with only one factor changing at a time and all other factors remaining unchanged. This enables us to estimate the impact of each factor on economic benefit indices and thus to analyze the project's risk resistance. The results of the sensitivity analysis are shown in figures below:

a. Sub-project 1: Distribution grid optimal operation and fault self-recovery module

Investment has the greatest impact on the economic benefits of the distribution grid optimal operation and self-recovery module. The second greatest impact is from purchase price. If all sensitivity factors change within ±20% and the comprehensive IRR is above 10%, the comprehensive benefits of the optimal operation and self-recovery module will be obvious, the IRR of the power supply bureau will achieve the benchmark yield, and the application promotion value will be high. See Figure 4.3.

[8] CNY, Official Chinese Currency

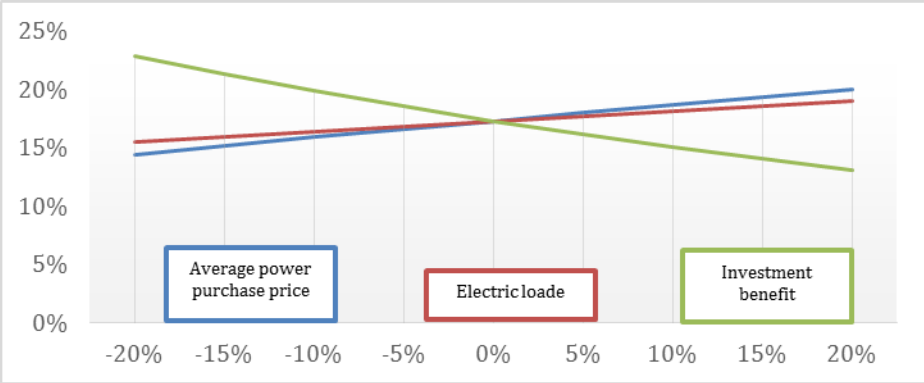

Figure 4.3. Benefit sensitivity analysis of optimal operation and fault self-recovery module of distribution grid. Note: X-axis represents change in the parameters and Y-axis represents change in IRR.

b. Sub-project 2: Distributed energy coordination and dispatching

The benefits of the distributed energy coordination and dispatching module are not obvious, and the project cannot achieve its investment return target if various uncertain factors change within ±20%. The distributed energy scale of the demonstration zone is small, and the environmental value compensation mechanism for renewable energies is incomplete. If the distributed energy coordination and dispatching module is widely promoted and a renewable energy market mechanism becomes established, the benefits of the distributed energy coordination and dispatching module will be improved. See Figure 4.4.

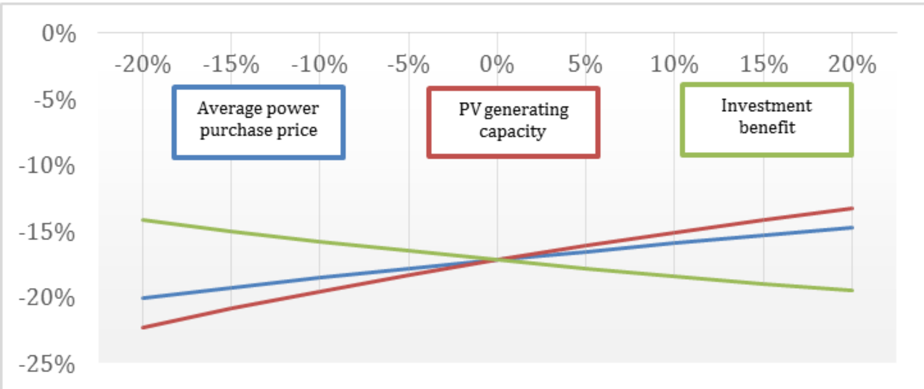

Figure 4.4. Benefit sensitivity analysis of distributed energy coordination and dispatching. Note: X-axis represents change in the parameters and Y-axis represents change in IRR.

c. Sub-project 3: AMI System

Investment has the greatest impact on the economic benefits of the AMI system module. Purchase price has the second greatest impact. If all sensitivity factors change within ±20% and the comprehensive IRR is above 7%, the comprehensive benefits of the AMI system module will be obvious, and the application promotion value will be high. See Figure 4.5.

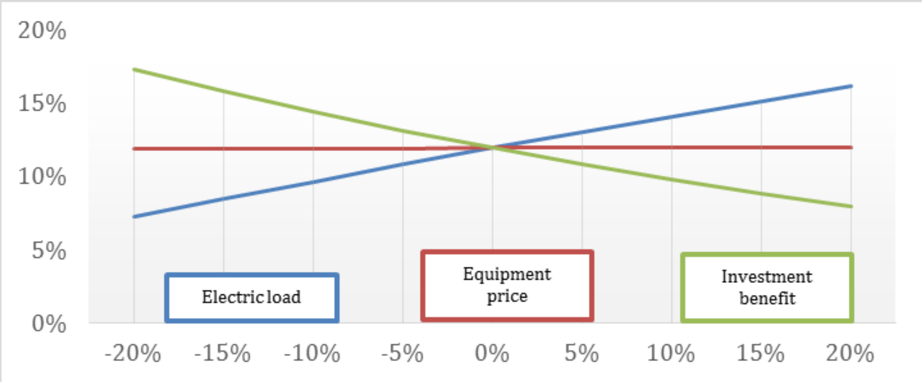

Figure 4.5. Benefit sensitivity analysis of AMI system. Note: X-axis represents change in the parameters and Y-axis represents change in IRR.

d. Sub-project 4: Distribution grid operation state sensory system

The economic benefits of the distribution grid operation state sensory module are heavily affected by investment and equipment price. If the investment drops by 10%, the IRR will reach 8%, and the project will have high application promotion value. See Figure 4.6.

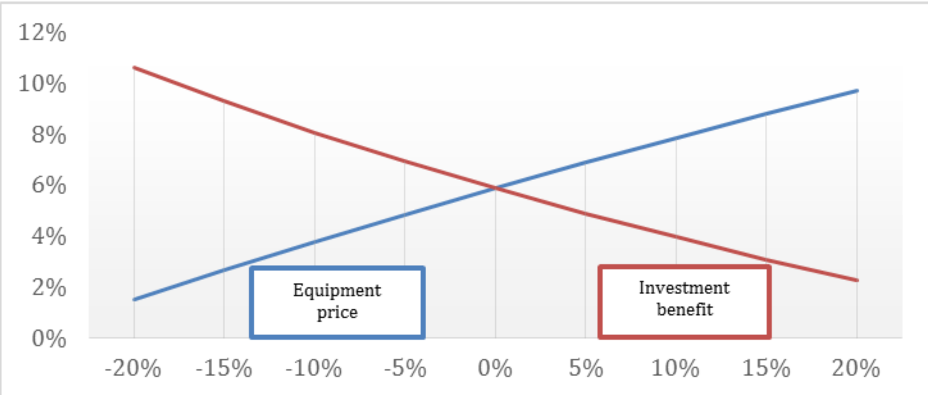

Fig. 4.6. Benefit sensitivity analysis of distribution grid operation state sensory system. Note: X-axis represents change in the parameters and Y-axis represents change in IRR.

e. Sub-project 5: Load center energy storage station

Among the various factors, investment has a significant impact on IRR indices. If the investment drops by 10%, the comprehensive IRR of the project will reach approximately 12.72%. In addition, the peak and off-peak price difference has considerable impact on the benefit rate. If the peak and off-peak price difference grows by 15%, the comprehensive IRR will reach approximately 10%. However, because the IRR of the power supply bureau as the investor is negative, if the unit investment of the energy storage station drops by 50% and benefits from ancillary services can be achieved, the energy storage station profit will achieve the benchmark yield, and the project will have high promotion value. See Figure 4.7.

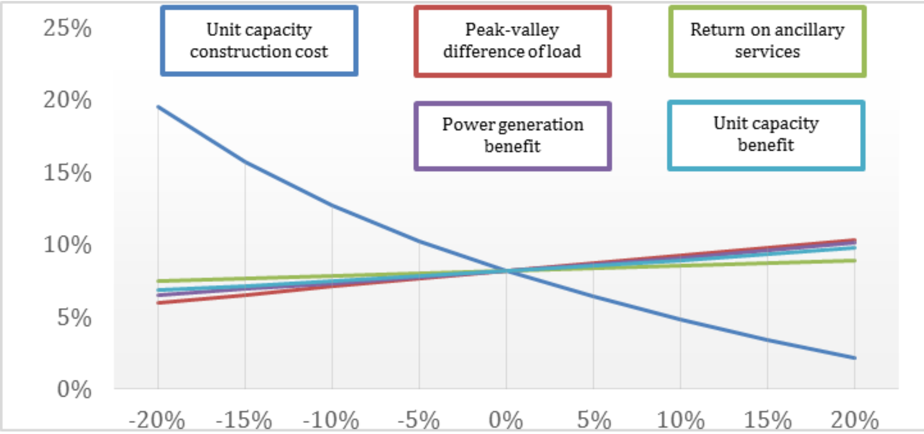

Figure 4.7. Benefit sensitivity analysis of load center energy storage station**.** Note: X-axis represents change in the parameters and Y-axis represents change in IRR.

5. Benefit Analysis of Smart Grid Projects in the U.S.

5.1. Benefit Analysis of ISGD and UCI Projects

5.1.1. Benefit Analysis of ISGD Project (using EPRI/U.S. DOE Method)

(1) General Assumptions

This subsection presents BAs of ISGD sub-projects 1, 3, and 4. The following assumptions were made in preparing the BAs of these sub-projects:

- Homes on each block have different levels of retrofit, and some differ within the same block. The average costs associated with each upgrade are detailed in Table 5.1. It is assumed that replacement upgrades of white goods (smart refrigerators, dishwashers, clothes washers, and efficient hot-water heaters) would be more expensive than common models. For those technologies, only incremental cost over similar models is included. For new technologies, such as home EMS displays, RESUs, community energy storage (CES), and PV systems, the equipment total cost is used.

Table 5.1
Average cost of retrofit by project block in ISGD sub-project 1

Blocks	Average cost per home ('000 2010USD)
ZNE Block	USD146.3
Demand response	USD12.2
Energy-efficiency measures	USD48.0
Residential energy storage unit	USD66.7
Solar PV panels	USD19.5
RESU Block	USD115.6
Demand response	USD12.2
Residential energy storage unit	USD66.7
Solar PV panels	USD36.7
CES Block	USD60.7
Demand response	USD12.2
Community energy storage unit	USD22.3
Solar PV panels	USD26.2

Because the EPRI method and SGCT tool do not consider equipment lifetime or technology model survival, the survival probability of each technology was calculated exogenously and implemented as a cost input. Survival probabilities are assumed normally distributed with a mean lifetime and variance of 3 years.

- Applying a social discount rate to costs and benefits gives us the value of the project to society regardless of actual project costs. International practices recommend rates varying from 1 to 15% with the highest rates used in developing countries (Harrison, 2010). The U.S. Office of Management and Budget uses a discount rate of 7% and recommends 3% as a sensitivity, and the U.S. Environmental Protection Agency uses 2-3% with a sensitivity rate of 7%. The European Commission suggests 5%, and the United Kingdom Treasury uses 3.5%. Given this range, we assumed a societal discount rate of 5% and performed sensitivity analysis for 2.5, 7.5, and 10%.
- Project input parameters are for 2014 because ISGD was activated in 2013, so 2014 was a full representative test year. Baseline parameters are from 2012.
- The time horizon from the beginning of the project is 25 years.

- The value of T&D capacity is based on projected total cost to add capacity system wide over a 5- to 10-year horizon although actual benefits will depend on the location of peak reductions. In addition, T&D losses of 4.8% and 2.7%, respectively, were used.

The analysis and results reported here should be regarded as preliminary and illustrative for the purpose of demonstrating and assessing the SGCT. Broader conclusions regarding the relative efficacy of the technologies demonstrated in ISGD sub-projects should not be drawn based on this work. SCE will file its official benefits report when the project is completed.

(2) Benefit Analysis

a. *Mapping*

Figure 5.1 illustrates the assets identified for each sub-project, listed in left side boxes, with mapping to functions activated by the assets. Figure 5.2 summarizes the subsequent functions-to-benefits mapping for each test case sub-project. The right side cells labeled "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 functions link as expected, and one function links to an unexpected benefit. Optimized generator operation is a benefit not directly realized from the distributed production of electricity function in sub-project 1. Although it is credible that coordination between outputs from distributed sources and operation of centralized assets might improve overall fuel efficiency, this coordination implies a detailed level of operational control. In this study, no input was made for this benefit to eliminate it from calculations. Likewise, the automated voltage and VAR control function in sub-project 4 is only linked to the following benefits: reduced electricity losses, reduced CO_2 emissions, and reduced sulfur oxide (SOx), nitrogen oxide (NOx), and 2.5-micron particulate matter (PM2.5) emissions; however, field experiments have shown that this DVVC implementation produces significant customer energy savings ranging between 1.6% and 3.6% with an average of 2.6% (Irwin and Yinger, 2015).[9] Figure 5.3 illustrates customer voltages realized in field experiments with and without DVVC. The technology also delivers benefits from deferred generation and T&D capacity investments and reduces distribution equipment maintenance costs. Benefits not identified by the tool for DVVC are marked in red (with +YES) in Figure 5.2. To address this limitation, a phantom asset was added to generate the missing benefits at no cost.

[9] 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).

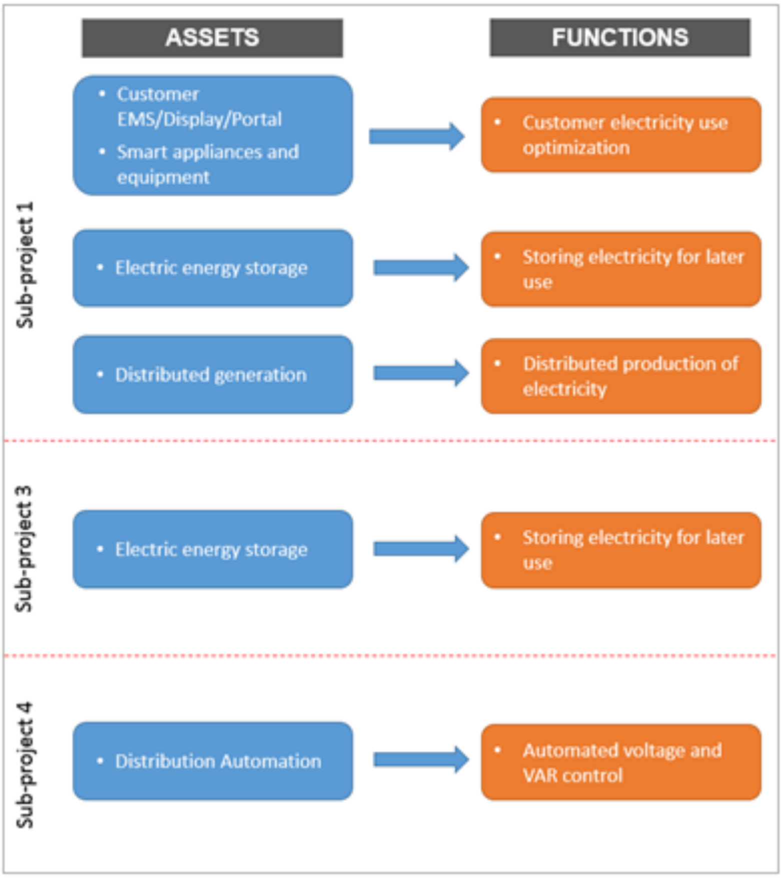

Figure 5.1. Asset-to-function mapping of each sub-project case

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 5.2. Function-to-benefit mapping of each sub-project case. Note: Green cells are identified by SGCT; red cells are additional.

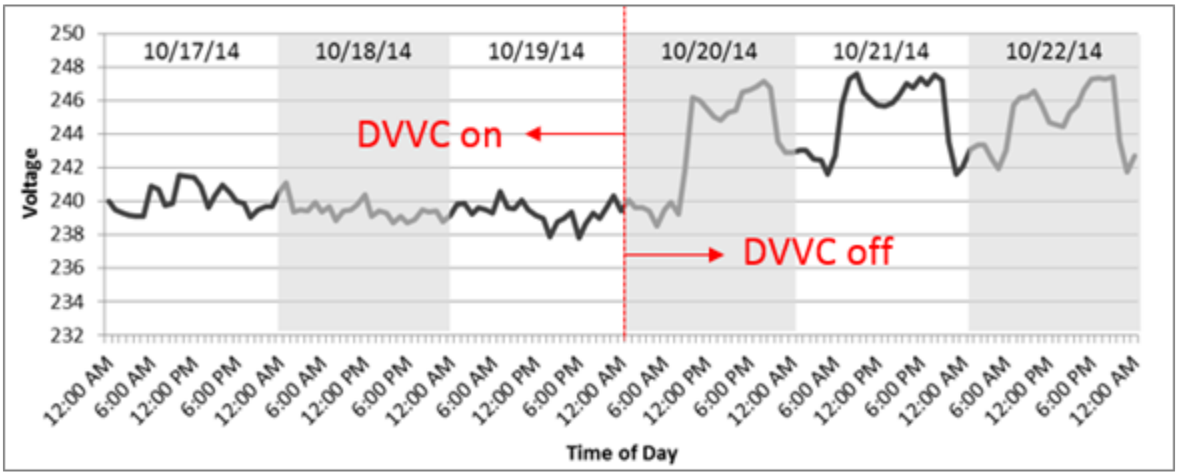

Figure 5.3. Customer voltages with and without DVVC (17 October 2014 to 22 October 2014). *Source:* Irwin and Yinger, 2015.

b. *Results*

Table 5.2 summarizes the estimated benefits for the three stakeholder groups shown. Utility benefits are reductions in the cost of providing service, i.e., any changes in generation or T&D costs. Showing benefits in this way is controversial because a regulated utility is unlikely to retain all of them as some will likely be ultimately returned to customers via reduced future rates. In California, deviations from expected revenues and fuel costs are explicitly tracked and mostly incorporated into future rates although treatment of changes in other costs, as listed in Table 5.2, is less clear cut. Nonetheless, because this analysis is intended to be a trial application of the SGCT, we apply it as designed.

Table 5.2
Overview of stakeholders and benefits in ISGD sub-project cases

	Utility	Consumer	Society
Economic	Deferred generation capacity investments Reduced ancillary service cost Reduced congestion cost Deferred transmission capacity investments Deferred distribution capacity investments Reduced T&D equipment maintenance cost Reduced electricity losses	Reduced electricity cost	
Environment			Reduced CO_2 emissions Reduced SO_x, NO_x, and PM2.5 emissions

Consumers are mainly affected through changes in electricity consumption resulting from adoption of 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, sub-project 1 reduces the total consumption by 75%, as shown in Figure 5.4 (a). In addition, 74% of total electricity consumption, i.e., 95 of 129 MWh, is met by PV generation. Electricity efficiency improvements only lower consumption by 5.5 MWh. These effects significantly reduce coincident peak load, as shown in Figure 5.4 (b). The total peak load of the 22 project homes drops from 17 kW in the baseline period to 3.7 kW during the test period.

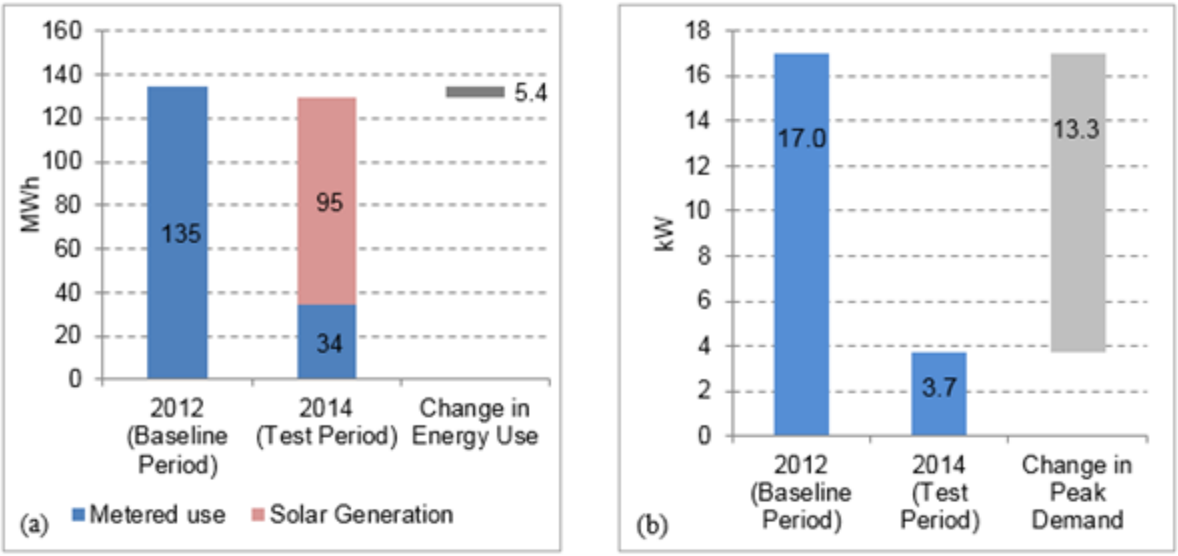

Figure 5.4. 22-home annual electricity consumption and coincident peak in ZNE block

For sub-project 4, the 2.6% energy savings rate demonstrated in these field experiments was applied to the seven MacArthur substation circuits, which serve roughly 8,300 customers. Shaving peak load postpones, reduces, or even eliminates the need to install expensive generation and T&D capacity. In addition, higher load incurs disproportionately more losses, so managing the peak, i.e., reducing maximum demand and flattening the load curve, improves electricity delivery efficiency. All sub-projects investigated in this paper help decrease peak load. The technologies implemented in sub-project 1 reduce the peak as a result of efficient appliance usage, demand shift, PV generation, and battery discharge at peak times. The 2 MW battery can be discharged at peak hours in sub-project 3, and optimizing voltage/VAR control in sub-project 4 also reduces peak demand and T&D losses.

Environmental benefits are reduced CO_2 emissions and other pollutant damage costs. Estimation relies on physical quantification of the emissions and their conversion to monetary costs using California carbon and pollutant costs.[10] Increased consumer awareness of electricity use and decreases in electricity consumption achieved by efficient smart appliances reduce both electricity generation and its associated emissions. PV panels provide electricity without CO_2 emissions, contributing to the reduction of overall CO_2 emissions of sub-project 1. Electricity use reductions from sub-project 4 lower generation and associated emissions. Calculation of emission reductions in the EPRI method is only based on consumption reduction and excludes any additional peak reduction benefit from lower peaker operation.

NPVs for total costs and benefits of each sub-project are summarized in Table 5.3. Results appear to be significantly different among the sub-projects analyzed. The overall B/C ratio of sub-project 1 is 0.1 (with -USD4.3M annual net benefits) while sub-projects 3 and 4 have B/C ratios of 2.5 (with USD1.3M annual net benefits) and 12.9 (with USD6.8M annual net benefits), respectively.

[10] USD12/t CO_2 was used based on the average California carbon price in 2014 (http://calcarbondash.org/), USD3,000/tNOx and USD250/tSOx are based on SGCT default data for Western Electricity Coordinating Council (Navigant, 2011).

Figure 5.5 shows 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 for sub-project 1 are far from turning positive during the investigation period; i.e., the blue line is strongly and increasingly negative. Sub-project 3 turns to positive starting from 2019, and sub-project 4 turns positive starting in 2013, i.e., even before project deployment is completed. These SGCT results indicate that sub-project 1 is not economically attractive at current project performance and expenditures. The cost of sub-project 1 needs to be about 94% lower to achieve a B/C ratio greater than 1, i.e., to break even. Nonetheless, a low B/C ratio is acceptable for a pure technology demonstration project such as sub-project 1 in which most of the equipment installed is at an emerging stage of development and requires a steep learning curve. The ZNE Homes block is very much a technology demonstration, and not intended to reach break even. Recent announcements of residential battery cost reductions underscore the early vintages of the equipment installed in the 22 homes. Nonetheless, B/C ratio results are still valuable for providing suggestive estimates of the cost-performance gap between current generation technology and break-even or viable commercialization. The EPRI/U.S. DOE method does not include uncertainty on cost reductions over time, which would be a welcome extension of these results.

Sub-projects 3 and 4 appear to be economically viable, the latter strongly so. The result for sub-project 4 parallels SCE's experience, and the company is already moving to widespread deployment of DVVC. 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 limit and only considers storage power. This causes overestimates of utility capacity deferrals because the system may not have sufficient energy capacity to sustain its maximum power level and achieve an equivalent lower the peak.

Table 5.3
Costs and benefits of each ISGD sub-project (in NPV)

	Sub-project 1	Sub-project 3	Sub-project 4
NPV of cost	USD(4.64M)	USD(0.85M)	USD(0.59M)
NPV of benefit	USD0.30M	USD2.14M	USD7.58M
NPV of net benefit	USD(4.34M)	USD1.30M	USD6.99M
B/C ratio	0.1	2.5	12.9

Figure 5.6 breaks down the benefits. In both sub-projects 1 and 4, more than 80% of the benefits are from reduced electricity costs, which is a consumer benefit. For sub-project 3, almost 70% of the benefits come from deferral in generation capacity investments and 25% derive from reduction in losses, with the remaining benefit from T&D deferral, so the utility is the only stakeholder that benefits in this sub-project (see Figure 5.7); however, many would argue the EPRI/U.S. DOE method treats some of the consumer benefits as utility benefits, as explained above. For example, if energy procurement and operating costs are reduced, or capital investment is deferred, this savings may ultimately accrue to customers through subsequent reduced rates.

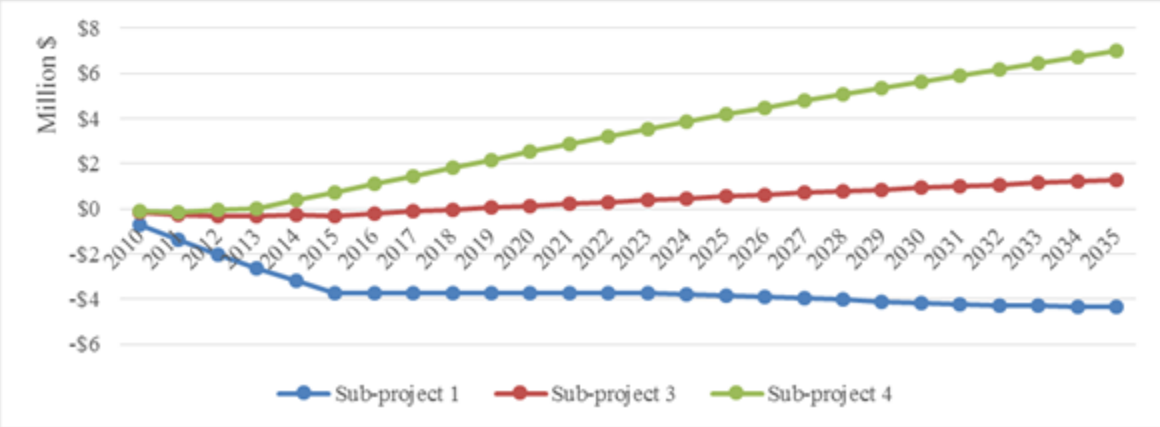

Figure 5.5. Cumulative net benefits of each ISGD sub-project

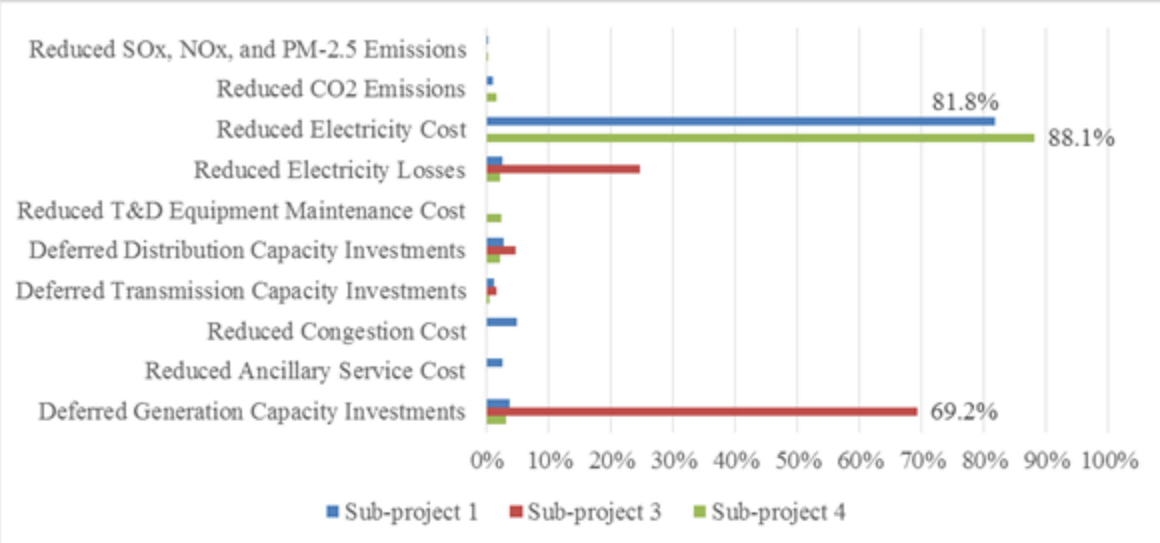

Figure 5.6. Distribution of benefits in each ISGD sub-project.

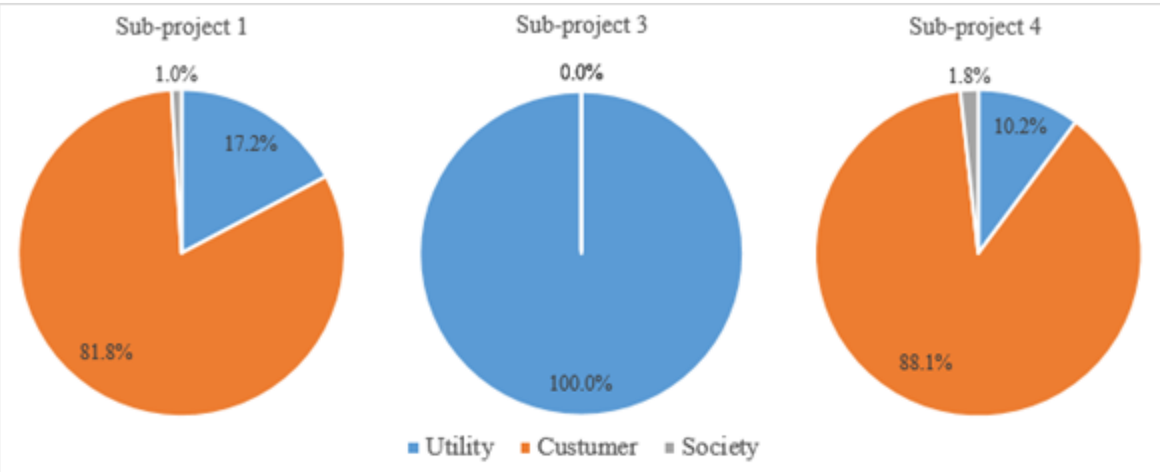

Figure 5.7. Distribution of benefits to stakeholders in each ISGD sub-project

c. *Sensitivity Analysis*

Figure 5.8 compares the cumulative net present benefits of sub-project 1 with and without energy storage technologies and heat pumps. Heat pumps are the second-most-expensive technology in the project, listed after energy storage technologies. Net benefits are improved when the batteries are excluded from the analysis with or without heat pumps; however, benefits are still negative. In addition, the results showed that the B/C ratio is only increased to 0.2 when only batteries are excluded, or to 0.3 with heat pumps excluded.

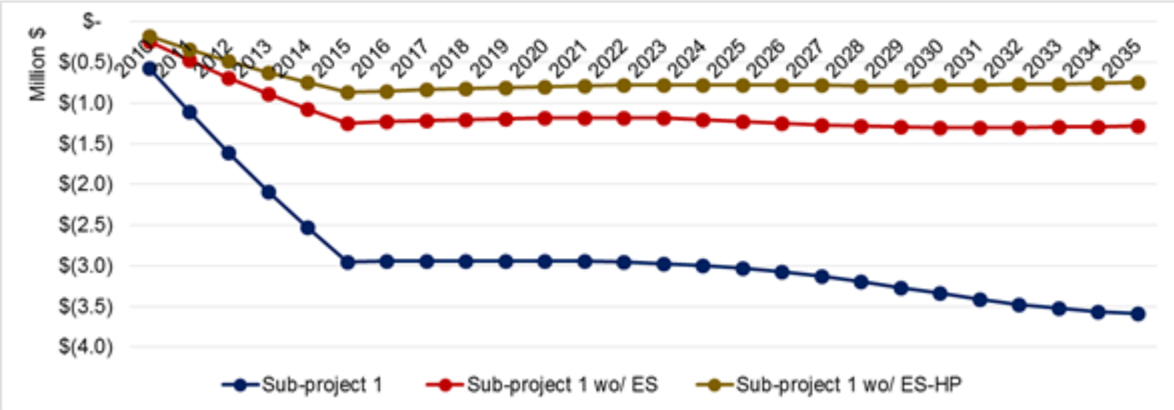

Figure 5.8. Cumulative net benefits of sub-project 1. *Compared to the scenarios "without Energy Storage Technologies" and "without Energy Storage Technologies and Heat Pump."* Note: Sub-project 1 wo/ ES represents a sensitivity run that does not include energy storage technologies, and Sub-project 1 wo/ ES-HP represents a sensitivity run without does not include energy storage technologies and heat pumps.

The sensitivity of B/C 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 because costs are incurred predominantly at the beginning of the scenario while benefits may be sustained over the long term. Figure 5.9 and Table 5.4 illustrate the sensitivity of each sub-project case to discount rate. Naturally, the results show that the higher the discount rate, the lower the NPV. Nonetheless, results are fairly robust, all NPVs are negative, and all sub-project 1 B/C ratios are close to zero regardless of the discount rate. Sub-projects 3 and 4 always generate positive NPVs and B/C ratios above break even.

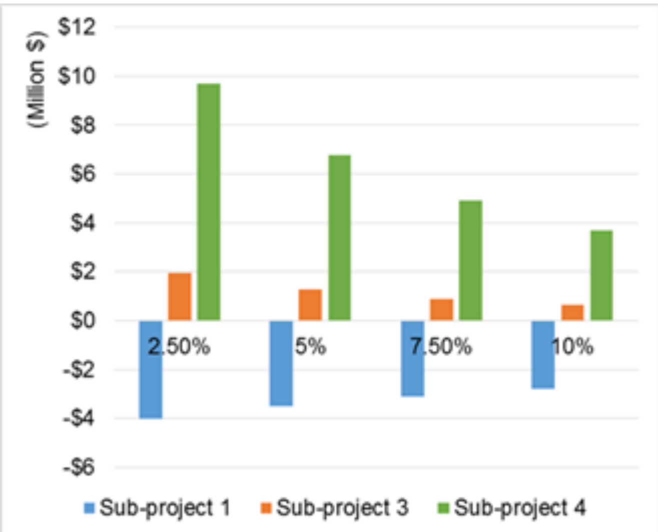

Figure 5.9. Sub-project NPVs vs. discount rates

Table 5.4
ISGD project B/C ratios with varying discount rates

Discount rates	2.5%	5.0%	7.5%	10.0%
Sub-project 1	0.11	0.09	0.07	0.06
Sub-project 3	3.07	2.53	2.16	1.92
Sub-project 4	14.4	12.9	11.0	9.61

5.1.2. Benefit Analysis of UCI Campus Project (using EPRI/U.S. DOE Method)

(1) General Assumptions

This section presents B/C analyses of the following UCI Microgrid sub-projects: 1) 19 MW CHP plant, 2) 3.6 MW PV, 3) MgC, and 4) 2 MW battery. The following assumptions were made in these BAs.

- The annual microgrid load reduced by 3% per year as a result of energy-efficiency measures.
- The natural gas price follows the prices paid by the UCI Microgrid over the first 5 years of the CHP project (Figure 5.10). (In addition, we analyzed a scenario with a constant natural gas price of USD4.74/gigajoule [GJ]).

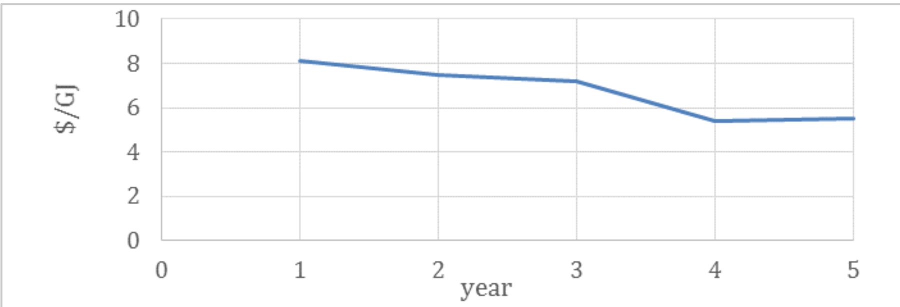

Figure 5.10. Natural gas prices paid by the UCI Microgrid in the first 5 years of the CHP

- The 2 MW battery is used to reduce utility imports by buffering the error of the CHP plant's manual load-following control. This allows an electricity import reduction of approximately 200 kW, which saves USD140,000 annually, according to simulations.
- The following cost information was used for the CHP plant: Debt service and O&M – approx. USD1.5M annually with a USD30M installed cost.
- For the 3.6 MW PV, we used a USD12M capital cost with default interest rates in the SGCT, which has similar yearly project costs to the actual financial arrangement using several PPAs across the campus.
- For the battery we used a USD500,000 installed cost (USD1,000/kWh).
- The MgC was assumed to cost USD1M. This controller would enable islanding if the current CHP plant was already installed but incapable of islanding.
- Discount Rate = 3% and Interest Rate = 4% were used.
- The emission factors in Table 5.5 were used.

Table 5.5
Emission factors used for analyzing UCI Microgrid projects

Emission Factor	Grid [kg/MWh]	CHP [kg/MWh]	Boiler [kg/MWh thermal]
CO_2 emission factor	350	624	181
SO_x emission factor	0.0088	0.0059	0.000911
NO_x emission factor	0.0388	0.024	0.167
$PM_{2.5}$ emission factor	0.0092	0.0088	0.0116

- The following assumptions and sources were used in determining the emission factors in Table 5.5. The boiler was assumed to have 85% efficiency. The CHP calculations were based on electric-only efficiencies from collected data (~30%). For the grid, the factors were based on data from the California Air Resources Board Emissions Inventory (2013) that show the CO_2 emission factor from the California electricity grid as 315 kilograms (kg)/MWh. A slightly higher CO_2 emission factor was used based on the typical assumption that DG will offset more natural-gas load-following grid electricity than renewable grid electricity, so the value of 350 kg/MWh appeared to be a low estimate representative of new highly efficient load-following technology (~52% electric efficiency) with the higher estimate of 450 kg/MWh for offset of current load-following technology (~40% electric efficiency). The results for 450 kg/MWh are shown in the sensitivity results section. For criteria pollutants, the CHP emission factors were based on collected data and efficiencies. For the criteria pollutants from boilers, AP-42 was used (U.S. EPA, 1995 and Shaffer et al. 2015). For the criteria pollutants from the grid, the California Air Resources Board Emissions Inventory (2013) was used.
- The following sources and assumptions were used for emissions pricing:
  - For CO_2 pricing, the default SGCT value of USD20/t was used. For comparison, the most recent California cap-and-trade settlement price, from the February 2016 auction, was USD12.73.
  - For NO_x pricing, the default SGCT value of USD3,000/t was used. For comparison, the following values come from the South Coast Air Quality Management District, which is responsible for the Los Angeles air basin and operates the RECLAIM emission credit trading market for NO_x and SO_x emissions. The RECLAIM January – December 2015 rolling average NO_x trading credits price was USD1,642, and the January – December 2014 rolling average NOx trading credits price was USD3,779.
  - For SOx pricing, the default SGCT value of USD520/t was used. The RECLAIM 2015 SOx trading credit price was USD380.
  - For $PM_{2.5}$ pricing, the default SGCT value of USD36,000/t was used.
- The following reliability information was used to evaluate reliability improvements as a result of the MgC. The baseline SAIDI (which reflects hours of sustained outages per customer per year) is 1.17 and was calculated from UCI data on outages from the past 5 years. The improved SAIDI after installation of the MgC is set at 0.17, which assumes elimination of all utility-caused outages.
- The assumed customer characteristics are: 3,000 residential accounts paying a rate of USD0.12/kWh, and 500 commercial accounts paying a rate of USD0.10/kWh.
- The utility electricity pricing values are: energy charge = USD70/MWh, demand charge = USD16.89/kW.
- The following sensitivity studies were completed using the following adjusted parameters: marginal generation = 450 grams (g) CO_2e/kWh, flat natural gas price = USD4.74/GJ, and SAIDI varied to 0.583 and 0.99 hours of sustained outages per customer per year.

- Applying a societal discount rate to costs and benefits provides the value of the project to society regardless of actual project costs. As noted earlier, international practices recommend rates varying from 1 to 15% with the highest rates used in developing countries (Harrison, 2010). The U.S. Office of Management and Budget uses a discount rate of 7% and recommends 3% as a sensitivity, and the U.S. Environmental Protection Agency uses 2-3% with a sensitivity rate of 7%. The European Commission suggests 5%, and the United Kingdom Treasury uses 3.5%. Given this range of views, a societal discount rate of 3% was assumed and a sensitivity was performed for one scenario using a discount rate of 6%. Note the UCI team chose a different discount rate than the 5% used for ISGD, as explained in Section 5.1.1.
- Project input parameters are from the year 2010.
- The time horizon from the beginning of the project is 25 years.

The analysis and results reported here should be regarded as preliminary and illustrative for the purpose of demonstrating and assessing the SGCT. Broader conclusions regarding the relative efficacy of the technologies demonstrated in the UCI Microgrid project should not be drawn based on this work.

(2) Benefit Analysis

This study contains BAs of the following UCI Microgrid projects: (1) 19 MW CHP plant (currently installed): (2) 3.6 MW PV (currently installed); (3) MgC (installation planned in fall 2016); (4) 2 MW battery (installation planned in spring 2016)

a. Mapping

Figure 5.11 illustrates the assets identified for each project and defines the functions provided by those assets and the resulting benefits. It is important to note that some benefits were included that actually resulted in a cost. For example, the CHP plant was originally planned to provide CO_2 emission reductions, but the California electricity system has substantially reduced its carbon emissions so that the CHP plant is now more carbon-intensive than purchased electricity. Since the CHP plant was planned to reduce carbon emissions, it was input into the SGCT as a benefit (Figure 5.11) although under current conditions it would result in a cost.

b. Results

Table 5.6 shows the total present value of the net benefits for each UCI Microgrid sub-project analyzed. The MgC project shows an extremely high value, which results from the reliability benefits of reducing SAIDI (see Figure 5.13). Based on historical data on UCI campus outages, we observed that removal of outages caused by SCE system issues would reduce SAIDI from 1.17 to 0.17 hours per customer per year. This is an impressive increase in reliability that is assumed to be the optimistic upper bound on what may be achievable. The sensitivity study below further investigates the impact of the SAIDI on the benefits calculated by the SGCT. The CHP plant also shows significant value, and Figure 5.13 shows that this is largely a result of the economic benefit associated with the category "optimized generator operation."[11] The significant value of the CHP plant is not surprising given trends in natural-gas prices over the past several years, which have made electricity generated from the CHP cheaper than electricity purchased from the utility. The net benefit of installing PV is much lower than the value of the CHP plant and MgC projects because of the higher cost of the PV. If the cost of carbon were to increase substantially, this would change slightly, but

[11] Note that there is no optimization of CHP plant operation; rather, this category was used to identify the operational cost reductions achieved by generating electricity on site instead of purchasing it from the utility.

in order for the PV to compete with the CHP, cost reductions are still needed. The battery shows a very high B/C ratio compared to the other projects although the absolute value of the net benefit is much smaller than the values of the other projects.

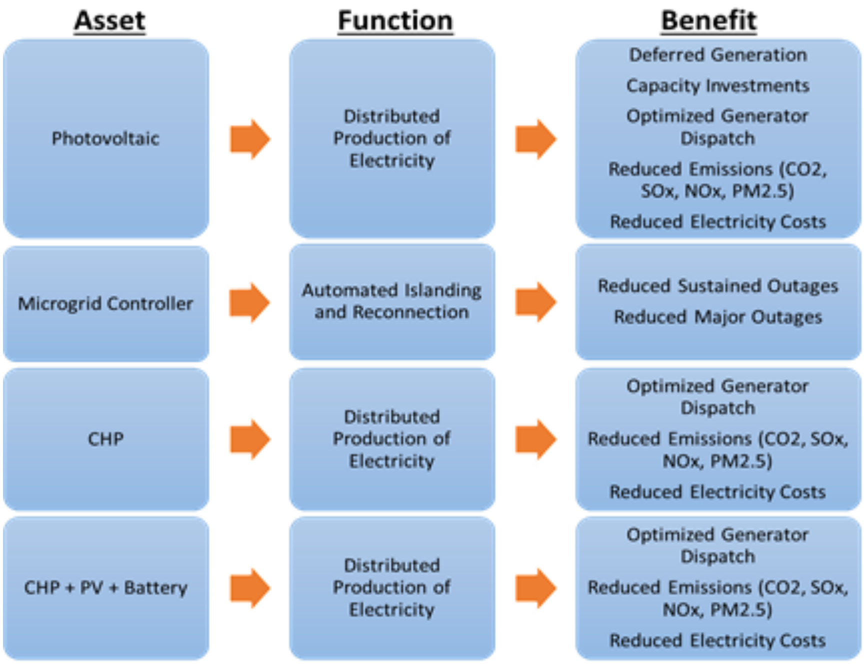

Figure 5.11. Schematic of the functions and resulting benefits for the different UCI Microgrid project assets

Table 5.6
Costs and benefits of each UCI sub-project (in NPV)

	CHP	PV	MgC	Battery
NPV of cost	USD(30.6M)	USD(13.7M)	USD(1.14M)	USD(0.51M)
NPV of benefit	USD124M	USD43.2M	USD242M	USD3.47M
NPV of net benefit	USD93.1M	USD29.5M	USD241M	USD2.96M
B/C ratio	4.0	3.2	212	6.8

Figure 5.12 shows the evolution of the present value of the net benefits over each project's life. It is interesting to note the slope change in each of the curves. This is a result of project input data and projections that the SGCT makes for later years. In particular, the CHP plant data show large variation in the early years as a result of variation in the input data for this project, specifically the natural gas price variation and the reductions in load that occur each year.

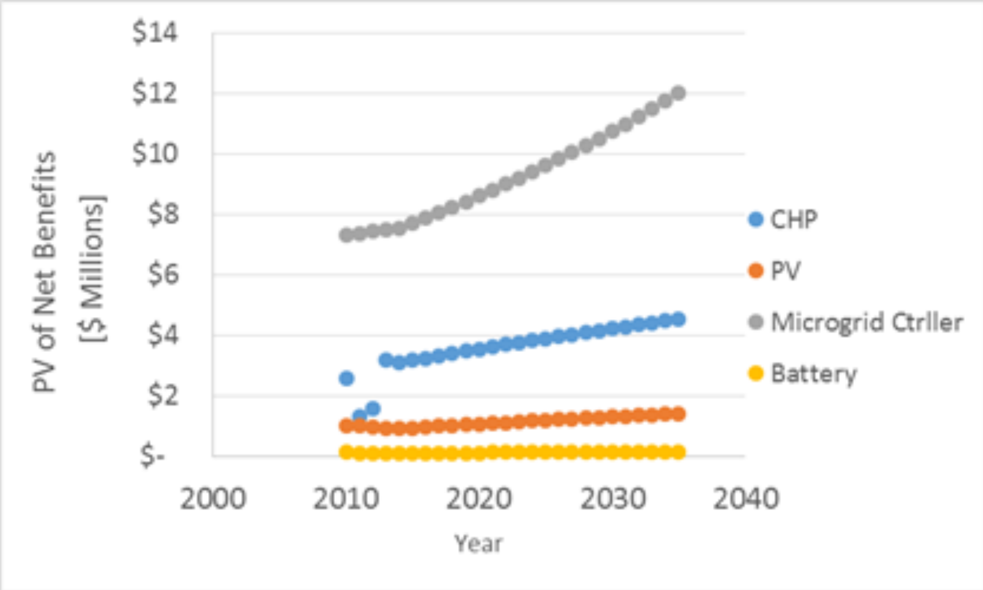

Figure 5.12. Annual present value of net benefits over project life

Figure 5.13 shows how the benefits are distributed among the different benefit categories. As noted previously, the CHP plant results in negative benefits for the category "reduced CO_2 emissions" because the CHP plant results in a CO_2 emission increase despite having been originally planned to reduce CO_2 emissions. It is likely that the plant did reduce CO_2 emissions prior to 2010, but the California electricity system has reduced its carbon emissions significantly since then, so additional planned CO_2 emission reductions have not actually occurred, resulting in a negative benefit, i.e., a cost. In fact, the increase in carbon emissions resulting from the CHP plant are large enough that the installation of 4 MW of PV is not enough to fully offset the increase. In our sensitivity analysis, we investigate a higher emission factor for the California electricity system to examine the benefit that might result if the CHP plant would offset only marginal generators, which have higher emissions than the bulk system. Surprisingly, the CHP plant results in lower PM2.5 emissions than those of California's bulk electricity system. The PV installation resulted in benefits in many of the categories but did ultimately have the lowest B/C ratio of the different projects. The benefits of the MgC resulted only from reliability considerations, with nearly all of the benefits in the reduced sustained outages category and very small benefits in the reduced major outages category. The battery system resulted in benefits in the optimized generator operation category. The battery system allows the generator to operate at a slightly higher power output by minimizing imports from the electric utility. This resulted in an annual savings of USD140,000 and an ultimate B/C ratio of 6.8, which is higher than the B/C ratio of the CHP plant.

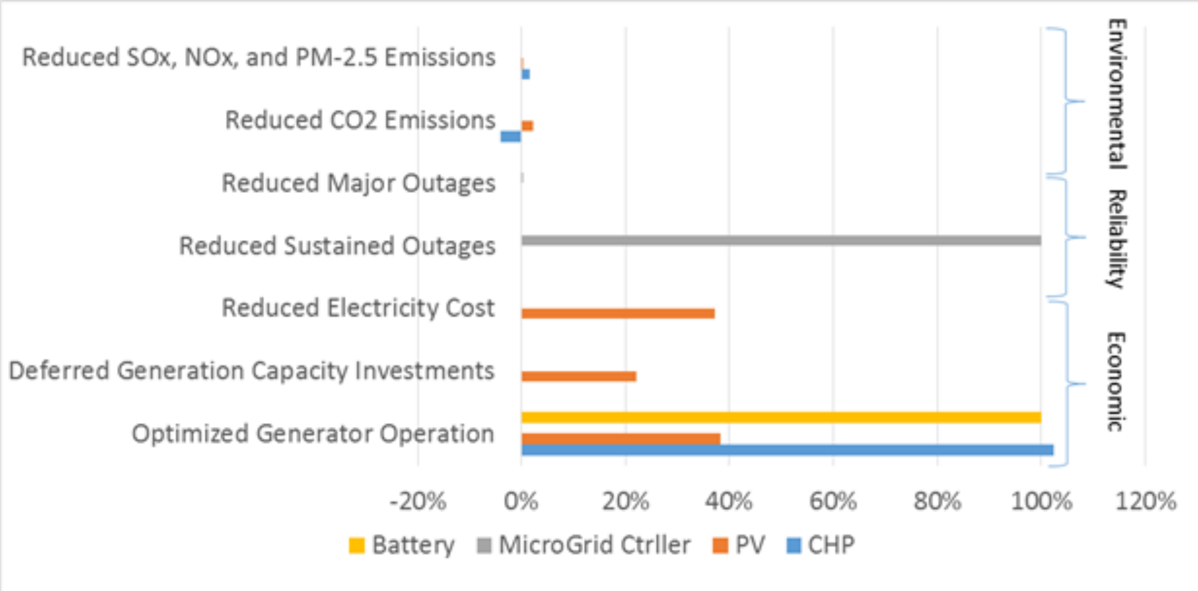

Figure 5.13. Distribution of benefits among categories

c. *Sensitivity Analysis*

This subsection examines the sensitivity of the CHP, MgC, and PV projects to several factors. For the CHP project, the following factors were varied:

- "No PM 2.5" assumes that the CHP plant results in no PM2.5 emission reduction.
- "Marginal" California grid carbon emissions assumes that the grid emission factor is 450 gCO_2/kWh instead of 350 gCO_2/kWh; see General Assumptions section for justification.
- "FlatNG" assumes a flat natural gas price.

For the MgC project, the capital cost was varied from USD1M to USD3M, and SAIDI was also varied to 0.583 and 0.99 hours/customer/year.

For the PV project, the discount rate was varied from 3% to 6%.

For the CHP project sensitivity studies, all of the impacts were in the economic category as was shown for the CHP plant in Figure 5.13. The impact of the PM2.5 reduction from the CHP plant was very small, as expected given that it was only a small benefit in the baseline study. The effect of the grid carbon emission factor selected was noticeable. The B/C ratio increased from 4.0 to 4.2 when the grid emissions offset by the CHP plant were assumed to be from marginal generators, i.e., those with higher emissions than the bulk grid. This offsetting of marginal generation likely does occur in part on a small scale; however, if CHP plants were deployed at a wider scale then other, higher efficiency resources would also be offset. The effect of a lower, flat natural gas price (USD4.74/GJ) was significant, increasing the B/C ratio to 4.6.

Table 5.7
Sensitivity studies for UCI CHP plant project (in NPV)

	CHP	CHP No PM2.5	CHP Marginal	CHP Flat NG
NPV of cost	USD(30.6M)	USD(30.6M)	USD(30.6M)	USD(30.6M)
NPV of benefit	USD124M	USD122M	USD129M	USD140M
NPV of net benefit	USD93.1M	USD92.2M	USD97.9M	USD110M
B/C ratio	4.0	4.0	4.2	4.6

Table 5.8 shows the MgC project sensitivity study results. The impacts of these sensitivity studies were in the reliability category, as was shown in Figure 5.13. Increasing the capital cost to USD3 M had a limited impact on the annual net benefit (~1% reduction in net benefit); however, the effect on the B/C ratio was pronounced with a reduction greater than 50%. The SAIDI reductions of 0.583 and 0.99 (reductions of 50% and 15%, respectively) had large impacts on the annual benefits, 42% and 82%, respectively. This parameter can have a significant impact on the analysis of a given project and should be estimated carefully. This is a result of the "value of service" as defined by the SGCT as a default input. The "value of service" is defined as

"the true value of the electricity service to the specified customer without regard to the actual cost of providing the service. This input captures the value of service reliability quantified by the willingness of customers to pay for service reliability, taking into account the resources (e.g., income) of the residential customer or by a firm's expected net revenues associated with the added reliability."

UCI does not have estimates for the "value of service" and therefore relied on the default values in the SGCT, which are USD2.31/kWh for residential customers, USD295.70/kWh for commercial customers, and USD16.04/kWh for industrial customers. We were unable to find information on how these values were estimated. From these "value of service" numbers and the equation used to calculate the benefits of reduced sustained outages as shown below, it becomes clear that the high "value of service" for commercial customers resulted in very large benefits for UCI from improving reliability.

$$
\begin{aligned}
&Value(\$) \\
&= \sum \Bigg\{ \Bigg[SAIDI(System) \times Total\ Customers\ Served\ within\ a\ class(\quad) \\
&\times Average\ Hourly\ Load\ Not\ Served\ During\ Outage\ per\ Customer\ by\ class(kW) \\
&\times VOS\ by\ class \left(\frac{\$}{kWh}\right) \Bigg]_{Baseline} \\
&- \Bigg[SAIDI(System) \times Total\ Customers\ Served\ within\ a\ class(\quad) \\
&\times Average\ Hourly\ Load\ Not\ Served\ During\ Outage\ per\ Customer\ by\ class(kW) \\
&\times VOS\ by\ class \left(\frac{\$}{kWh}\right) \Bigg]_{Project} \Bigg\}
\end{aligned}
\tag{7}
$$

Table 5.8
Sensitivity studies for UCI MgC project (in NPV)

	MgC	MgC	MgC	MgC
NPV of cost	USD (1.14M)	USD (3.42M)	USD (1.14M)	USD (1.14M)
NPV of benefit	USD 242M	USD 242M	USD 141M	USD 42.4M
NPV of net benefit	USD 241M	USD 239M	USD 140M	USD 41.2M
B/C ratio	212	71	124	37

Table 5.9 shows the sensitivity of the net benefits to the discount rate. An increase in the discount rate from 3% to 6% significantly reduces the present value of the benefits and costs;

however, the discount rate reduces the benefits (31%) more than it does the costs (27%), which reduces the B/C ratio.

Table 5.9
Sensitivity studies of discount rates on the UCI PV project (in NPV)

	PV	PV 6% disc rate
NPV of cost	USD (13.7M)	USD (10M)
NPV of benefit	USD 43.2M	USD 29.8M
NPV of net benefit	USD 29.5M	USD 19.8M
B/C ratio	3.2	3.0

5.2.Benefit Analysis of TNY Project (using TNY Method)

Benefit analysis of TNY project focuses on evaluating the smart grid project cases where assets would be interconnected to SS93 in TNY's industrial zone and would be operated for two primary purposes: a) to shave peak externally supplied energy and demand during the most difficult electric supply conditions, and b) to participate as a generation asset in PJM energy markets to earn revenue. In addition, the MgC in combination with the on-site generation sources will meet the following key objectives:

- Improving resilience and system reliability for customers by supporting seamless islanding and reconnection in the event of external supply grid outages
- Reducing carbon emissions by maximizing utilization of renewable (solar and storage) assets
- Improving system efficiency across energy value chain in electric power generation, transmission, and delivery, together with financial efficiency and economic growth efficiency

This section analyzes the following prospective cases/scenarios for the planned Navy Yard microgrid.

1. *Microgrid Operation - Scenario I*: MgC with 6 MW Natural Gas Peaker Unit

   This scenario includes MgC integrated with a 6 MW internal combustion generator set (IC-genset). SS93 is at or near capacity at certain times of the year, so the 6 MW unit will delay the need to expand the substation and thus avoid significant capital expense. In addition, the asset will provide resiliency and financial benefits by participating in PJM markets.
2. *Microgrid Operation - Scenario II*: MgC with 2 MW PV and 2.5 MW Storage

   This scenario includes MgC with 2 MW of solar PV and 2.5 MW of battery storage. Daily solar PV output would coincide with typical peak load periods, and the solar - storage asset would provide multiple potential benefits including helping to delay the need to expand the substation; reducing peak loads; and participating in PJM markets, which would have financial benefits.
3. *Microgrid Operation - Scenario III*: MgC with 6 MW Natural Gas Peaker Unit, 2 MW PV, and 2.5 MW Storage

   MgC with 6 MW IC-genset with 2 MW solar PV and 2.5 MW battery storage would be interconnected to SS93 in TNY's industrial zone and would be operated to shave peak demand, participate in energy markets to earn revenue, and provide resilience to customers served by the substation.

(1) General Assumptions

Analysis of the TNY project relies on several important assumptions that are combined to reach the overall conclusions concerning the net benefit of the three prospective case/scenario alternatives. These assumptions are:

- Use of weights for weighed priority calculation: Weights are developed and used to determine the overall priority of outcomes based on various considerations at multiple steps. Detailed assumptions and approaches for the weights data are described in the Appendices.
- Use of heuristic values and algorithms in the analysis framework: *System Operation: Cost of Grid Interruption*, U.S. DOE's Interruption Cost Estimator (http://www.icecalculator.com/), was used to determine the benefit of improved reliability and resilience based on TNYEU's actual performance. Table 5.10 shows the specific values for cost per average kW and cost per unserved kWh.

Table 5.10
TNY Project interruption cost estimates

Sector	No. of Customers	Cost Per Event (2016USD)	Cost per Average kW (2016USD)	Cost per Unserved kWh (2016USD)	Total Cost of Sustained Interruptions (2016USD)
Medium and Large C&I*	18	USD7,230	USD80	USD197	USD14,316
Small C&I	132	USD918	USD185	USD456	USD13,327
Residential	1	USD3.8	USD3.2	USD8	USD0.4
All Customers	151	USD1,664	USD110	USD271	USD27,644

* C&I - commercial and industrial

- Environmental: System Carbon Footprint – Many factors impact the net environmental benefits of energy projects. The Distributed Energy Resource – Customer Adoption Model (DER-CAM) includes various algorithms to calculate cost or benefit for each case scenario. When evaluating net carbon emissions related to the operation of the 6 MW natural gas peaker unit, it was decided that the net output would vary only slightly if at all from grid-supplied power-related emissions. The reasoning is that because the 6 MW unit will be natural-gas fired and operate predominantly as a peak shaver, it will offset grid-supplied peak power that is also produced using natural gas. At non-peak periods, the 6 MW unit would be largely offsetting a combination of base-loaded coal (37%) and nuclear (36%) generation. Moreover, the 6 MW unit will be producing power on site, which eliminates all grid-related T&D losses. In totality, it was assumed that the on-site 6 MW unit will emit marginally (approximately 5% to 7%) more carbon than equivalent electricity purchase.
- Sustainability: Tenant Impact and Sustainability – TNY tenants and stakeholders place varying degrees of emphasis on sustainability. Recognizing that this is an essentially qualitative factor for the client base, it is challenging to derive a financial value. PIDC has decided to value it at USD250,000 NPV to indicate that it is a significant factor, which PIDC believes is representative of the degree of this factor's importance.
- Innovation and Economic Growth: Private Investment Value – Being able to attract private investment is an important non-financial consideration. The degree of private investment at TNY bears on the scale of investment that will continue to occur. Although

an important qualitative consideration, private investment value is estimated by PIDC as USD50,000 NPV for each project that can be financed privately versus with public funds.

- Innovation and Economic Growth: Grant Research Opportunity Value – Similar to the issues related to private investment but even more important to the overall Navy Yard project is to deploy research projects that earn some form of grant funding. This consideration is important for two reasons: first, a project that earns this form of investment in most instances "competes" in the open marketplace for the funding; thus, when earned, these funds roughly equate to the societal importance of the project. Second, grant funding is usually an effective means of avoiding the need for public subsidy that would likely be otherwise required. For these two reasons, PIDC estimates that the NPV of grant research projects supporting innovation areas is USD25,000, USD75,000, and USD200,000 in scenarios 1 through 3, respectively.
- Innovation and Economic Growth: Real Estate Efficient Use Value – TNY includes 1,200 acres, and efficient land use is part of monetizing the value of any given project scenario. PIDC has assigned USD25,000 NPV to this consideration.
- Use of existing TNY load profiles and usage data: Electrical Hourly Load profiles – These are compiled from meter data for SS93. Three profiles are created: (a) weekday, (b) weekend, and (c) peak. Detailed profiles and shapes are described in the Appendices. Key assumptions related to the profiles are:
    - The "weekday" profiles reflect increasing demand as the workday begins, a flat trend during the workday, and a typical drop-off as the workday ends.
    - The "weekend" load profiles show mostly flat demand trends that are likely the result of limited commercial activity but steady industrial load to support 24 x 7 operations.
    - The "peak" profiles show less clear or consistent trends, reflecting a combination of periodically high industrial loads and an overall tendency for peak demand to coincide with workday hours.
- Other data such as tariff, price, asset operation performance, model data, etc. for TNY: A number of other data assumptions have been made for this analysis:
    - Utility tariff and fuel price
    - Electricity tariff
    - Natural gas price
    - PJM market prices
    - DER data
    - natural gas fueled IC-genset and performance
    - PV
    - Storage

The values of these data line items are described in the Appendices.

(2) Benefit Analysis

a. Comparison Summary of Scenario Benefit Analysis Results

Table 5.11 summarizes the comparison of results from the three TNY scenarios.

Table 5.11
Summary of TNY scenario results

	Scenario 1	Scenario 2	Scenario 3
Total system cost	USD2.41M	USD2.03M	USD3.18M
Financial/economic	USD3.32M	USD2.21M	USD5.54M
Operation/reliability	USD0.36M	USD0.33M	USD0.69M
Environmental benefit	USD(0.15M)	USD0.96M	USD0.29M
Innovation&growth	USD0.08M	USD0.13M	USD0.30M
Weighted B/C	2.79	4.05	3.87
Non-weighted B/C	1.50	1.79	2.14

Note: Table 5.11 also includes a non-weighted B/C ratio, which has different relative profiles across the three scenarios than the profiles for the weighted B/C ratio.

A number of summary observations result from analyzing the results of the three scenarios:

- The highest payback-to-cost ratio for weighted B/C is achieved under scenario 2 whereas the highest payback-to-cost ratio for non-weighted B/C is achieved under scenario 3.
- One of the key components that results in scenario 2 being the highest-payback scenario is realization of significant environmental benefits when weighted computation is applied.
- Even though scenario 1 has the cheapest system cost/MW and a higher financial/economic benefit/MW, it lags in the overall B/C ratio because of much lower environmental benefit than in other scenarios.
- Significantly higher financial/economic benefit in terms of absolute numbers will be achieved by deploying all three on-site assets.
- Considerable "economies of scale" are achieved by deploying the three on-site assets versus considering the B/C analyses for scenario 1 or scenario 2. Thus, decision makers may choose scenario 3 over scenario 2 depending on preference for "economies of scale" versus absolute B/C index.
- The net B/Cs (non-weighted B/Cs) rank differently than the weighted B/C equivalents illustrating the importance of considering each stakeholder's priority when developing the value proposition for a community microgrid.

b. Comparison of Scenario Benefit Analysis by Each CBAC

Table 5.12 summarizes a comparison by assessment category across the three TNY scenarios.

Table 5.12
Summary of scenario by each assessment category in TNY Project

	Scenario 1	Scenario 2	Scenario 3
Financial / economic benefit	2.32	1.86	2.63
Operation / reliability benefit	0.50	0.60	0.65
Environmental benefit	(0.14)	1.38	0.32
Innovation & growth benefit	0.10	0.21	0.27
Weighted B/C	2.79	4.05	3.87

Note: Table 5.12 provides components of the overall scenario B/C ratio by decomposition into each of the CBA categories' B/C ratio for purposes of the analysis.

A number of summary comments emerge when we analyze the results of the three scenarios by each CBAC:

- The highest payback-to-cost ratio (CBAC weighted B/C – 2.63) is achieved under scenario 3 for the financial / economic benefit category. This result is also supported by the fact that this scenario also provides the best in "economy of sale."
- When we exclude the financial / economic benefit category, the second-highest payback-to-cost ratio (CBAC weighted B/C – 1.38) is achieved under scenario 2 for the environmental benefit category. This is due to emissions reduction through integration of solar and storage and good revenue potential through PJM ancillary service market value streams.
- Even though scenario 3 is a clear addition of scenario 1 and scenario 2, benefits in absolute numbers as well as B/C by any CBAC are not simply additive computations.

c. *Specific Analysis and Comments for Scenario 1*

In addition to the DER-CAM analysis to determine the benefits and costs of each case, PIDC completed a project finance comparison for the 6 MW peak generator case that is integral to the overall financial analysis of this scenario. Specifically, two critical factors, in addition to the DER-CAM computations, are included in the PIDC project finance analysis:

1. An estimate of the revenue that the 6 MW peak generator will earn in the open PJM marketplace for various ancillary services, over and above the avoided costs as determined by the DER-CAM model
2. The comparative financial returns from the 6 MW peak generator versus the business-as-usual alternative of installing traditional PECO capacity at the TNYEU substation

PIDC's project finance analysis compares the 6 MW peak generator at a capital cost of USD11,000,000 to the estimated USD8,000,000 cost of providing a similar 6 MW of new capacity from PECO. On face value, the cost of the PECO option (i.e., additional feeder capacity) saves USD3,000,000. However, by factoring in PJM revenues from opportunistic market participation combined with the value of avoided peak electric costs, the analysis supports opting for the 6 MW peak generator project. This comparison includes the total costs that PIDC would incur for operating the 6 MW peak generator along with the capital amortization costs of the project. Based on comparing the costs and benefits of operating the 6 MW peak generator over a 20-year period versus the traditional PECO-supplied capacity alternative, the PIDC project finance analysis concludes that the NPV for the 6 MW peak generator is USD365,003 compared to negative USD8,000,000 for added PECO capacity. Another benefit provided by the 6 MW peak generator is a hedge against rising and sometimes volatile electric costs. On-site generation also offers energy resilience in support of critical Navy Yard operations and to tenants who and are willing to pay a premium for resilience.

d. *Specific Analysis and Comments for Scenario 2*

An off-line pre-analysis was performed to assess the potential of solar and storage for PJM ancillary services markets, including the regulation market, synchronized reserve and non-synchronized reserve markets, and the day-ahead scheduling reserve market.

- PJM's regulation market is a single real-time market. Regulation is provided by generation and demand-response resources that qualify to follow a regulation A or D signal. Regulation D - Dynamic was developed specifically for energy storage devices with limited storage capabilities.
- Synchronized reserve is energy or demand reduction synchronized to the grid and capable of increasing output or decreasing load within 10 minutes. Synchronized reserve is of two distinct types, tier 1 and 2.

- Non-synchronized reserve comprises non-emergency energy resources not currently synchronized to the grid that can provide energy within 10 minutes.
- Day-ahead scheduling reserve is provided by generation and demand response resources within 30 minutes.

Table 5.13 compares prices for each PJM ancillary service market.

Table 5.13
TNY project benefit-cost correspondence by assessment category

PJM	Regulation Market	Synchronized Reserve	Non-Synchronized Reserve	Day-Ahead Scheduling Reserve
Historical weighted average prices (year to date) per MW	USD37.1	USD5	USD1.5	USD1
% of PJM West Hub real-time prices	95%	12%	4%	2%

Energy storage participation in regulation markets will help maximize TNY's profits. Minimal benefits will be realized from participation in the synchronized reserve, non-synchronized reserve, and day-ahead scheduling reserve markets. The optimization problem for scenario 2 included consideration of solar-storage asset participation in the PJM regulation market only. The annualized revenue from the PJM regulation market was approximately USD500,000 with the 2.5 MW storage asset as planned in the scenario 2.

e. *Specific Analysis and Comments for Scenario 3*

The optimization problem for scenario 3 was analyzed both in a commercial/contractual framework and a smart grid operation framework. Some of the key analytical observations were:

- Commercial optimization included multi-aggregator operation with TNYEU because each of the DER – the 6 MW generator unit, 2 MW solar PV unit, and 2.5 MW storage unit – can be owned and/or operated by different private investors with their own affiliated arm or aggregator in the PJM market.
- Smart distribution grid operation managed by TNYEU would need to be the central coordination entity across multi-aggregator operation to ensure that local grid reliability and contractual constraints are met.
- In addition to private investors, Navy Yard tenants (Tenant A Stakeholder) could be part of a commercial/contractual framework. For example, Tenant A may want to enter into a premium service agreement to own part of the 6 MW natural gas generator asset; in return, in addition to asset equity benefits, Tenant A may enter contract with TNYEU to guarantee a designated amount of service and response time from the asset in case of emergency outages resulting in islanded microgrid operation.

To keep the formulation and analysis simple, we limited scenario 3's scope to a single contract framework for integrated DER operation. Considerable "economies of scale" are achieved by deploying the three on-site assets versus considering the B/C analyses for scenario 1 or scenario 2. Hence, decision makers may choose scenario 3 over scenario 2 depending on the preference for "economies of scale" versus an absolute B/C index

f. *Detailed Comparison among Scenarios 1 through 3*

The following analysis compares the benefits from the three scenarios being tested, as shown in Table 5.14 and Table 5.15.

Table 5.14
Detailed comparison of TNY project benefit scenarios

CBAC	CBAV	Scenario 1	Scenario 2	Scenario 3
Cost benefit Category	Benefit assessment Variable	Benefit	Benefit	Benefit
Financial/Economic	Annual electricity usage cost	USD0.78M	USD0.47M	USD1.24M
	Annual electricity demand cost	USD1.20M	USD0.41M	USD1.59M
	Annual avoided CAPEX cost	USD1.10M	USD0.83M	USD1.93M
	Annual revenue from DER	USD0.24M	USD0.50M	USD0.78M
	Financial/economic subtotals	USD3.32M	USD2.21M	USD5.54M
Operational reliability & efficiency	System reliability cost impact	USD0.28M	USD0.30M	USD0.36M
	System efficiency cost gain	USD0.07M	USD0.03M	USD0.34M
	Financial /econ & operational Subtotals	USD0.35M	USD0.33M	USD0.69M
Environmental & economic growth	System carbon footprint	USD(0.15M)	USD0.71M	USD0.04M
	Tenant impact & sustainability		USD0.25M	USD0.25M
	Financial/econ operational subtotals	USD(0.15M)	USD0.96M	USD0.29M
Innovation & economic growth	Private investment	USD0.05M	USD0.05M	USD0.10M
	Grant/research opportunity value	USD0.03M	USD0.08M	USD0.20M
	Non-economic totals	USD0.08M	USD0.13M	USD0.30M
Cost Benefit Category	Cost Assessment Variable	Cost	Cost	Cost
Financial/ economic	Annual CAPEX cost	USD0.42M	USD0.59M	USD1.01M
	Annual OPEX cost	USD1.26M	USD1.26M	USD1.26M
	Annual OPEX – on-site DER	USD0.09M	USD0.01M	USD0.1M
	Annual OPEX - fuel costs	USD0.52M		USD0.52M
	Financial risk	USD0.10M	USD0.14M	USD0.28M
Innovation & economic growth	Real estate efficient use value	USD0.03M	USD0.03M	USD0.03M
	Total	USD2.41M	USD2.02M	USD3.18M
	Scenario B/C Ratio	2.79	4.05	3.87

Table 5.15
Detailed Comparison of Weighted Benefit Scenarios in TNY Project

CBAC	CBAV	Scenario 1	Scenario 2	Scenario 3
Category	Variable	Weighted Benefit	Weighted Benefit	Weighted Benefit
Financial/economic	Annual electricity Usage cost	USD1.53M	USD0.92M	USD2.44M
	Annual electricity demand cost		USD1.20M	USD4.67M
	Annual avoided CAPEX cost	USD3.06M	USD2.30M	USD3.53M
	Annual revenue from DER	USD0.55M	USD1.14M	USD1.80M
	Financial/economic subtotals	USD8.67M	USD5.56M	USD1,428M
Operational reliability & efficiency	System reliability cost impact	USD1.54M	USD1.65M	USD1.98M
	System efficiency cost gain	USD0.33M	USD0.14M	USD1.52M
	Financial /econ & operational subtotals	USD1.87M	USD1.79M	USD3.50M
Environmental & economic growth	System carbon footprint	USD(0.51)M	USD2.51M	USD0.13M
	Tenant impact &		USD1.61M	USD1.61M

	sustainability Financial/econ operational Subtotals	USD(0.51)M	USD4.12M	USD1.74M
Innovation & Economic Growth	Private investment	USD0.27M	USD0.27M	USD0.54M
	Grant/research opportunity value (USD)	USD0.11M	USD0.34M	USD0.92M
	Non-economic totals	USD0.38M	USD0.61M	USD1.46M
Cost Benefit Category	Cost Assessment Variable	Weighted Cost	Weighted Cost	Weighted Cost
Financial/ economic	Annual CAPEX Cost	USD0.98M	USD1.40M	USD2.39M
	Annual OPEX Cost	USD134M	USD1.34M	USD1.34M
	Annual OPEX – on-site DER	USD0.21M	USD0.01M	USD0.22M
	Annual OPEX - fuel costs	USD1.04M		USD1.03M
	Financial risk	USD0.15M	USD0.21M	USD0.41M
Innovation & economic growth	Real estate efficient use value	USD0.01M	USD0.01M	USD0.01M
	Total	USD3.73M	USD2.97M	USD5.40M
	Scenario B/C ratio	2.79	4.05	3.87

Some key analytical observations are:

- Financial/economic benefits as well as system operational reliability and efficiency benefits were fairly additive as evident from comparing scenario 3 to scenarios 1 and 2.
- Environmental benefits are considerably for scenario 3 compared to scenario 2, and are actually negative for scenario 1. This is because the optimization formulation drives much broader use of the 6 MW natural gas unit, which reduces the environmental benefits.
- Innovation and economic growth benefits are much greater for scenario 3, which includes all of the DER.

6. Benefit Analysis of Smart Grid Projects in Europe

Among the different BA approaches used in Europe and described in Chapter 2, CBA seems to be the most commonly used, thanks in part to EU legal requirements for the development of smart grids and energy markets. Directive 2009/72/EC (European Directive on Electricity Market, 2009) provided for "an economic assessment of all the long-term costs and benefits to the market and the individual consumer" and addressed implementation of metering systems in the EU. This has been further detailed in the guidelines for trans-European energy infrastructure that explicitly refer to the CBA method.

Several versions of BA have been applied to different contexts and projects. For the Malagrotta project analyzed in this white paper as well as other projects in different EU countries and contexts, JRC has applied its own BA method. The projects studied include national-level pilot projects (e.g., Evora in Portugal) (European Commission, JRC 2012a) and multinational projects (e.g., Projects of Common Interest in the field of smart grids, Benchmarking report on Smart Metering in EU [European Commission, JRC, 2013, 2016, 2014a b, c,]).

Since the publication of the JRC's method (European Commission, JRC 2012a), it has been thoroughly tested on actual smart grid projects and refined with the aim of allowing comparisons across projects realized within different contexts (i.e., in different EU countries under their regulatory frameworks). For this reason, the JRC method seems the most appropriate equivalent of the EPRI/U.S. DOE method applied in the U.S., which been used to compare different smart grid projects financed by ARRA. There has also been bilateral cooperation with U.S. DOE to illustrate the two methods together (European Commission, JRC 2012).

The JRC method entails more than a CBA; the method might be defined as an assessment framework in which CBA is the core (Step B, as explained below) of the evaluation, complemented by additional techniques that add important information that can capture the complex reality of a smart grid project. CBA is very effective in capturing the monetary value of a project, but JRC also developed KPIs to capture quantitative, non-monetary impacts. Each JRC project assessment includes an analysis of qualitative impacts (see Figure 6.1).

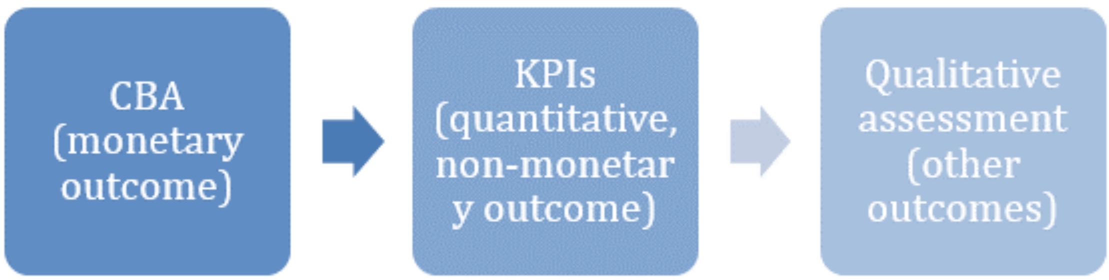

Figure 6.1. JRC assessment framework

Distinguishing characteristics of the JRC method include:

- First, the method is conceived as a societal BA, so it takes into account all the potential costs and benefits accruing not only to the project promoters but also to other categories of stakeholders such as consumers, regulatory agencies/governments, the general public, and the environment.
- Second, the method follows a step-by-step logical flow to identify costs and benefits; this step-by-step process can be replicated for virtually any project.

- Finally, the method includes a sensitivity analysis of the results that examines selected uncertainties. Sensitivity analysis is crucial in smart grid projects, which are mostly infrastructure, capital-intensive projects in which costs are typically incurred in the very first years of investment but benefits are gained over the long run. Sudden changes in the context in which the project is realized or an uncertain estimation of some parameters (e.g. changes in fuel prices, status of the general economy, uncertainty related to consumers' responsiveness) can therefore strongly affect the project's financial profile.

6.1.JRC Benefits Analysis Method

The JRC method is built around three central activities, which are performed in successive order: A) define the boundary conditions, B) identify costs and benefits, and C) calculate the NPV for the project and perform a sensitivity analysis. When used as a pre-investment analysis or when assessing the scale-up of pilot-tested solutions, this arrangement allows project promoters and other relevant stakeholders to go back to the first step if the results are negative and adjust key variables to determine what is needed to make the project successful (e.g., delaying investment in specific assets, adding/remove some technical features that enable some additional functionalities or removing those that do not add substantial benefits).

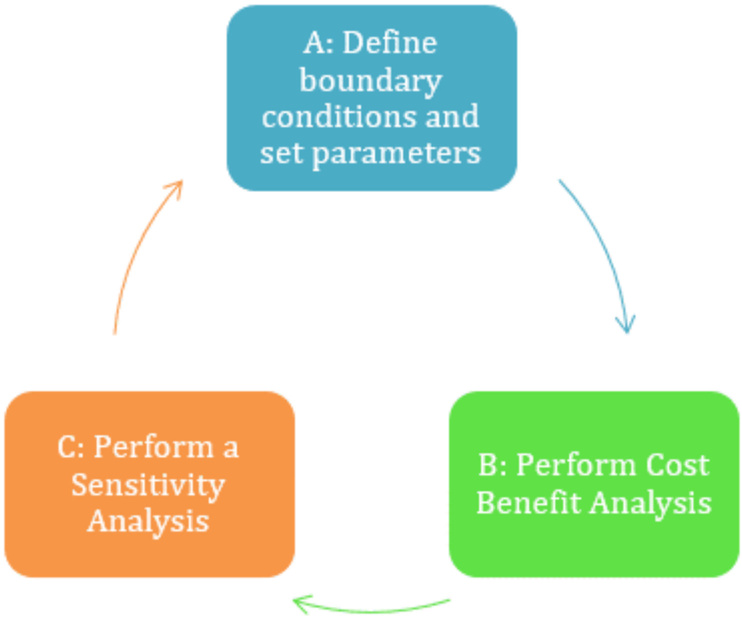

Figure 6.2. JRC method: beyond CBA

A. Define the boundary conditions – This step encompasses selecting the parameters that will define both the context in which the project is realized and the characteristics of the project itself (e.g., roll-out time, functionalities, type of technical solutions that will be installed, etc.).
B. Perform CBA: This step identifies costs and benefits and calculates the NPV, including discounting appropriately over time.
C. Perform a sensitivity analysis – This step tests the robustness of the analysis outcome.

Although the definition of the appropriate parameters and testing of their impact on the final project through sensitivity analysis are one-step activities, the Step B (the CBA element of the analysis) is a composite process made up of several sub-steps as shown in Figure 6.3.

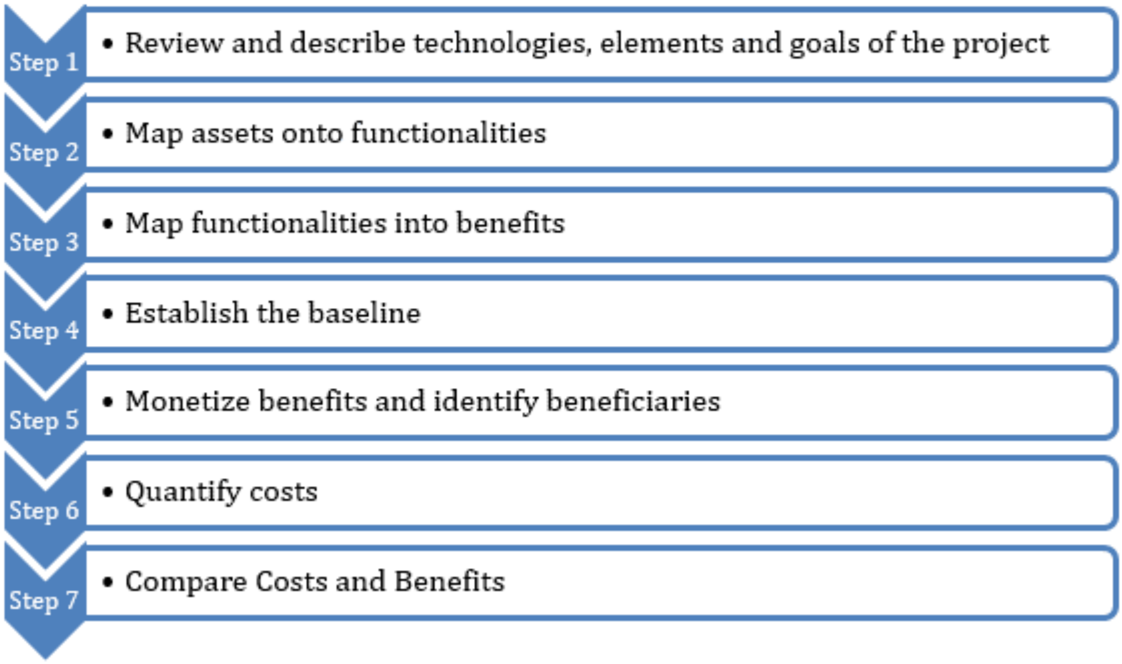

Figure 6.3. The sub-steps of the JRC Step B (the CBA element)

Although the general context in which the project is realized is defined under the aforementioned “boundary conditions," Step A in the method consists of also defining the characteristics of the project itself, including the technologies to be used, the timeline of the investment, the project goals, the stakeholders involved, the local characteristics of the grid, and the regulatory provisions applicable to the project.

Once the project's features have been clearly identified, Step B is the core of the method, the quantification of benefits through the mapping of assets into functionalities. For each asset, composed of each of the technical solutions implemented, we identify one or more functionalities that are enabled by the asset itself, e.g., installing a smart meter enables the functionality of remote meter reading. JRC, within its work supporting the European Commission's Smart Grid Task Force, identified 33 different functionalities that might be enabled by a smart grid asset. The process of executing Step B of the JRC method constitutes the main difference between this method and the EPRI/U.S. DOE methodology. Where the JRC method identifies very specific assets (smart meter, meter data management module, etc.), the EPRI/U.S. DOE approach uses generic assets (e.g., AMI).

As shown in Figure 6.3, there are seven intertwined sub-steps within Step B of the JRC method. Once the functionalities of the project have been identified (sub-step 2), they are mapped to benefits (sub-step 3); that is, for each functionality, one or more benefits is identified. The list of benefits is derived from the EPRI/U.S. DOE method and adopts the EPRI/U.S. DOE categorization of benefits as economic, reliability, environmental, or security. Using the example from above, several benefits might stem from the functionality of remote meter reading, including reduced manual metering costs or a decrease in expenses for litigation over electricity bills (VaasaETT, 2013).

FUNCTIONALITES

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)		•	•	•	•	•	•	•		•	•	•		•	•				•														

FUNCTIONALITES

BENEFITS	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
Optimized Generator Operation																	•																
Deferred Generation Capacity Investments																									•					•			
Reduced Ancillary Service Cost			•			•				•																							
Reduced Congestion Cost																																	
Deferred Transmission Capacity Investments																									•								
Deferred Distribution Capacity Investments						•	•	•								•		•	•		•				•					•			
Reduced Equipment Failures						•	•	•										•	•														
Reduced Distrib. Equipment Mainten. Cost								•										•											•				
Reduced Distribution Operations Cost					•			•																					•				
Reduced Meter Reading Cost																												•	•				
Reduced Electricity Theft									•						•									•				•					
Reduced Electricity Losses			•			•	•	•	•	•		•	•				•		•	•	•			•						•			
Detection of anomalies on Contracted Power							•																										
Reduced Electriciy Cost								•				•										•			•			•	•				
Reduced Sustained Outages			•	•	•			•					•				•			•													
Reduced Major Outages					•									•																			
Reduced Restoration Cost					•	•	•																						•				
Reduced Momentary Outages					•	•	•																						•				
Reduced Sags and Swells						•	•																										
Reduced CO2 Emissions	•	•				•	•	•	•	•		•					•		•			•	•		•			•	•	•	•	•	
Reduced SOx, NOx, and PM- 10 Emissions	•	•				•	•	•	•	•		•					•		•			•	•		•			•	•	•	•	•	
Reduced Oil Usage	•	•				•	•																•					•	•				
Reduced Wide-scale Blackouts																																	

Figure 6.4. JRC method mapping of assets to functionalities and functionalities to benefits

The next sub-step (4) within Step B is establishing a baseline for comparison when monetizing the project benefits. To calculate any impact of a project, including a monetary one, it is crucial to define the "size" of the impact arising from the project. This cannot be done without defining the baseline against which the project’s impacts are measured. Smart grid projects are usually implemented within an existing electricity grid that likely needs maintenance and reinforcement. The key factor in establishing a consistent baseline is therefore distinguishing between maintenance interventions that would have been undertaken anyway and the interventions that are undertaken only in order to realize the smart grid project. This phase of the evaluation process is also included in the EPRI/U.S. DOE method where a "baseline scenario" and a "smart grid scenario" are defined. A baseline must be established for each of the project impacts that are to be monetized in the CBA in Step B.

Monetization of benefits is sub-step 5 of the CBA portion (Step B) of the JRC method. For each benefit identified in previous steps, and only for the part of it that accrues to the smart grid project (compared to the baseline) a monetary value is calculated. Continuing with the smart metering example, monetization would count the number of manual meter reading activities that would be replaced by remote meter reading and multiply that by the number of employee hours spent and the cost of the personnel involved. Other important features of monetization are careful identification of all beneficiaries and introduction of some form of uncertainty (e.g., assigning a probability to the monetization of benefits).

Once the evaluation of total benefits has been completed, it is possible to quantify the costs of realizing the smart grid project (sub-step 6). The basis for identifying the costs is the same baseline defined under Step B, sub-step 4. As JRC's method is designed to allow comparison of projects implemented within different contexts, taxes should not be incorporated, but depreciation and amortization should be considered because they represent the investor's cost of replacing assets.

Once both costs and benefits have been thoroughly quantified, the last sub-step (7) appropriately discounts and compares them, which results in calculation of the project's NPV and IRR. JRC also recommends using the B/C ratio.

These economic indicators are then scrutinized through the sensitivity analysis that constitutes Step C of the JRC method. The final result of the JRC and EPRI/U.S. DOE methods is likely to be different because what is defined as an asset in EPRI/U.S. DOE's method is treated as a group of assets in JRC's method.

6.2. Project Description

ACEA, the third distribution system operator in Italy, wanted to pilot-test some smart grid solutions and possibly replicate them over its whole distribution grid, which serves the city of Rome (ACEA, 2013).

ACEA undertook this project with the goals of:

1. Achieving real-time control of the distribution grid
2. Improving the quality of power supply (reliability) in terms of duration and number of interruptions
3. Improving the energy efficiency of the grid itself by minimizing technical losses

The project was realized between 2011 and 2014 in the Malagrotta area west of Rome. It entailed installation of new technical solutions on six medium-voltage underground and aerial lines (approximately 69.5 km and a range of 20 kV). The project area has several characteristics that will be typical future smart grid challenges: in addition to managing different voltage levels (from two primary substations to 76 secondary substations), there are four DG plants line (one PV and three biomass accounting for about 20 MW of installed capacity) directly connected to the medium-voltage lines as well as seven users directly connected to the medium-voltage grid, accounting for about 3.5 MW of EVs and storage solutions. These latter resources are meant to be used for several purposes: backup during short-term interruptions as well as peak shaving and compensation for fluctuations caused by injection of generation of PV. All the solutions tested were planned to be rolled out over all of Rome's electricity network starting in 2015. The project is made up of three main components, that are additive to one other:

1. Medium-voltage grid automation: This component focuses on enabling the automatic selection of fault line segments and allows management of remote distributed generators on the basis of actual grid conditions (e.g., avoiding reserve flows).
2. At both medium and low voltage, 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 of technical characteristics of the grid at both medium and low voltage.
3. At the central level, development and application of a new grid management algorithm will allow ACEA to manage load flow, optimize load profiles, and minimize technical losses.

One key aspect of the Malagrotta project is the speed of the telecommunication infrastructure required to implement automatic fault selection. Two medium-voltage substations should be able to communicate within a 10 ms range; therefore, ACEA chose to test solutions such as optic fiber, cellular, and power line carrier (PLC) along a HyperLAN that was the first choice for the communication system.

The project was formulated under the National Regulatory Authority (AEEGSI – Autorita per l'energia elettrica, il gas e i servizi idrici) 2010 favorable incentive for smart grid pilot projects testing innovative solutions at the MV level. The Italian regulatory framework for distribution system operators has three incentive components: an output regulation, monetary rewards, and penalties for performance. The rewards and penalties are based on reliability (i.e., SAIDI and SAIFI), and the distribution system operator can recover its usual OPEX through the CPI-X regulatory mechanism. For investments (CAPEX), operators obtain via the network tariff a pre-determined rate of return (RoR) that corresponds to an extra-weighted average cost of capital (WACC) and that, for smart grid projects, is set at an additional 2% on top of the usual RoR, defined by AEEGSI for each regulatory period and for any infrastructural investment.

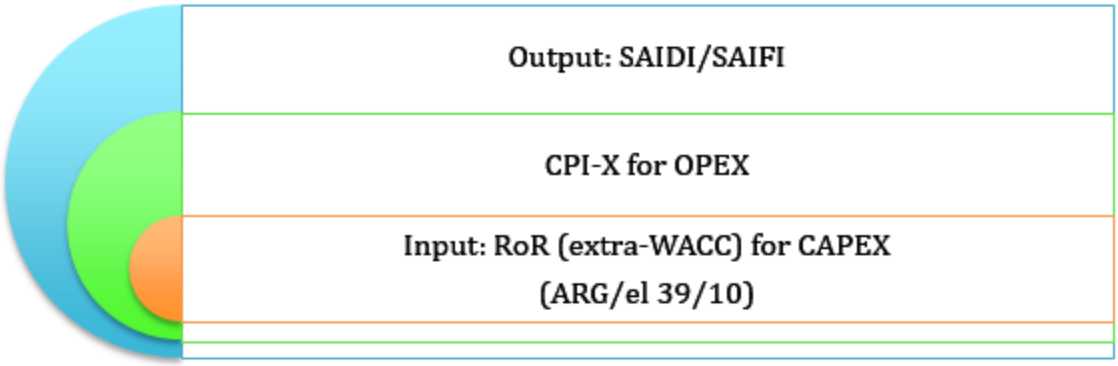

Figure 6.5. Components of the Italian regulatory framework for distribution system operators investing in smart grid solutions across their networks

6.3.Benefit Analysis of Malagrotta Smart Grid Project

Because JRC is a scientific advisor to policy makers within the European Commission, JRC's smart grid BA method has been used to evaluate several smart grid programs at the national and EU-wide levels, as mentioned above. The aim of any BA method is to answer the question of whether is it worth it to invest in a given project. In addition to providing scientific advice to the EU, JRC carries out independent assessments of single projects across the EU, gathering valuable feedback on the method and on key variables that affect a smart grid project's outcome in terms of NPV (European Commission, JRC, 2015). The methodology can also be used also for ex-post assessments of existing pilot projects, e.g., to compare the profitability of different solutions and identify the success factors for specific projects.

The ACEA project is one of the projects selected by JRC to test its method because of the project's combination of characteristics, regulatory environment, and scale-up options. The Malagrotta project represents a typical smart grid project for two main reasons:

- The pilot is within a metropolitan area, and the solutions tested will be replicated within ACEA's grid, which serves the whole city of Rome. In Europe, metropolitan areas account for about half of projects realized and budget spent (European Commission, JRC, 2014b), so the Malagrotta project is typical of the types of projects and challenges encountered.

- The pilot and its scale-up focus on network management solutions, providing a good example of technical solutions tested on many smart grid projects in the EU (European Commission, JRC, 2014b)

JRC Method Step A – Identify the goal of the project: The method starts by identifying the aims of the smart grid project. As described above, the Malagrotta pilot project targets quality of electricity supply (reliability) and energy efficiency across the grid portion included in the pilot study. New technical solutions were installed at each of the 76 secondary substations involved in the project and on each of the six medium-voltage lines and also several low-voltage lines (with a range of 8.4 kV). In addition, a new central SCADA system was implemented, and new grid management criteria were developed to exploit the full potential of the smart grid solution hardware.

ACEA divided implementation of the project into three sub-projects: medium-voltage automation, low-voltage remote control and monitoring, and new grid management criteria. These are sub-additive; that is, in the ACEA technical staff's view, it did not make sense to install remote control and monitoring on the low-voltage grid if medium-voltage grid automation was not yet implemented. Similarly, the adoption of a new grid management system would meaningless if medium-voltage automation and low-voltage monitoring and control were not in place.

Step B (CBA) sub-steps 2 and 3 – Asset – functionality – benefit mapping: For a new project, the key steps of a CBA quantify benefits. These are usually difficult to attribute to the different stakeholders involved. The JRC method approaches this problem by building a list of assets to be installed/realized within the project and then identifying the multiple functionalities enabled by each asset.

Given the large number of lines and substations on which ACEA aimed to replicate the project, the distribution system operator used internal expertise to develop its own "priority indicators" that not only mapped assets to functionalities and then to benefits, but also identified (for each line involved) the contribution to the functionalities of installing the smart grid assets and the assets' relative benefit in terms of SAIDI/SAIFI for each line segment. These indicators were constructed 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 was repeated for each of the three sub-projects, resulting in a priority indicator for each line segment for each sub-project.

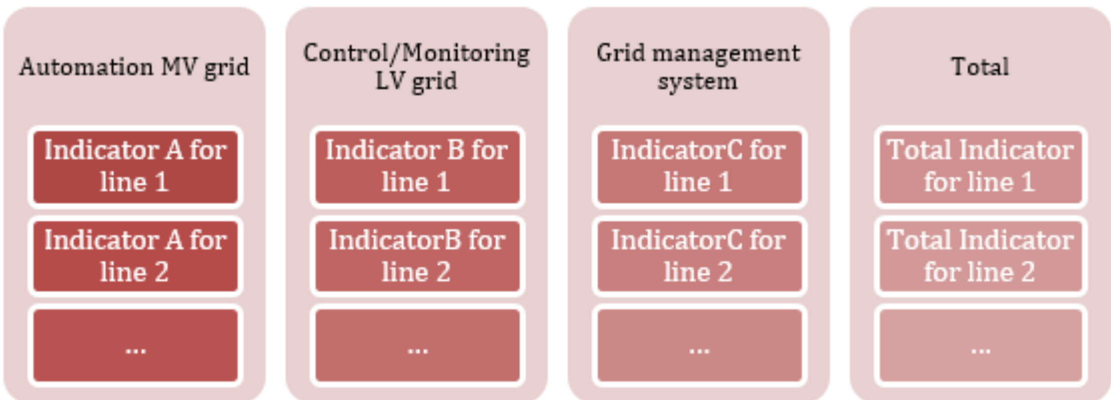

Figure 6.6. ACEA's per-line indicators of benefits stemming from implementation of the smart grid project

When evaluating the scale-up of the pilot to the entire Rome grid, ACEA replicated this exercise on every line of Rome's distribution network to determine the lines/grid sections that would contribute the most to the project's economic benefit and thus in what order the lines should be upgraded.

After the priority indicator is built, the monetization entails calculating the decrease in compensation that ACEA would owe consumers for electricity supply interruptions, the decrease in costs for manual interventions on the lines, and the avoided investment costs for reinforcing the grid and complying with reliability standards.

CBA sub-step 4 – Estimating the baseline: To quantify benefits, it is important to define the BAU condition to which the smart grid project contribution should be compared. In the Malagrotta case, the BAU case is the grid in its pre-project status, including planned regular maintenance.

CBA sub-step 5 – Monetize benefits: Benefits deriving only from the realized smart grid installation (vs. the BAU case) are transformed into monetary values using financial discount rate of 3%. JRC and ACEA performed the BA not only from the standpoint of the private investor (ACEA) but also from the standpoint of social benefit. In the case of social benefit (not treated here), the social discount rate considered is 2.5%.

Among the sources of benefits monetized, the main ones are the ROI of the smart grid project, as recognized by the National Regulatory Authority, and the avoided regulatory penalties imposed by the same authority for reliability issues. Another important source of benefits that can be monetized is avoided costs for maintenance and intervention required in response to grid faults.

CBA sub-step 6 – Financial model – costs: For each year considered in the BA, CAPEX and OPEX are calculated for each sub-project. This project exhibits the typical trend of any pilot project: CAPEX is concentrated in the very first years when infrastructure is installed.

Interestingly, when the same assessment is repeated for the scale-up of the smart grid solutions to the entire Rome network, CAPEX shows a slightly different pattern, with virtually no significant CAPEX expense for the new grid management criteria project (because the investment has been taken place at the pilot stage), and CAPEX on medium- and low-voltage automation and low-voltage remote control and monitoring increase up to the year 2020 when the roll-out across the whole grid is expected to be completed.

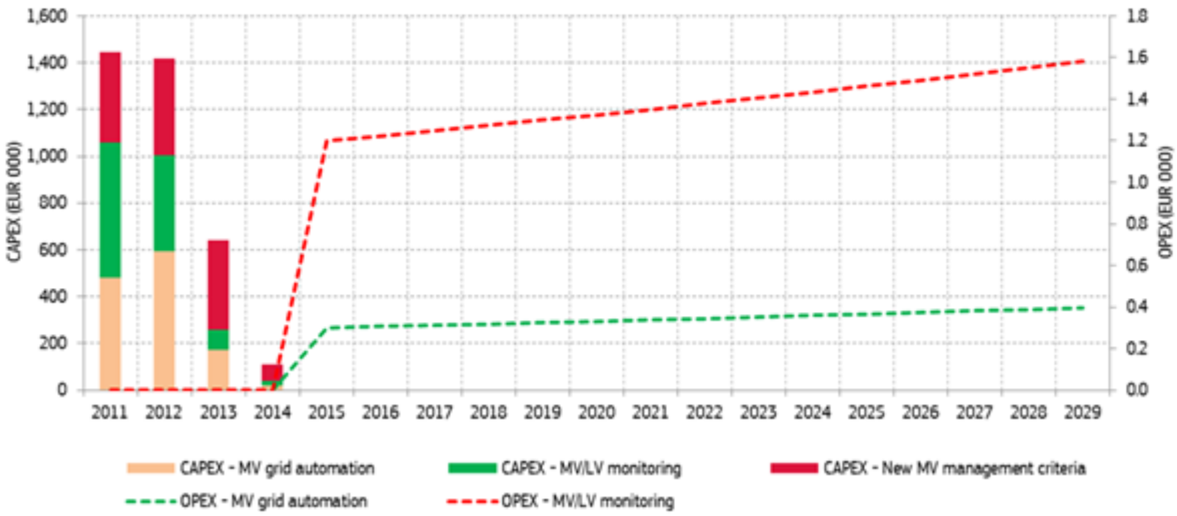

Figure 6.7. CAPEX and OPEX for Malagrotta project

CBA sub-step 7 – Financial model – benefits: Benefits for the Malagrotta pilot are also calculated. The sub-project "low-voltage remote control and monitoring" is the most important in monetary terms, as shown in Figure 6.8.

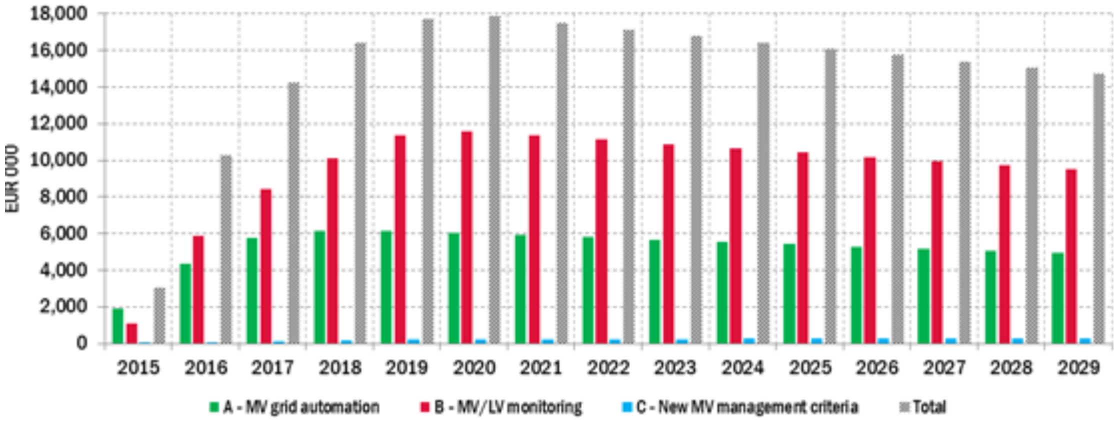

Figure 6.8. Benefits of Malagrotta project

Summing up, the results of applying JRC's BA method to the Malagrotta pilot project are extremely promising. Including cautious adjustments to the assessment, e.g., a yearly rate of decrease in benefits calculated, 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 IRR for Malagrotta of 1.23%. However, the IRR is 16.6% when the solutions tested in the pilot are scaled up to the whole Rome grid.

The most promising sub-project, in terms of contribution to total benefits, is clearly the low-voltage monitoring and remote control, as shown in Figure 6.9.

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

Figure 6.9. Results of JRC BA for Malagrotta pilot project and its scale-up to entire Rome grid

JRC's method as illustrated for the Malagrotta project demonstrates the ability to answer the question of whether this smart grid investment was justified. The same analysis method can be used to identify ways to maximize benefits to private investors and society.

7. Comparison of Benefit Analysis Methods

This white paper provides a comparative analysis of four Sino-U.S. methods, along with the JRC approach from Europe, for analyzing the benefits of smart grid projects. Our review of the methods reveals that even though they share common features, they differ in their goals, analysis procedures, and data requirements. All of the approaches discussed in this white paper have limitations. Table 7.1 summarizes the general characteristics of the methods. Livieratos et al. (2013) group benefits of smart grid demonstration projects into four basic categories: economic, reliability, environmental/social, and security/safety. Table 7.1 follows this same categorization with some additions specific to the approaches discussed here, such as the technical benefit in the SG-MCA method and the innovation benefit in TNY's method. In addition, what each benefit category encompasses may not be consistent from one method to another. For example, economic benefits listed in the EPRI/U.S. DOE method may not perfectly coincide with the economic benefits listed in the QPA method.

Table 7.1
Summary of benefits analysis methods

Benefit Analysis Method	SG-MCA (China)	QPA (China)	EPRI/U.S. DOE (U.S)	TNY (U.S.)	JRC (EU)
Approach	Multi-criteria Analysis	Single criteria	Single criteria	Single criteria	Single criteria
Decision criterion	Qualitative	Quantitative	Quantitative	Mixed	Mixed
Benefit types	Economic, Reliability, Environmental/ Social, Security, Technical, Practical	Economic, Reliability, Environmental/ Social	Economic, Reliability, Environmental/ Social, Security	Economic, Reliability, Environmental/Social, Innovation	Economic, Reliability, Environmental/ Social, Security
Evaluation	Weights/shares	Monetary values	Monetary values	Monetary values/shares	Monetary values/KPIs
Stakeholder involvement	Direct involvement	No involvement	No involvement	Indirect involvement	No involvement
Data requirement	Moderate	Intense	Intense	Intense tense	Intense
Project capital cost	Not included	Included	Included	Included	Included
Transparency	Not transparent	Not transparent	Transparent	Not transparent	Transparent
Application feasibility	Micro-scale	Micro-scale	Large-scale	Micro-scale	Large-scale
Results	Performance indicator	NPV, IRR, P_t	NPV	B/C ratio	NPV, B/C ratio, P_t

The QPA, EPRI/U.S. DOE, and JRC methods all start with identification and classification of the assets deployed in a smart grid project and then map the assets to the functions that generate benefits. All of the benefits and costs are expressed in monetary terms. After the benefits and costs are quantified, a social discount rate is applied to translate future monetary values to their present-day worth. These three methods differ in their level of detail, however. The EPRI/U.S. DOE method is intended to be generally applicable to highly diverse projects. It provides lists of assets, functions, and impacts, with clear definitions, and the user can pick those that apply to the project. The method then generates a benefits map. In contrast, the user defines the assets, functions, and benefits in the QPA and JRC methods; there is no pre-defined set or list. In this regard, the EPRI/U.S. DOE method offers a more generic approach.

The EPRI/U.S. DOE method is well documented but U.S.-oriented and offers minimal customization for particular projects, assets, functions, or benefits. Consequently, it is too generic to address the subtleties of a particular project or technology. Possible variations in the nature of smart grid projects are not well considered, and all projects are effectively evaluated using the the same set of criteria. In addition, analysis of widespread application is poor because all costs are assumed unchanged between small and large scales.

By contrast, the QPA and JRC methods are created for specific project arrangements. Both methods are flexible enough to be tailored to different projects and to larger scales; however, these tools are not intended to cover a wide range of projects, and there are no associated software models yet. The user needs to customize the model to specific project features, e.g., to generate mapping and establish benefits formulas. This may pose a challenge for users who are unfamiliar to the theoretical underpinnings of the calculations.

A critical drawbacks of all three methods discussed above is the need for large data sets that would require long trial periods before the analysis. In the absence of real data, input parameters must be estimated, which increases the uncertainty of results. None of the approaches has sophisticated methods for treating uncertainty; all rely on sensitivity analysis by the user.

The SG-MCA method differs from the other methods discussed in applying multi-criteria analysis and combining AHP and fuzzy logic approaches. This method starts with establishing a smart grid index system with technological, economic, social, and practical benefit categories. Indicators, weights, and indices used in the method are based on an expert consultation questionnaire designed for the particular smart grid project. A total score for the smart grid project, is the final output of the method, comparable to NPV from other methods. In contrast to other methods, the SG-MCA method requires fewer quantitative data. However, it depends solely on the subjective judgment of experts and stakeholders, which increases the uncertainty of the results. The SG-MCA method is more useful at a micro-scale where all stakeholders are easily accessible and able to express their opinions and priorities. It does not effectively represent public and private costs; it focuses on a technology's effectiveness in achieving the project's overall goal. This method barely evaluates the investment cost of smart grid projects. By contrast, the QPA and EPRI/U.S. DOE methods do not assess qualitative impacts, such as practical feasibility, as the SG-MCA method does. Qualitative impacts have the potential to be relevant to policies and strategies for achieving smart grid benefits. The JRC method uses KPIs to capture some qualitative impacts.

Like the other monetary methods, (QPA, EPRI/U.S. DOE, JRC) TNY's method converts benefits to monetary values. The main difference between TNY and the other methods is the involvement of stakeholders in TNY's calculation. TNY method assigns a percentage weight to each stakeholder in the decision-making processes to represent that stakeholder's preference. This method requires usage of multiple tools for calculating benefits, which significantly increases the complexity of the analysis compared to the other methods. In addition, the fact that percentages assigned to stakeholders are based on subjective judgments creates similar uncertainty and scaling-up problems to those found with the SG-MCA method.

Table 7.2 compares the methods based on their strengths, weaknesses, stakeholder representations, and applicability.

Table 7. 2
Comparison of Benefit Analysis Methods

Method	Strengths	Weaknesses	Stakeholders	Applicability
SG-MCA	- Systematic - Simple and practical - Direct stakeholder involvement - Fewer data needed - More realistic	- Subjective expert judgment - Poor evaluation of project cost - Data need increases with index numbers - Decision matrix becomes too complex to solve if many indexes	- Utility - Power suppliers - Consumer - Government - Society	Could be applied to most smart grid projects
QPA	- Modular thinking - Simple principles - Easy expansion - Clear quantification & objective conclusions - Stratified analysis (from individual devices to large-scale projects) - Analysis from perspectives of different stakeholders	- Method's analysis framework only applicable to a few examples, i.e., projects with technical frameworks similar to Qianhai's - Excludes non-monetary values - No stakeholder involvement	- Utility - Power suppliers - Consumer - Government - Load integrators	Applicable to other projects by initially selecting a sub-project or module, then establishing the analytical framework
TNY	- Business model Driven - Multi-stakeholder involvement - Integration framework	- Elements of subjective/ qualitative approach - Excludes non-monetary values	- Direct project participating entities	Applicable, but only after customization
JRC	- Flexibility - Well-understood theoretical foundation for economic analysis - KPIs and qualitative analysis	- Large set of data needed - No stakeholder involvement	- Utility - Power suppliers - Consumer - Society	Can be tailored to virtually any project

EPRI/U.S. DOE	- Simple, explicit, transparent mappings - Clear definition of technologies, impacts, and benefits - Well-understood theoretical foundation for economic analysis - Same setup for all projects makes comparison easier	- Excludes non-monetary values - Large set of data needed - Inflexibility - No stakeholder involvement	- Utility - Power suppliers - Consumer - Society	EPRI/U.S. DOE method can be applicable to all types of projects; however, SGCT is locked to any changes, making it poorly applicable to projects beyond straightforward technology deployment or outside U.S. conditions.

There are limitations to using all of these methods for estimating smart grid benefits. Choosing which method to use is difficult but can be based on various criteria including the characteristics of the smart grid project to be analyzed and the analysis outcome desired. The QPA and EPRI/U.S. DOE methods might be more useful for decisions based on monetary results. The EPRI/U.S. DOE method facilitates the analysis by providing a generic, documented setup. The SG-MCA method might be a better choice for projects aiming to achieve non-monetary benefits such as practicability. Users who want some qualitative analysis in addition to monetarized benefits might prefer the JRC method. Analyses that aim to provide a detailed financial picture on which to base investment might benefit from TNY method's business perspective.

A combination of methods could be considered although this may not be the best way forward because combining multiple methods may increase uncertainty and reduce transparency. Uncertainty is a central issue, so assessing sensitivity of the results to key parameters should be a key aspect of any analysis.

Section 8 presents our recommendations and conclusions regarding next steps.

8. Conclusion

The smart grid BA methods discussed in this white paper aim to provide basic guidelines and information for decision makers, including investors, vendors, utilities, policy makers, and others evaluating smart grid demonstration projects to determine whether and how an integrated smart grid solution should be implemented or adjusted to maximize benefits for all parties. The results of a BA are particularly important when system-wide deployment of smart grids is planned.

This paper focuses on comparative analysis of five BA methods: SG-MCA and QPA from China, EPRI/U.S. DOE and TNY from the U.S., and JRC from Europe. These methods are applied to five smart grid demonstration projects, respectively: TEC and B-TEC in China, ISGD - UCI and TNY in the U.S., and ACEA's Malagrotta project in Italy.

Originating from different methodological backgrounds, all approaches contribute to a broad evaluation perspective for smart grid demonstration projects. QPA, EPRI/U.S. DOE, TNY, and JRC present NPV or B/C ratio as outcome while SG-MCA provides a total benefit score based on expert judgment.

Our case studies demonstrate how the different characteristics among the methods can be used to assess smart grid demonstration projects. By presenting case studies and comparing the methods, this paper takes an essential first step to enable effective communication and collaboration among parties using different methods. As noted in Section 7, simply combining elements of the methods is likely to increase the uncertainty of the results. Instead, review and comparison of the methods should continue, and further exchange of results and cross-fertilization of ideas could be fostered by development of universal software. Such software could be based on the EPRI/U.S. DOE method because the EPRI work underlying it provides a solid basis of definitions and formulas for the basic financial indicators but in an open-source form and expanded or modified to be applicable internationally.

Appendices

References in the text to technical appendices refer to additional documents material prepared separately by the research teams. The table below shows where these appendices can be found, and whom to contact for additional information.

Project	Contact/URL
TEC	Dong Zhang jackzhangua@sina.com, TECHNICAL APPENDIX
B-TEC	Jiao FengShun jiaofs_ceee@foxmail.com, TECHNICAL APPENDIX
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UCI	Brendan P. Shaffer bps@apep.uci.edu, NO TECHNICAL APPENDIX
TNY	Will Agate wagate@nzmsolutions.com, TECHNICAL INDEX
ACEA	Silvia Vitiello, Silvia.VITIELLO@ec.europa.eu, NO TECHNICAL APPENDIX

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