Benefits Analysis of Smart Grid Demonstration Projects

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***Abstract*—**Three example benefits analyses of smart grid demonstration projects are reported. Two U.S. projects are both in Irvine, CA. Southern California Edison's Irvine Smart Grid Demonstration project achieved excellent results for Volt-VAR control, but 9 demonstration zero net energy homes proved far from economic. A microgrid controller being developed for the U.C. Irvine campus promises valuable reliability benefits, and its combined heat and power plant delivers significant ongoing benefits. At the Tianjin Eco-city, multiple demonstrations have been effective technically, but fall short of economic viability.

***Index Terms*—**benefits analysis, microgrids, smart grid, combined heat and power.[1]

I. INTRODUCTION

The smart grid is rolling out internationally, with the United States (U.S.) nearing completion of a partic- ularly significant 4 plus billion-dollar Federal program funded under the American Recovery and Reinvest- ment Act (ARRA-2009). Multiple approaches to benefits analysis (BA) have appeared, and an under- standing of their differences is needed. A coherent basis for international evaluation of project perform- ance can facilitate comparison and transfer of results, and accelerate smart grid deployment. This work has been conducted under the auspices of a joint U.S.- China research effort, the Climate Change Working Group (CCWG) Implementation Plan, Smart Grid.

Comparative BA of smart grid demonstrations are presented for U.S. and China projects. The first, the University of California, Irvine campus (UCI) actually consists of 2 distinct demonstrations, Southern Calif- ornia Edison's (SCE) Irvine Smart Grid Demon- stration Project (ISGD)[2], and the UCI campus itself. The China cohort covers several smart grid aspects of the Sino-Singapore Tianjin Eco-city (TEC). The Irvine sub-projects BAs are completed using the U.S. Depart- ment of Energy's (DOE) Smart Grid Computational Tool (SGCT), which is built on methods developed by the Electric Power Research Institute (EPRI). The TEC sub-project BA uses Smart Grid Multi Criteria Analysis (MCA) developed by State Grid Corporation of China (SGCC) based on the Analytic Hierarchy Process (AHP) with fuzzy logic.

II. METHODS

A. SGCT

The EPRI BA method, as embodied in the SGCT, defines a benefit as the monetized impact of a smart grid project to a firm, a household, or society in general [1,2]. All benefits must be expressed in monetary terms, must accrue to the 3 stakeholders, consumers, utility, or society as a whole, and must lie in the following four benefit categories.

a) Economic: reduced costs, or increased production at the same cost
b) Reliability and power quality: reduction in inter- ruptions and power quality events
c) Environmental: reduced greenhouse gas emissions and other pollution
d) Security and safety: improved energy security, increased cybersecurity, and reductions in injuries, loss of life, and property damage

The benefits estimate is based on the difference between the monetary values associated with a base- line scenario, which represents the system state with- out 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 insults, etc., whether to firms, consumers or to society at large.

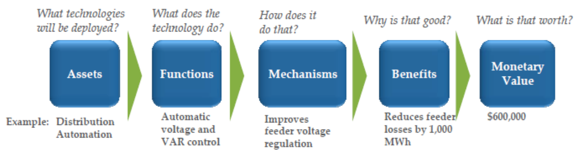

Fig. 1: Logic Flow of the SGCT

Fig. 1 shows SGCT logic, starting from a listing of smart grid assets, then identifying asset functions, and ultimately monetizing benefits. The first step lists all the smart grid assets deployed in the project for evaluation. Step 2 identifies the functions of each asset, for example, Distribution Automation can provide Customer Electricity Use Optimization, Power Flow and Control, Automated Feeder and Line Switching, Automated Islanding and

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Reconnection, Automated Voltage and VAR Control, and so on. Step 3 maps the benefits of each of those functions. Step 4 monetizes all the benefits. Since one function might have multiple benefits, all are summed up to estimate the project's total monetized benefit.

B. AHP with Fuzzy Logic

The MCA method includes four dimensions: technology, economy, sociality, and practicality, including qualitative and quantitative indicators, employing a combined AHP and fuzzy evaluation method [3,4]. The basic principle of AHP is to divide the various elements of the program evaluation system into an orderly multilevel hierarchy, and to then make comparisons between elements of each level and between them and previous levels, thereby obtaining 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 fuzzy comp- rehensive evaluation initially determines evaluation indices, such as the practical, technical, economic, and social levels, while the second level is based on the first, and can be applied to multi-dimensional assess- ment, i.e. a total evaluation is formed by synthetically considering the four attribute index. By combining these 2 evaluation methods, a composite index score can be found that reflects all attributes.

III. PROJECT OVERVIEWS

A. ISGD

SCE operated the ISGD project, and many of the project components were located on or near UCI, which is 60 km southeast of the Los Angeles airport [5]. The purpose of the field experiments was to evaluate the physical effects of various technologies on the electric grid, and to quantify the associated benefits for different types of stakeholders. The project included four domains, with each domain including one or more of eight sub-projects, only 3 of which are included in this analysis: *Sub-project 1:* Zero Net Energy (ZNE) homes; *Sub-project 3:* Distribution Battery Energy Storage System (DBESS); *Sub-project 4:* Distribution Volt/VAR Control (DVVC)

i) Sub-project 1: Zero Net Energy Homes

One 9-home block from a faculty housing neigh- borhood built in 2003 was used to demonstrate and evaluate strategies and technologies for achieving ZNE. A building achieves ZNE when it produces at least as much on-site renewable energy as it consumes over a given period, measured in California (CA) on an annual basis [6]. The homes include a variety of technologies designed to reduce energy use, to empower families to control their energy pattern, to improve grid performance, and to produce and store energy with photovoltaic arrays (PV) and residential energy storage.

a) Demand response devices
b) Energy efficiency upgrades, e.g. LED lighting and improved insulation

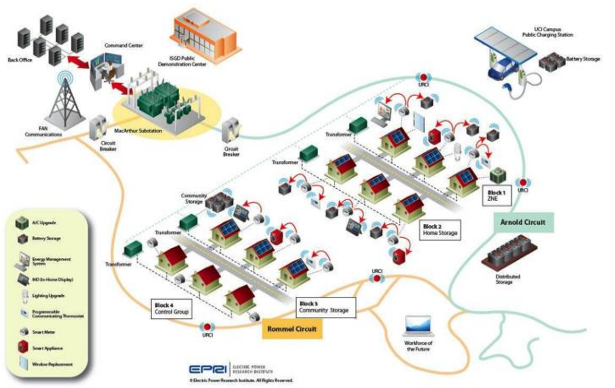

Fig. 2: Overview of ISGD (source: SCE)

c) Residential batteries (4 kW/10 kWh)
d) Solar PV arrays (~3.9 kW)

ii) Sub-project 3: Distribution-Level Battery

This sub-project involves a 2 MW/0.5 MWh battery connected to the Arnold 12 kV distribution circuit that keeps distribution circuit load within a set limit. This mitigates overheating of the substation getaway, and reduces peak load on the circuit.

iii) Sub-project 4: Distribution Volt/VAR Control

DVVC optimizes the customer voltage profiles in pursuit of conservation voltage reduction. This often proposed measure is helpful to CA utilities, which are required to maintain voltage as close as possible to the minimum acceptable level, nominal voltage minus 5%, i.e. between 114-120 V, at the customer connection. DVVC technology significantly improves this capability, and can also provide VAR support to the transmission system. Field experiments showed an average energy savings of approximately 2.5%, making this demonstration a major success, and SCE intends to deploy the technology system-wide.

B. UCI

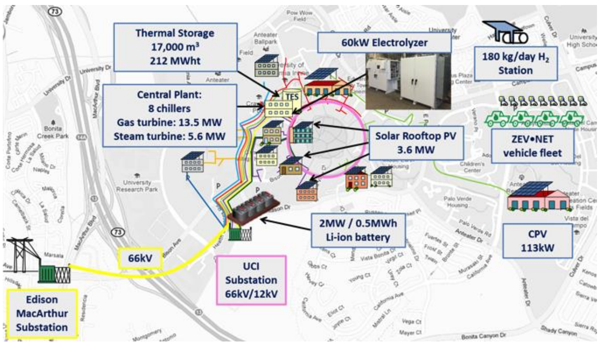

Fig. 3: Overview of the U.C. Irvine Campus

As shown in Fig. 3, the UCI Microgrid is a test bed that (1) is served by SCE through 2×15 MVA trans- formers at the UCI Substation stepping down voltage from 66 kV to 12 kV, (2) encompasses 3×12 kV circuits, (3) includes nearly 4 MW of solar power, (4) owns a 19 MW natural gas fired combined cycle plant with heat recovery (CHP), (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 diverse set of technologies including: (1) electric vehicle charging at multiple parking locations, (2) a 60 kW electrolyzer for production of pipeline hydrogen, (3) hydrogen fueling for fuel cell vehicles, (4) dual-axis tracking concentrating PV, (5) advanced building energy efficiency measures, (6) building monitoring and control, and (7) power quality and thermal metering. Since the Irvine campus has many advanced systems developed over a long period in pursuit of multiple projects and goals, a simple global BA is precluded. Consequently, 4 specific technologies are covered:

Sub-project 1: Central 19 MW plant (CHP);
Sub-project 2: PV arrays totaling 3.6 MW
Sub-project 3: Microgrid controller (MgC);
Sub-project 4: A 2 MW-0.5 MWh battery (LiB)

i) Sub-project 1: Central 19 MW CHP Plant

The Central Plant consists of 8 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 serves all campus heating and cooling, as well as the 96% of campus non-cooling electricity, the balance being served by solar resources (3.5%) and utility imports (0.5%). The power requirement averages 13.4 MW with an annual peak of 18.6 MW. The 8 electric chillers are capable of supplying 51.3 MW thermal, and the steam driven chiller is capable of an additional 7 MW thermal. Campus cooling load averages 11 MW thermal (263 MWh thermal per day) with a typical peak demand of 49 MW thermal. The storage tank can shift, on average, 65% of the chilling load to nighttime, when electricity prices are lower and chilling more efficient. The heating load is served entirely through recovered heat and the duct burner.

ii) Sub-project 2: PV Arrays Totaling 3.6 MW

UCI has 893 kW of fixed panel PV installed on the rooftops of 12 buildings and an additional 2.6 MW installed on 3 parking structures. The capacity factor for the rooftop panels, in operation since 2008, was 0.187 in 2012, in this coastal climate. An additional 113 kW of CPV with dual-axis tracking was installed in 2012, and there is an estimated total campus potential of 22 MW of dual-axis tracking and 15 MW fixed panel PV. Although campus solar resources are still at a low penetration, 3.5%, they are already causing the gas turbine to be turned down at times of low electricity demand and high solar irradiation. This is largely a result of the minimum turndown of the gas turbine to remain in emissions compliance and the inability of export, both of which present challenges for future solar development.

iii) Sub-project 3: Microgrid Controller

A recent DOE award will move the UCI Microgrid further toward full automation through development of the MgC being developed in partnership with SCE and ETAP, which will be generic for deployment at a wide array of different microgrid types. It will provide (1) seamless islanding and reconnection, (2) efficient, reliable, and resilient operation whether islanded or grid-connected, (3) existing and future ancillary services, (4) for the microgrid to serve the resiliency needs of participating communities, (5) communica- tion with SCE as a single controllable entity, and (6) increased reliability and efficiency with reduced emissions.

iv) Sub-project 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 appli- cations, the battery system will act to buffer small transient mismatches between load and generation. The application of interest for the benefit study here is the first, reducing utility imports. UCI's CHP operators are skilled at following load within a typical error band of 100-200 kW, but still requiring some electricity imports to prevent export, which trips the Central Plant. The target import is currently 500 kW, but the battery should reduce the band, allowing a lower import set-point of 300 kW.

C. TEC

On 18 November 2007, the leaders of China and Singapore signed an agreement to cooperate on building the TEC.

Fig.4: Structure of the 12 TEC Sub-Projects

The TEC represents the first comprehensive study of all aspects of smart grid technology in China, and building integrated smart grid demonstration projects, boosting Eco-city development. TEC is located in the 30 km^2 national development strategic area, 45 km from the Tianjin city center. The implementation of key projects focuses on the pilot ecological city zone, a 4 km^2 area located south of the TEC. Initial cons- truction in the Cheong Road area included a 110 kV intelligent substation, and a total of 123 planned distribution sites. The pilot area focuses on six major aspects of the smart grid platform, generation, transmission, substation automation, electricity efficiency, scheduling, and the communication -information platform. The overall comprehensive demonstration project is divided into 12 sub-projects, as shown in Fig. 4, 3 of which are included in this analysis: *Sub-project 2:* Microgrid with storage (MgS); *Sub-project 3:* Smart substation (SS); *Sub-project 4:* Distribution automation (DA)

i) Sub-project 2: Microgrid with Storage

The 380 V MgS is composed of 30 kW of PV, 6 kW of wind turbines, 15 kW×4 h of lithium-ion batteries, together with lighting loads of 5 kW to 10 kW, plus EV charging for a total 15 kW. Control is by an economic microgrid energy management system that includes distributed power, an energy storage inverter, microgrid intelligent terminals, a microgrid system controller, the server host, and an operator station. PV panels and a fan are installed on a hall roof, the microgrid energy management system and batteries are located in a fourth floor operations room, the 10 kW of intelligent operating room lighting is in a third floor office area, and the 5 kW battery is located in the field hospital operating room area.

ii) Sub-project 3: Smart Substation

The Cheong 110 kV SS, uses 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 the 2 networks, direct data mining network control using the IEC-61850 standard, a unified messaging platform technology, and access to the distributed power sources. Equipment includes 2×50 MVA transformers, 2×110 kV lines. The sub- station control layer network uses a single star topology, and its data model follows IEC-61850 to achieve substation monitoring, control, data recording, and other functions.

iii) Sub-project 4: Distribution Automation

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. The DA pilot area distribution network uses a ring network power supply, an open-loop operation mode, and the requirement for mutual interconnection capability to meet N-1, important individual line and load reaches the N-2 line break point and reasonable focal point set a clear and reliable network structure, with each load spread evenly between the lines to meet the N-1 criterion. Regional planning started with construction of the 110 kV Cheong Road substation, the 10 kV and 36 back outlets. The distribution Site Planning region totals 123 points, including 52 distribution stations, 15 switching stations, the front ring means (more power) 56. Since TEC is a new city, all the distribution network construction has to be coordinated with the simultaneous development progress of the region.

IV. RESULTS

A. ISGD

These SGCT results shown in Table 1 indicate that ZNE is far from being economically attractive at current project performance and expenditures. The equipment cost, about \$146 k/home would need to be about 94% lower to achieve break even, i.e., B/C ratio, greater than 1. The ZNE homes were a demonstration of an early stage technology, and are expected to become more economic over time. The results of this analysis should therefore only be considered illustrative for the purpose of evaluating the SGCT. In contrast, DBESS and DVVC appear to be economic, the latter strongly so.. Sub-project 3 results suffer from some methodological limitations listed below.

TABLE I

BENEFITS, COSTS AND B/C RATIOS FOR ISGD SUB-PROJECTS

NPV	ZNE	DBESS	DVVC
Cost	$(4.64M)	$(0.85M)	$(0.59M)
Benefit	$0.30M	$2.14M	$7.58M
Net Benefit	$(4.34)M	$1.30M	$6.99M
B/C Ratio	0.1	2.5	12.9

In both ZNE and DVVC more than 80% of the benefits are from reduction of electricity cost, which is a consumer benefit. For Sub-project 3, almost 70% of the benefits come from deferral in generation capacity investments, while 25% derives from reduction in losses, with the remaining benefit from T&D deferral. There is no beneficial stakeholder other than the Utility in this sub-project. The SGCT also has a number of limitations. For example, the tool calculates the peak reduction benefit based on power capacity, but ignores whether a given system has sufficient energy capacity to sustain the given power level for the peak duration. The tool also does not reflect charging/discharging inefficiencies and auxiliary loads for energy storage systems, nor does it include land acquisition costs.

B. UCI

Table II shows the net benefits for each project considered. The MgC project shows an extremely high value, driven by its highly valued reliability improvement. It was assumed 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 a result 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 CHP plant and MgC projects, resulting from the high investment cost of the PV. For the PV to compete with the CHP, cost reductions are still needed. The LiB case also shows a high benefit-cost ratio compared to the other projects although the absolute value of the net benefit is much smaller than the other projects.

TABLE II

BENEFITS, COSTS, AND B/C RATIO FOR UCI SUB-PROJECTS

NPV	CHP	PV	MgC	LiB
Cost	$ (1.2M)	$ (0.55M)	$ (46,000)	$ (20,000)

Benefits	$ 5M	$ 1.7M	$ 9.7M	$ 140,000
Net Benefit	$ 3.7M	$ 1.2M	$ 9.6M	$ 120,000
B/C Rat.	4.0	3.2	212	6.8

C. TEC

The MgS sub-project applies intelligent control and economic operation using a microgrid energy management system. (1) Practical: the MgS is operating well and its power generation efficiency meets expected goals. (2) Technological: qualified frequency and voltage rates are 100%. (3) Economic: the MgS can load shift, reducing installed capacities of generation units and distribution transformers. This MgS can generate 54 MWh in 1500 h; but, because battery prices are high, a solid business model is still needed. (4) Social: since the MgS is close to loads, losses are relatively small, and it reduces fossil energy by integration of renewables, saving 16.2 t of standard coal and 54 t of CO_2 annually.

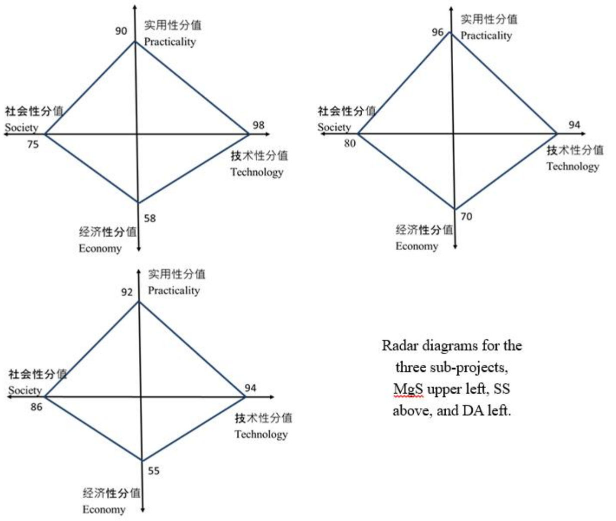

Fig. 5: Results for the Three TEC Sub-Projects

The SS sub-project employs several intelligent primary types of equipment. (1) Practical: the SS can effect- ively guarantee power supply to TEC, and provides a replicable model for the operation and maintenance of the follow-up smart substations. (2) Technological: intelligent primary equipment and electronic trans- formers bring the SS closer to optimal. Fiber reduces the use of low voltage cable, and thanks to primary equipment visualization and its auxiliary systems, it is convenient for operators and equipment life times are increased. (3) Economic: the SS decreases both land and building footprints, reducing annual maintenance cost, construction time, land requirement, building size, cabling, and maintenance. (4) Social: the SS improves reliability, reduces operation and maintenance cost, and promotes the application of new equipment.

The DA sub-project performed well overall, but the economic performance is relatively poor. (1) Practical: this subproject has already been extended to the whole TEC, and its self-healing capability has improved reliability and customer satisfaction. (2) Technological: several technologies, like self-healing and distributed resource integration, have been adopted with 100% maintenance of voltage quality, and N-1 met. (3) Economic: DA improves reliability, while reducing average outage time and line losses but double-loop network and distribution station with three remotes are expensive. (4) Social: this project promotes microgrids and other distributed resources, saving energy and reducing emissions.

V. CONCLUSION

This CCWG collaboration is not intended to be a rigorous benefit analysis, but is rather demonstrates and compares methods of smart grid demonstration evaluation. The first two of the three analyses were conducted with the SGCT, which produced a wide range of results. Some sub-projects that deliver reliability benefits appear attractive, some highly so. Generally, reliability and energy savings are valuable, while environmental improvements yield lower benefit. The AHP with the fuzzy approach produces more consistent results. All TEC sub-projects achieve solid performances, but all tend to be weakest in the economic dimension.

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