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Towards uniform benefit-cost analysis for smart grid projects: an example using the Smart Grid Computational Tool

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Abstract

Smart grid technology is being rolled out around the world, with the United States nearing completion of a particularly significant 4 plus billion-dollar Federal program funded under the American Recovery and Reconstruction Act (2009). Under the Climate Change Working Group Implementation Plan, Smart Grid activity comparative analyses are being conducted of benefits estimation methods with example applications to 4 case study smart grid projects, 2 in each country. In this first study, three of eight Southern California Edison's Irvine Smart Grid Demonstration Project sub-project benefits have been analysed over the period 2010-2035. The analysis uses the Smart Grid Computational Tool (SGCT) developed by Navigant Consulting Inc. for the U.S. Department of Energy based on Electric Power Research Institute methods. Results show significant benefits potential for technologies such as distribution voltage and VAR control and utility-scale batteries, while a 22-residence zero net energy home demonstration inspired by California's 2020 residential energy efficiency standard falls far short of economic breakeven at the current stage of costs and technology performance. The experience gathered indicates the SGCT being intended for widespread U.S. smart grid evaluation use is necessarily simple, and consequently has limited applicability for international applications or comparisons.

Keywords
smart grid, benefit-cost analysis, zero net energy homes, Smart Grid Computational Tool, EPRI method, American Recovery and Reinvestment Act

1. Introduction

This work has been conducted under the auspices of a joint U.S.-China research effort. Sharing research capabilities and results in the smart grid area between the two countries forms the overarching objective of the activity. Early discussions in 2014 between the research teams led to two focuses, advanced technology (not discussed further in this paper), and on the analysis of demonstration project benefits. Researchers in both the U.S. and China have developed formal methods for benefits assessment, so demonstrating them with example analyses was the logical approach. This paper reports on the first analysis conducted on the U.S. side using the Smart Grid Computational Tool (SGCT), which was developed specifically for the American Recovery and Reinvestment Act 2009 (ARRA) program. Primarily, this demonstration is intended to show the capabilities of the tool. Additionally, its applicability internationally is of interest, especially in China. As in many technical demonstrations, the purpose of the ARRA smart grid projects is multi-faceted, not least in this case, for economic stimulus.

Electrification of the economy is often cited as the crowning achievement of the last century, most notably by the United States (U.S.) National Academy of Engineering (Constable and Somerville, 2003). Nonetheless, during the latter quarter of the last century, interest in the transmission grid decayed in several ways, including a general lack of research activity, investment, and policy attention. In the U.S., this era was closed by a series of devastating hurricanes beginning with Hugo in 1989, then Andrew in 1992, followed by several others, notably Katrina in 2005 and, ultimately, Sandy in 2012. The paralyzing effect of power loss following these disasters, and the reminder that other infrastructures on which developed economies critically depend, communications, transport, sewage treatment, etc., are also lost when the grid goes black, sparked renewed interest in *the grid*. The Great East Japan Earthquake of 2011 has had a similar dramatic impact on that country's understanding of power supply resilience, and indeed worldwide (Ton et al., 2011; Marnay et al., 2015; Panteli and Mancarella, 2015). While other countries have not experienced quite such a sobering series of events, blackouts in many other places during recent times have similarly affected thinking elsewhere, e.g. the blackouts in London and Italy in 2003, Germany and Tokyo in 2006, and India in 2012. And of course, the U.S. also experienced a major non-weather-related blackout in 2003. In addition to reliability, there was growing concern that other threats to the grid are emerging too. A major one was fear that a high fraction of uncontrollable variable renewable generation in the supply mix would undermine established operating procedures based on dispatchable thermal and hydroelectric generators creating new stresses on power systems, an evolution generally known in California as *The Duck Curve* (CAISO, 2013). The name comes from its shape. With increasing solar generation during afternoon hours, the residual load to be met by traditional load-following generation gets hollowed out, the breast of the duck, while the evening ramp to evening operations becomes increasingly steep, the duck's neck, and nighttime operations remain little changed, the tail. California's immediate goal for renewable supply penetration is 33 % of retail electricity from renewables by 2020, which is driving rapid growth in solar, of which 4 GW was installed in 2014 alone. The failure of California's reformed electricity market in 2000 also raises concerns that market manipulation or other consequences of power sector reform would threaten grid performance. During the 2000 crisis, astronomical price spikes failed to evoke much demand response because very few customers were actually directly exposed to prices, rather the State struggled to keep them stable. Meanwhile on the supply side, generators were withdrawing capacity. Controlled *rolling* blackouts were required to balance supply and demand providing further stark evidence of the economic disruption that can result from market dynamics, while the financial damage inflicted on distribution companies further threated reliability. It is now recognized that if markets are to be so volatile, prices seen by customers need to reflect the resulting price variations.

Early in this century, it became clear that the technology embedded in the developed world's electricity supply system had become seriously inadequate to cope with the challenges described above, and to generally meet rising expectations for grid performance, often assumed necessary to support the emerging *digital economy* (Tapscott, 1995). *Smart Grid* emerged as an umbrella term to describe a number of technologies that had mostly already been proposed or actually developed separately, but which had failed to gain broad deployment. The notable example is advanced metering infrastructure (AMI), whose capabilities had been recognized as necessary for several decades. Other technologies too were brought under the smart grid umbrella. These can be boxed into three types. The first, already mentioned, involves establishing an appropriate AMI infrastructure to enable price-sensitive demand, and hence an efficient market. The second concerns improved operation of the legacy centralized grid. Many new applicable technologies have emerged, such as synchrophasers and better visualization tools (SEL). The third, and perhaps most radical leg of the smart grid stool is decentralized control of the power system, i.e. microgrids and community power (Marnay and Lai, 2012). This innovation has been rapidly gaining momentum since Sandy, largely driven by the exceptional performance of several microgrids during the disaster (Panora et al., 2011, Marnay et al., 2015).

The U.S. is unusual in that a definition of smart grid appears in legislation. The Energy Independence and Security Act (2007) established that U.S. Federal policy is to promote development of the smart grid. Title XIII covers the smart grid, and the list of its elements as shown in the bill has stood up well and has provided a solid definition that covers technologies in all the three areas listed above. This legislative basis made smart grid an attractive target for ARRA stimulus spending. A significant body of smart grid policy analysis had been established (TheCapitolNet, 2009). ARRA was the major U.S. macroeconomic stimulus package passed during the great recession by Congress and signed by President Obama on 17 February 2009. About $4.5B or 0.6 % of all ARRA spending was dedicated to smart grid development within the U.S. Department of Energy (DOE). Two types of grants were established. By far the larger is the Smart Grid Investment Grant (SGIG) Program, which includes 99 projects and accounts for most of the DOE funds committed. Together with private matching contributions the SGIG totals about $8B of investment, dominated by AMI deployment of an expected 65 million smart meters (DOE, 2014). The second much smaller ($650M of DOE funds) Smart Grid Demonstration Projects (SGDP) includes 32 more technically innovative projects of which the $80M Irvine Smart Grid Project (ISGD) covered in this paper is one (Irwin and Yinger, 2014; Irwin and Yinger, 2015).

Although ARRA was an economic stimulus program, from the beginning, the SGIG and SGDP programs were intended to be open demonstrations that would serve as catalysts for development and deployment of smart grid technology. One aspect of this perspective was an explicit intention to evaluate and disseminate the results of the projects, including their societal benefits (DOE, 2009). Consequently, during the first year of the programs, DOE's Office of Electricity Delivery and Energy Reliability made a substantial effort to develop a standard benefits method that could be applied to all projects in a consistent manner. An analytic approach was developed by the Electric Power Research Institute (EPRI), and on this foundation, the Smart Grid Computational Tool (SGCT) used in this study was built by Navigant Consulting, Inc. (EPRI, 2010; Navigant, 2011). All projects receiving DOE ARRA funds are required to provide benefits results but not necessarily using the EPRI approach or the SGCT. An effort was also made to harmonize approaches with Europe, and the EPRI approach has been applied outside the U.S. in at least one study, and incorporated in other tools (Giordano and Bossart, 2012; Giordano et al., 2012; Vitiello et al., 2015).

The work described in this paper has been conducted as part of a collaborative research effort between the U.S. and China under the Climate Change Working Group Smart Grid (CCWG) effort, which has identified smart grid as one of five areas of promising research collaboration (CCWG, 2014). Four notable smart grid demonstrations in the U.S. and China will be studied and compared during this three-year analysis for both technical and economic-social merit. ISGD is one of the showcase U.S. projects and the first one to be scrutinized in detail. It has eight sub-projects, but the analysis described here focuses on just 3. The first involves installation of multiple sophisticated residential technologies in a group of 22 pre-existing faculty homes on the University of California, Irvine (UCI) campus. The installed equipment includes smart appliances and equipment, photovoltaic arrays (PV), solar water heating, heat pumps, and battery storage. Some of the homes are intended to achieve the California Zero Net Energy (ZNE) standard, which is California's goal for all new residential construction by 2020 (CEC-CPUC, 2015). The other two sub-projects covered are distribution network technologies involving utility-scale storage and distribution voltage and volt-ampere reactive (VAR) control intended to conserve energy.

2. Methodology

2.1 EPRI Method

Benefit-cost (B-C) analysis is a commonly used tool in public policy discussion and decisions (Mishan and Quah, 2007). While the smart grid has now been around for some time, estimating its B/C ratios is still a new area of study (Bossart and Bean, 2011). Nonetheless, as smart grid projects are being demonstrated globally, the demand for analysis of project cost effectiveness is growing rapidly, with analysis developments and related tools in both the U.S. and Europe filling this gap. EPRI with the support of DOE researched methods for estimating the benefits of individual smart grid demonstration projects (EPRI, 2011). In this study, we discuss the EPRI B-C analysis method for assessing the economic, environmental, reliability, safety, and security benefits of involved project stakeholders.

The EPRI Method defines *benefit* as a monetized value of the impact of a smart grid project to a firm, a household, or society in general. The B-C analysis in the EPRI method is based on the difference between the benefits and costs associated with a baseline scenario (Formula 1), which represents the system state without the smart grid demonstration project, and a contrasting project scenario. The benefits are usually aggregated from deferred capacity investment, reduced electricity purchases, reduced or deferred transmission and distribution (T&D) investment, lower operation and maintenance, reduced transmission congestion, improved power quality, reduced environmental insults, and so on (see Table 1 for a complete list). Net benefits are the total reductions in costs and damages as compared to the baseline, accruing to firms, customers, and society at large, excluding transfer payments between these beneficiary groups. All future benefits and costs are reduced to a net present value (NPV) using a discount rate, and an inflation rate, over the project lifetime.

Formula 1:

$$B_{net} = NPV\{C_{baseline} - C_{project}\}$$

To learn more about the cost effectiveness of a smart grid project, the EPRI Method was extended to calculate the B/C ratio, and the breakeven time of the project. The B/C ratio is calculated from Formula 2, and the higher the ratio, the more attractive the project:

Formula 2:

$$B/C = \frac{Annualized\ \sum(B_{econ} + B_{reli} + B_{env} + B_{sec})}{Annualized\ Cost}$$

where, B/C ratio is the cost effectiveness of the project. B_{econ} represents the economic benefits, B_{reli} the reliability benefits, B_{env} the environmental benefits, and B_{sec} the security benefits. Both the benefits and costs are annualized. Benefits are categorized into four groups: economic, reliability, environmental, and security. Each group has a number of benefits generated by assets and their functions, as Table 1 summarizes.

There are multiple stakeholders involved in smart grid development, *consumer*, *utility*, and *society* as a whole. It needs to be noted that different stakeholders might have different focuses and shares of those benefits. The *consumer* and *utility* would share the economic benefits, the *utility* captures most of the reliability benefits, while environmental and security benefits accrue to *society* at large.

2.2 Smart Grid Computational Tool

User friendly tools should be able to scale up applications of smart grid B-C analysis, so DOE developed the SGCT[1] to facilitate monetary benefits evaluation based on the framework EPRI developed. The SGCT is an Excel-based model that allows the user to identify the functions to be demonstrated by a smart grid project's technologies, to calculate its benefits and costs, and to estimate the project's overall value (Navigant, 2011). The SGCT is currently locked for further revision, so it cannot be used on any other platform, such as Analytica, for uncertainty analysis, nor is it open for user enhancement.[2]

The logic of the SGCT starts from a listing of smart grid assets, then identifies the functions of those assets, and ultimately monetizes project benefits, as shown in Figure 1. The first step is to list all the smart grid assets deployed in the project for evaluation, for example, *Distribution Automation*, *Smart Appliances and Equipment (Customer)*, etc. Step 2 is to identify the functions of each asset, for example, *Distribution*

[1] More information at https://www.smartgrid.gov/recovery_act/publications/analytical_tools (accessed 5 March 2015)

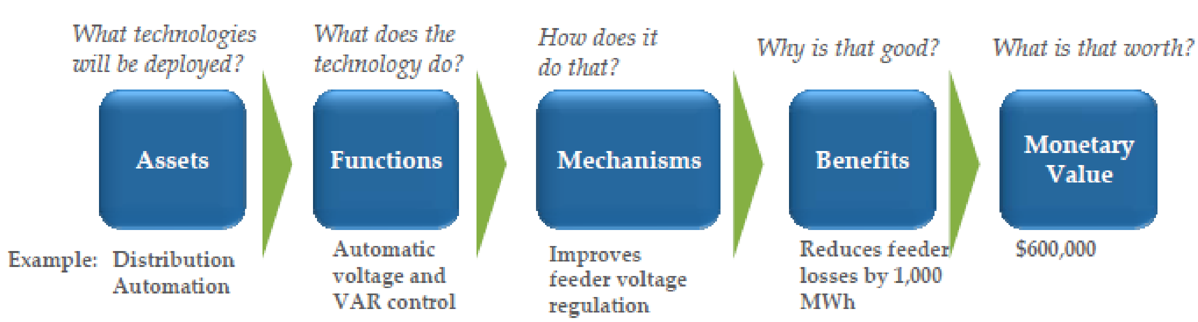
[2] www.lumina.com

Automation can provide *Power Flow Control*, *Automated Feeder and Line Switching*, *Automated Islanding and Reconnection*, *Automated Voltage and VAR Control*, and so on. Step 3 is to map the benefits of each of those functions. Step 4, the last step, is to monetize all the benefits. One function might have multiple benefits, therefore, all should be summed up to estimate the project's total monetized value.

Table 1 Itemized benefits of SGCT

Benefits
Economic: 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 T&D Equipment Maintenance Cost Reduced T&D Operations Cost Reduced Meter Reading Cost Reduced Electricity Theft Reduced Electricity Losses Reduced Electricity Cost
Reliability: Reduced Sustained Outages Reduced Major Outages Reduced Restoration Cost Reduced Momentary Outages Reduced Sags and Swells
Environmental: Reduced Carbon Dioxide (CO_2)Emissions Reduced Sulfur Oxide (SO_X), Nitrogen Oxide (NO_X) and Particulate Matter (PM)-2.5 Emissions
Security: Reduced Oil Usage Reduced Wide-scale Blackouts

(Source: This benefits table is adapted from Navigant (2011))



(Source: EPRI, 2010)

Figure 1 The logic flow of SGCT

In this paper, the SGCT tool is applied to analyze the cost effectiveness of the ISGD sub-projects. Data were collected for the key SGCT inputs and are used to conduct B-C analysis on selected ISGD sub-projects independently; a sensitivity analysis on discount rate was also conducted.

Clearly, uncertainty is a central issue that needs to be addressed in any analysis attempting to evaluate an evolving technology over a multi-decade horizon. All inputs should be questioned, but those regarding performance and cost of the technology generate the most discomfort and call most convincingly for attention. The SGCT provides only rudimentary uncertainty capability in the form of automated sensitivity analysis on roughly 110 input variables used in benefits calculation such as annual generation cost, price of capacity at annual peak, ancillary services cost, congestion cost, distribution investment time deferred, total T&D maintenance cost, T&D losses, CO_2 emission, CO_2 prices, and so on. However, there is no sensitivity analysis on some key variables, such as project capital cost, and some project costs are not included at all, e.g. installed equipment maintenance and operational costs. Possible price reduction due to future technological change is also uncertain and not considered in the EPRI method or the SGCT. In addition, modeling of technology capital costs could be enhanced if they included failure probability and/or equipment lifetime. Unfortunately, since the SGCT is available only in a locked version, omitted variables cannot be added, and using stochastic variables for Monte Carlo or other simple uncertainty analysis is not possible.

3. Case Study - Irvine Smart Grid Demonstration Project

3.1. Project Overview

Southern California Edison (SCE) operates the ISGD project primarily in California's Orange County City of Irvine. Many of the project components are located on or near the UCI campus, which is 60 km southeast of the Los Angeles airport (LAX). Key project participants include UCI, General Electric Energy, SunPower Corporation, LG Chem, Space-Time Insight, and EPRI. The primary objective of ISGD is to verify and evaluate the ability of smart grid technologies to operate effectively and securely when deployed in an integrated framework (Irwin and Yinger, 2015). ISGD is a comprehensive demonstration that spans the electricity delivery system and extends into customer homes. ISGD's evaluation approach includes four distinct types of testing: simulations, laboratory tests, commissioning tests, and field experiments. The ISGD project uses simulations and laboratory testing to validate a technology's performance capabilities prior to field installation. The purpose of the field experiments is to evaluate the physical impacts of the various technologies on the electric grid and to quantify the associated benefits for different types of stakeholders.

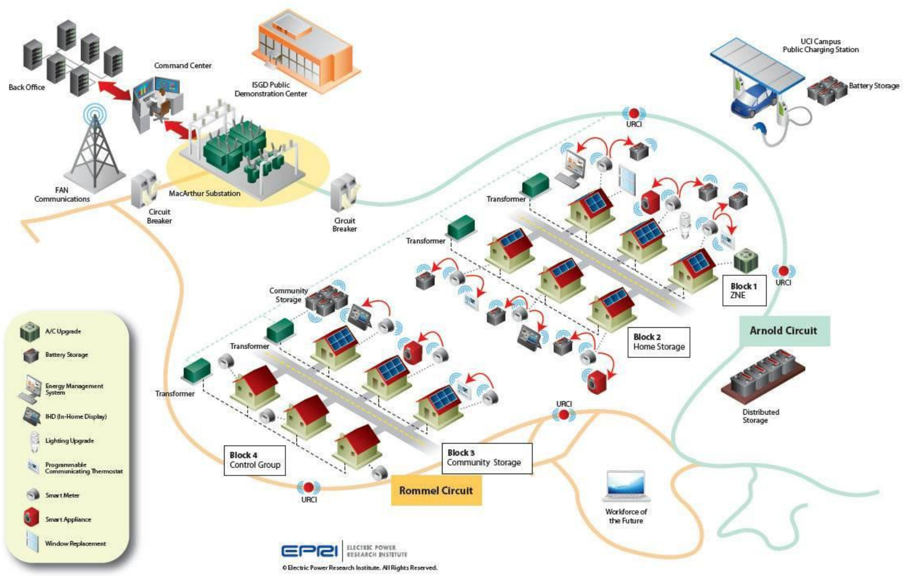


Figure 2 Irvine Smart Grid Demonstration (ISGD) project

The project includes four *domains*. Each domain includes one or more with distinct objectives, technical approaches, and research plans. There are 8 sub-projects within these 4 domains, only 3 of which, shown *italics* below, are included in the analysis in this paper, as shown below:

- Smart Energy Customer Solutions (Sub-Projects 1 & 2)
  - *Sub-project 1: Zero Net Energy 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)

3.2. Sub-project 1: Zero Net Energy Homes

In Sub-project 1, ISGD is evaluating a variety of technologies designed to help empower customers to make informed decisions about how and when they consume (or produce) energy. Such technologies have the potential to better enable customers to manage their energy costs, while also improving grid reliability and stability (Irwin and Yinger, 2015). This project domain includes a variety of technologies designed to help empower customers to make informed decisions about their energy use. The project extends into a residential neighborhood on the UCI campus used for faculty housing. ISGD has equipped three blocks of homes with an assortment of advanced energy technologies, including energy efficiency upgrades, energy storage, rooftop solar photovoltaic (PV) panels, thermostats and smart appliances capable of demand response, and in-home displays.[3] The project is using one block of homes to evaluate strategies and technologies for achieving zero net energy (ZNE) or near-ZNE. Energy efficiency upgrades are only included in this block of homes. A building achieves ZNE when it produces at least as much (usually renewable) on-site energy as it consumes over a given period, including both natural gas and electricity, typically on an annual basis. The concept of ZNE buildings is widespread and has been incorporated into California's next Title 24 building code, effective in 2017 (CEC-CPUC, 2015). From this point of view, the objectives of this sub-project are to evaluate the impact of advanced demand side measures to better understand their impacts on the electric grid, as well as their contributions toward enabling homes to achieve ZNE. Three levels of home retrofits and details are as follows:

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

[3] Additionally, there is a fourth block of homes, which is aimed to provide baseline data in B-C analysis, although in this work a time series comparison is used.

Table 2 Demand response capable devices deployed in Sub-Project 1

Energy Star Smart Refrigerator
Energy Star Smart Clothes Washer
Energy Star Smart Dishwasher
Programmable Communicating Thermostat
Home Energy Management System
In-Home Display

Table 3 Energy efficiency upgrades and onsite renewable technologies deployed in Sub-Project 1

Central Air Conditioning Replacement (Heat Pump)
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
Solar PV Panels

ISGD is evaluating two types of residential-scale batteries in this neighborhood; additionally, a utility-scale battery was demonstrated in Sub-Project 3, as described in more detailed below. All batteries used in ISGD are Li-ion, but from 3 separate vendors. Individual residential energy storage units have been installed in 14 homes as mentioned above, and they are being evaluated using a variety of control modes. In addition, 7 homes share a community battery, which is also being evaluated using a variety of control modes. Both devices can provide load leveling, storage of daytime PV output for later use, and a limited amount of backup power during electricity outages. These batteries underwent extensive testing prior to commissioning. ISGD performed various field experiments over a one-year period to evaluate the impacts of the Sub-project 1 capabilities.

Field Experiment A: The objective of this experiment is to quantify the impact of energy efficiency upgrades and other IDSM measures on the home and transformer load profiles. This experiment helped the team determine how the homes, particularly on the ZNE block, but also on the RESU and CES blocks, perform against the goal of achieving zero net energy, and assess the impact on the distribution transformer temperature and load profile.
Field Experiment B: The objective of this experiment is to quantify the impacts of demand response devices on the load profiles of smart devices, the homes, and the secondary transformers.
Field Experiment C: The objective of this experiment is to quantify the ability of the RESU to shift coincident peak load to the off-peak period by discharging during the peak period.
Field Experiment D: The objective of this test is to quantify the ability of the RESU to automatically level demand over a 24-hour period. RESUs operate in the Level Demand mode, which directs the RESU to discharge during periods of high demand and charge during periods with little load, thereby flattening the home's demand curve.
Field Experiment E: The objective of this experiment is to quantify the CES's ability to shave demand on the secondary transformer. The CES automatically adjusts its discharge power level based on real-time load provided from a locally installed power quality meter. This control reduces the demand on the transformer.
Field Experiment F: The objective of this experiment is to quantify the impacts of rooftop solar PV generation on the load profile of the secondary transformer.

3.3. Sub-Project 3: Distribution Circuit Constraint Management Using Energy Storage

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

This battery 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 from distributed energy resources, such as demand response resources or energy storage.

3.4. Sub-Project 4: Distribution Volt/VAR Control

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

3.5. General Assumptions

This study contains B-C analyses of Sub-Projects 1, 3, and 4 of ISGD, for which the following assumptions were made.

- Homes on each block have different levels of retrofits, as mentioned earlier in Section 3.1. The retrofits differ from even home-to-home in the same block. The average cost associated with each upgrade is detailed in Table 4. In calculation of project costs, it is considered that upgrades of white goods in homes, namely smart refrigerators, smart dish washers, smart clothes washers, and efficient hot water heater, would be more expensive varieties of common models. Thus, for those technologies, only incremental cost, via comparison with similar model prices in the market, was included in the analysis. On the other hand, for the new technologies such as home EMS display, RESU, CES, and PV panels, the total cost of the equipment is used. Table A1 in Appendix summarizes the key inputs and parameters used in the study. In addition, details of the technology costs and assumptions on incremental costs are also presented in Table A2 and A3 in Appendix.
- Since the EPRI method and the SGCT tool do not consider equipment lifetime or model survival of technologies, survival probability of each technology was calculated exogenously and implemented in the SGCT as input costs. Survival probabilities are assumed normally distributed with a mean average lifetime (see Table A3 in Appendix) and variance of 3 years for each technology.
- Discounting costs and benefits at a societal discount rate provides the value of the project to society, regardless of actual project costs. International practices recommend real discount 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, while the U.S. Environmental Protection Agency uses 2-3 % with a sensitivity rate of 7 %. The European

Commission suggests 5 %, while the United Kingdom Treasury uses 3.5 %. Given this range of views, a societal discount rate of 5 % was assumed and sensitivities performed for 2.5, 7.5, and 10 %.

- Project input parameters are employed for 2014 because ISGD was activated around mid-2013, making 2014 a full representative test year, while baseline parameters are based on historical 2012.
- A time horizon of 25 years from the beginning of the project is chosen.
- The value of T&D capacity is based on projected total cost to add capacity system-wide over a 5-10 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.

Table 4 Average cost of retrofit by project blocks in Sub-project 1

Blocks	Average Cost per home ('000 2010$)
ZNE Block	$164.0
Demand Response	$12.2
Energy Efficiency Measures	$65.7
Residential Energy Storage Unit	$66.7
Solar PV Panels	$19.5
RESU Block	$115.6
Demand Response	$12.2
Residential Energy Storage Unit	$66.7
Solar PV Panels	$36.7
CES Block	$60.7
Demand Response	$12.2
Community Energy Storage Unit	$22.3
Solar PV Panels	$26.2

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

4. Results

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

4.1. Mapping

Figure 3 illustrates the assets identified for each Sub-project, listed in blue boxes, and mappings to functions activated by the assets. Once the functions are identified, the tool in turn maps them on to a standardized set of benefits.

Figure 4 summarizes the functions to benefits mapping provided by the SGCT for each test case Sub-project. The green cells with *YES* mark the benefits of each Sub-project identified through the mapping exercise; however, this second mapping shows that functions to benefits links are not accurate in every case. Some identified functions do not appear to be linked as expected to benefits, and one function is linked to an unexpected benefit. *Optimized Generator Operation* is a benefit not directly realized from the *Distributed Production of Electricity* function in Sub-project 1. It is certainly credible that coordination between output from distributed sources and operation of centralized assets might improve overall fuel efficiency, but such coordination implies a detailed level of operational control. In this study, no input was made for this benefit to eliminate it from calculations. Likewise, *Automated Voltage and VAR Control* function in Sub-project 4 is only linked to the benefits *Reduced Electricity Losses*, *Reduced CO_2 Emissions*, and *Reduced SO_x, NO_x, and PM-2.5 Emissions*; however, field experiments have shown DVVC produces an average customer energy savings of 2.6 %, ranging between 1.6 % and 3.6 % (Irwin and Yinger, 2015)[4]. Figure 5 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 the cost of distribution equipment maintenance is reduced. These benefits not identified in the tool for DVVC are marked in red (with *+YES*) in Figure 4. To overcome this limitation, a phantom asset was added to generate the missing benefits at no cost.

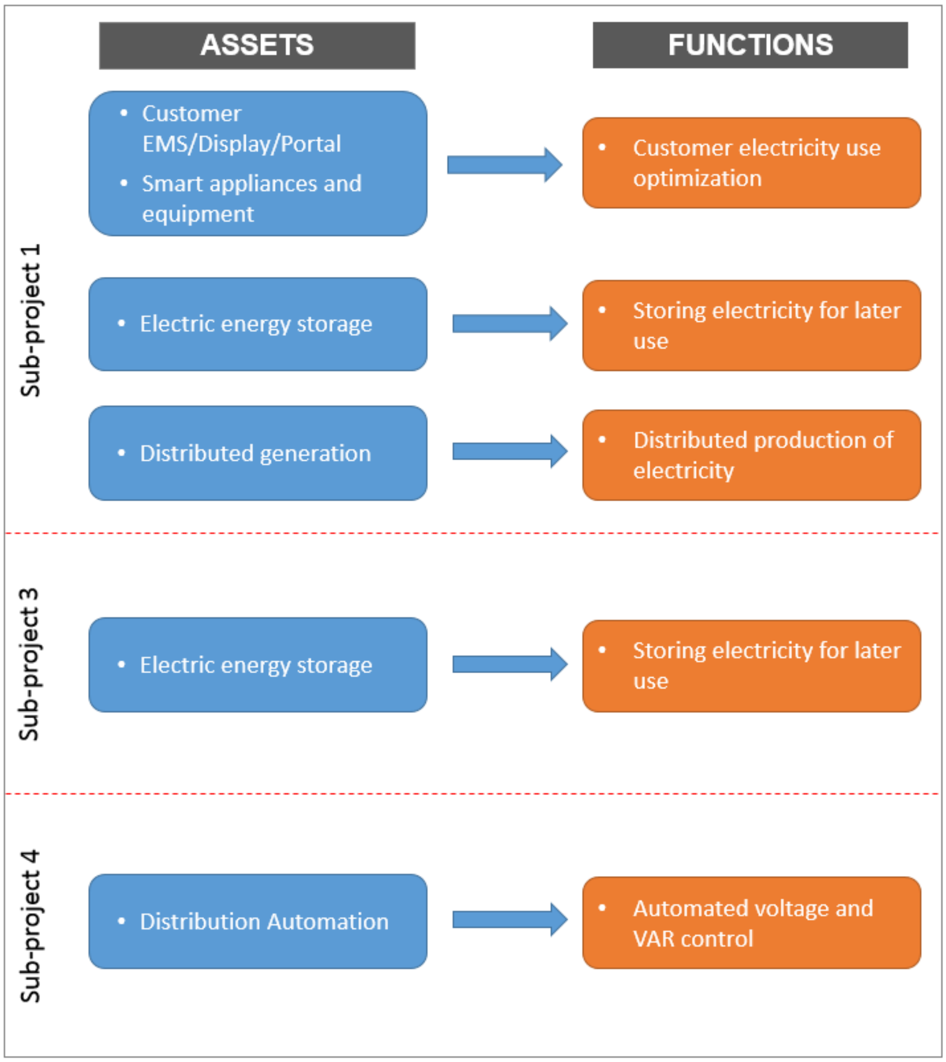


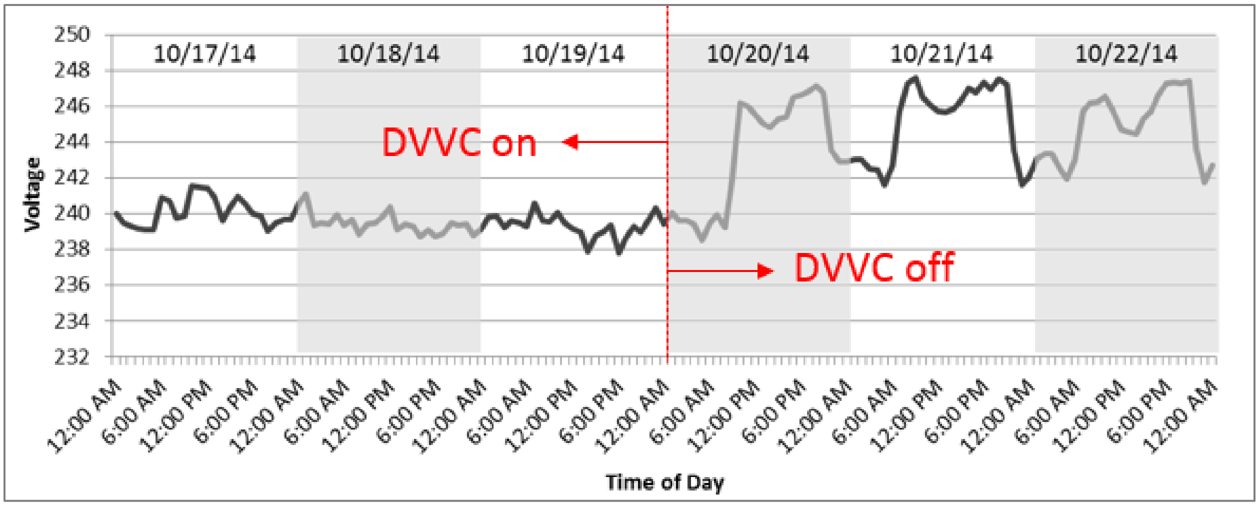
Figure 3 Assets to functions mapping of each case Sub-project

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

Benefits			Sub-project 1 Functions			Sub-project 3 Functions	Sub-project 4 Functions
			Customer Electricity Use Optimization	Storing Electricity for Later Use	Distributed Production of Electricity	Storing Electricity for Later Use	Automated Voltage and VAR Control
Economic	Improved Asset Utilization	Optimized Generator Operation			YES		
		Deferred Generation Capacity Investments	YES	YES	YES	YES	+YES
		Reduced Ancillary Service Cost	YES	YES	YES	YES	
	T&D Capital Savings	Reduced Congestion Cost	YES	YES	YES	YES	
		Deferred Transmission Capacity Investments	YES	YES	YES	YES	+YES
		Deferred Distribution Capacity Investments	YES	YES	YES	YES	+YES
	T&D O&M Savings	Reduced Equipment Failures					
		Reduced T&D Equipment Maintenance Cost					+YES
		Reduced T&D Operations Cost					
	Theft Reduction	Reduced Meter Reading Cost					
	Energy Efficiency	Reduced Electricity Theft					
	Electricity Cost Savings	Reduced Electricity Losses		YES	YES	YES	YES
Reliability	Power Interruptions	Reduced Electricity Cost	YES		+YES		+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)					

(Note: green cells are identified by the SGCT, red cells are additional)

Figure 4 Functions to benefit mapping of each case Sub-project



(Source: Irwin and Yinger, 2015)

Figure 5 Customer voltages with and without DVVC (October 17, 2014 to October 22, 2014)

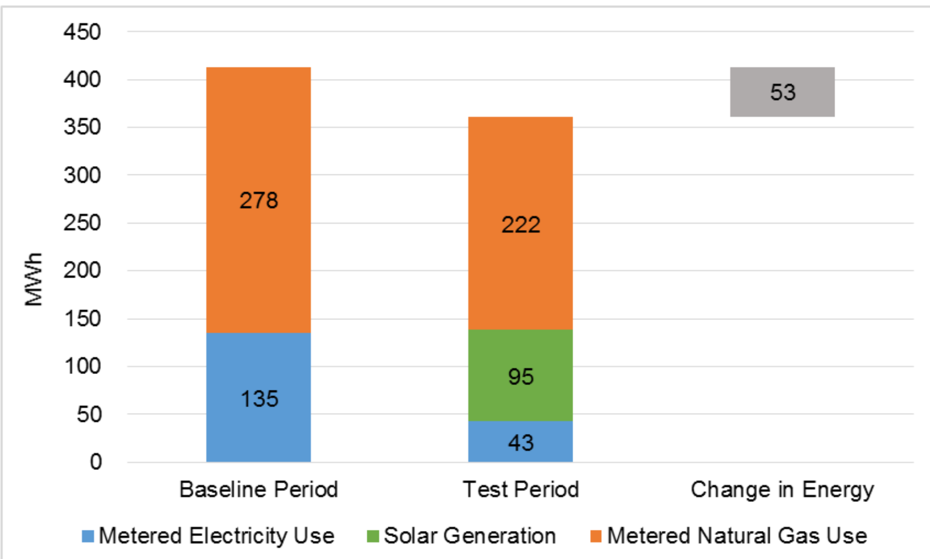
4.2. Benefits and Costs

Table 5 summarizes the estimated benefits for the three stakeholder groups shown. *Utility* benefits are reductions in the cost of providing service. This relates to any cost changes in generation or T&D. Showing benefits in this way is controversial because a regulated utility is unlikely to retain all of them, as some will be ultimately returned to customers via reduced future rates. In the case of California, deviations from expected revenues and fuel costs are explicitly tracked and mostly incorporated into future rates, although changes in other costs, as listed in Table 5, are less clear-cut. Nonetheless, since this exercise is intended to be a trial application of the SGCT, its usage is followed.

Table 5 Overview of stakeholders and impacted benefits in case sub-projects

	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 PM-2.5 Emissions

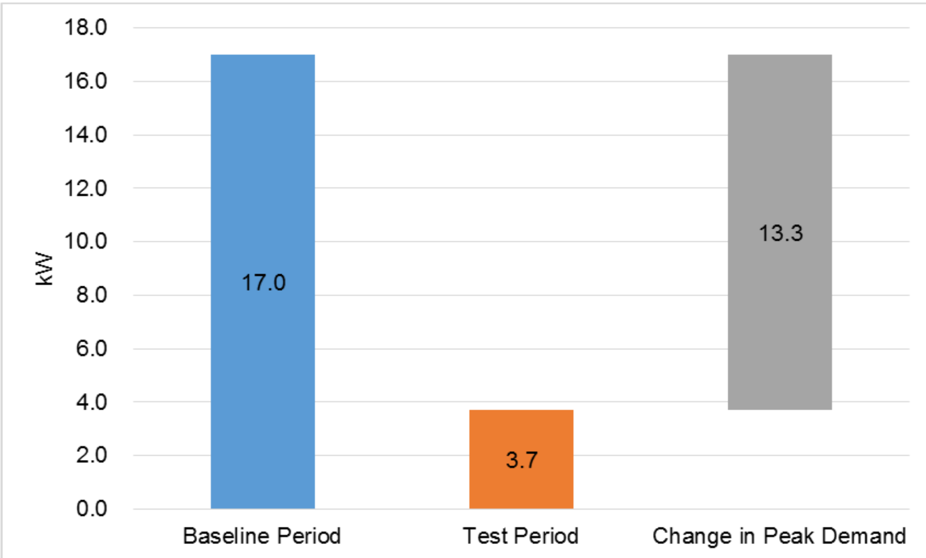
Consumers are mainly affected through changes in electricity and natural gas consumption due to efficient and/or smart equipment, feedback on electricity usage, substitution of grid electricity by on-site PV generation, energy storage, and DVVC. The SGCT evaluation method for *Consumer* benefits relies on the decrease in annual total electricity cost. For the 22 project homes, Sub-project 1 reduces the total electricity bill by 68 %, as shown in Figure 6. In addition, 69 % of total electricity consumption is met by PV generation, i.e. 95 MWh of 138 MWh. These effects result in a large reduction of coincident peak load, as shown in Figure 7. 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. However, electricity requirements grow by 3.4 MWh. The substitution of heat pump heating in the ZNE block homes and behavioral changes tend to increase electricity consumption, while PV and other measures reduce it. [5] As shown in Figure 6, energy savings are in largely in the form of reduced natural gas consumption, not electricity. In the baseline, 67% of the total energy consumed in three blocks of homes of the Sub-project 1 comes from natural gas energy usage, valuing electricity at its site equivalent. In the test period, natural gas consumption is decreased 20%, and total saving, after subtracting additional electricity, is equivalent to 53 MWh. A reduction in natural gas consumption results from energy efficiency measures affecting usage, especially the solar hot water systems and heat pumps, but also the ENERGY STAR clothes washers, which are one of the demand response devices used. Natural gas consumption was not reduced as much as these investments would suggest, a result that remains largely unexplained; however, warmer weather during the test period, compared to the baseline, did decrease space and water heating demand somewhat.



(Source: Irwin and Yinger, 2015)

Figure 6 Combined 22-home annual energy consumption (MWh)

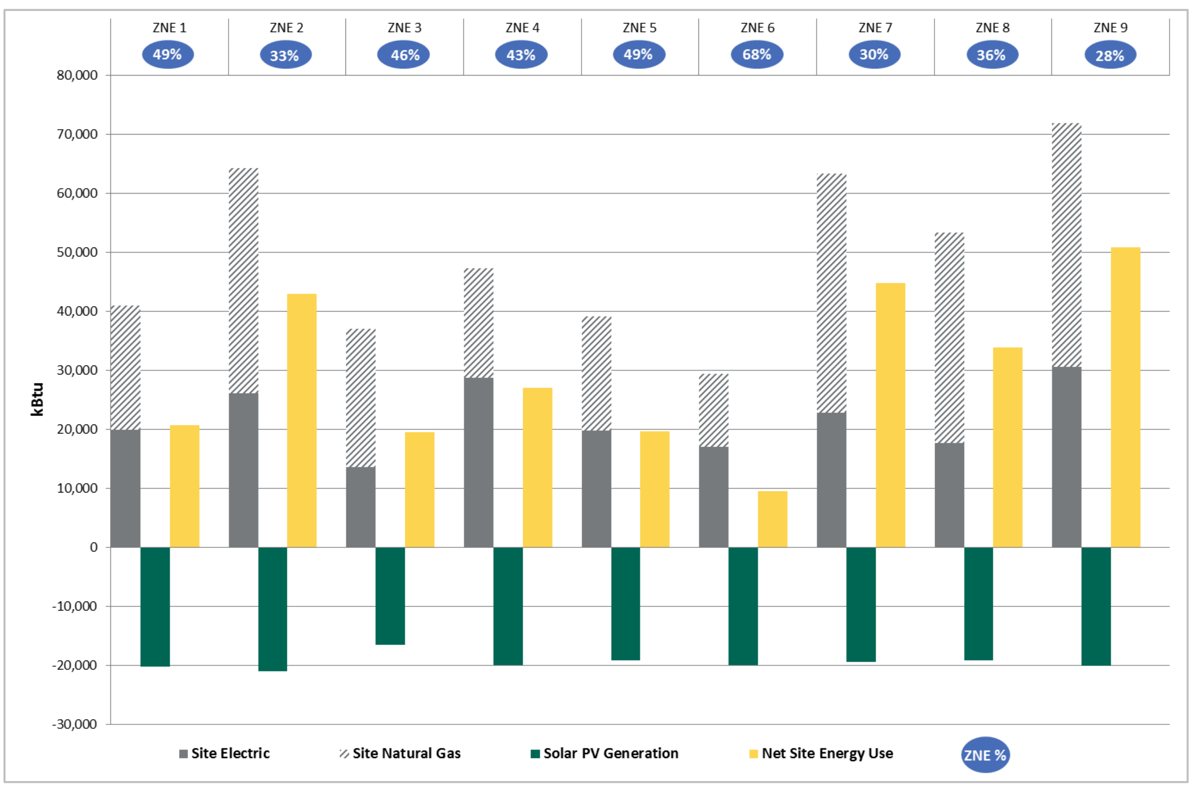
[5] In the calculation of energy saving, the following heat pump adjustment approach was used: (1) If there is no air conditioning use in the baseline (i.e., 2012), remove all heat pump use; (2) if there is air conditioning, remove November to February heat pump usage only. In addition, charging station usage and losses due to RESU are not included. To calculate source energy equivalent, EPA suggests one kWh of electricity from onsite solar PV generation offsets 3.14 kWh of natural gas source equivalent energy (Irwin and Yinger, 2015).



(Source: Irwin and Yinger, 2015)

Figure 7 Combined 22-home coincident peak (kW)

Figure 8 shows the ZNE status for homes in the ZNE Block based on site energy for a period of a year starting on November 1, 2013. The ZNE status represents a home's progress toward achieving ZNE. The ZNE status is equal to a home's solar PV generation divided by its total energy consumption (i.e., electricity and natural gas energy use). As an example, ZNE 1's ZNE status is 49%, which is equal to 20,153 kBtu (solar PV generation) divided by 40,882 kBtu (total energy consumption).



(Source: Irwin and Yinger, 2015)

Figure 8 ZNE Site Energy Status for ZNE Block Homes (November 1, 2013 to October 31, 2014)

SCE reported that the actual ZNE status of homes, measured in the test period, is nearly 50% below what the SCE team originally forecasted by using eQUEST simulation model[6] (see Figure 8). The difference is believed to result from technical assumptions in the calculations, such as using higher PV arrays and solar hot water capacities than installed, not including RESU and possible related efficiency losses in the analysis, and behavioral changes. In its prospective analysis, the SCE team assumed that the energy efficiency improvements and DR measures applied in each of three blocks are cost-effective, and the team sized the solar PV array to offset the remaining customer load. Using a RESU to store energy was not included in the original plan.

For Sub-Project 4, the 2.6 % energy savings rate demonstrated in these field experiments were applied to the seven circuits, which serve roughly 8300 customers, served from MacArthur substation.

Shaving of peak load would postpone, reduce, or even eliminate the need to install expensive generation and T&D capacity. In addition, peak load tends to drive delivery losses more than average load; thus, managing the peak, i.e., reducing maximum demand and flattening the load curve, leads to improvements in electricity delivery efficiency. All sub-projects investigated in this paper help decrease peak load. The technologies implemented in Sub-project 1 reduces the peak based on efficient appliance usage, demand shift, PV generation, and battery discharge at peak times. The 2 MW battery can be discharged at peak hours in Sub-project 3, and optimizing voltage/VAR control in Sub-project 4 also reduces the peak demand and the amount of T&D losses.

Benefits for the environment relate to CO_2 emissions' and other pollutants' damage costs. Estimation relies on physical quantification of the emissions and subsequently on their conversion to monetary costs, using California carbon and pollutant costs.[7] Increased consumer awareness of electricity use and decrease in electricity consumption achieved through improved efficiency of smart appliances reduces both the electricity generation required and the associated emissions. PV panels provide electricity without CO_2 emissions, contributing to the reduction of overall CO_2 emissions of Sub-project 1. Electricity reductions based on improved efficiency and energy conservation voltage reduction in Sub-project 4 reduce generation and associated emissions. There is also potential for emissions reductions by decreasing peak, although calculation of emission reductions in the EPRI method is based only on consumption reduction and excludes peak reduction.

NPVs for total costs and benefits of each Sub-project are summarized in Table 6. Results appear to be significantly different among the sub-projects analyzed here. The overall B/C ratio of Sub-project 1 is 0.1 (with -$3.6M annual net benefits), while Sub-Projects 3 and 4 have B/C ratios of 2.5 (with $1.3M annual net benefits) and 12.9 (with $6.8M annual net benefits), respectively. Moreover, Figure 7 shows present net benefits cumulatively over time, i.e., the cost of each year is the sum of that year's value plus all previous years. As can be seen, net benefits are far from turning positive in the investigation period for Sub-project 1, i.e. the blue line is always 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 91 % lower to achieve a B/C ratio greater than 1, i.e. breakeven. Nonetheless, a low B/C ratio is acceptable for a purely technology demonstration project, as Sub-project 1, in which most of the equipment installed is at an emerging stage requiring a steep learning curve. The ZNE Homes are very much a technology demonstration, and were not intended to reach breakeven. Recent announcements of residential battery cost reductions underscore

[6] For more information on eQUEST model, http://www.doe2.com/equest/

[7] We used $12/t$CO_2$ based on the average California carbon price in 2014 (http://calcarbondash.org/), $3000/tNOx and $250/tSOx, based on SGCT default data for Western Electricity Coordinating Council (Navigant, 2011).

the early vintages of the equipment installed in the 22 homes (Tesla, 2015). Nonetheless, B/C ratio results are still valuable for providing suggestive estimates of the cost-performance gap between current generation technology and breakeven, or viable commercialization. The EPRI method does not include uncertainty on cost reductions over time, which would be a welcome extension of these results. In addition, performing a separate B-C analysis for each technology group (i.e., demand response, energy efficiency measures, energy storage, and PV panels) could provide a better understanding on B/C ratio. Cost of some of the technologies such as energy storage dominates the overall cost of Sub-project 1 and prevents some other technologies from showing their benefit performances. For example, even though the demand response technologies could generate much higher B/C ratio when evaluated separately, it becomes invisible when combined with other group of technologies in the analysis. However, such analysis requires more detailed and disaggregated data, which were not available in this part of study.

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

Table 6 Total costs and benefits of each Sub-project (in NPV)

	Sub-project 1	**Sub-project 3**	**Sub-project 4**
NPV (of annual cost)	$(3.92M)	$(0.85M)	$(0.59M)
NPV (of annual benefit)	$0.34M	$2.14M	$7.58M
NPV (of annual net benefit)	$(3.59)M	$1.30M	$6.99M
B/C Ratio	0.1	2.5	12.9

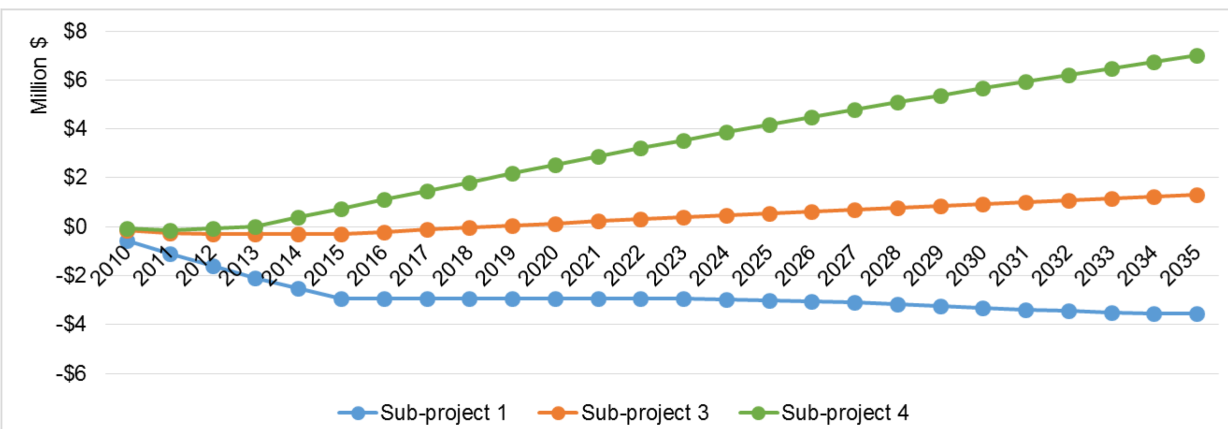


Figure 9 Cumulative net present benefits of each Sub-project

Figures 8 and 9 provide the breakdown of benefits. In both Sub-Projects 1 and 4 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 *Utility* in this Sub-project (see Figure 9); however, many would argue the EPRI method treats some of the *Consumer* benefits as *Utility* benefits, as explained above. For example, if energy procurement cost and operating cost are reduced, or capital investment is deferred, this saving may ultimately accrue to customers through subsequent reduced rates.

In addition, energy storage technologies (i.e., RESU and CES) in Sub-project 1 do not contribute reduction in electricity cost benefit, and they are responsible for 57% of the total project cost. Thus, it is beneficial to perform a separate sensitivity analysis and calculate B/C ratio by excluding energy storage. Since the benefits are highly dominated by reduction of electricity cost, the error margin in benefit calculation would be very small.

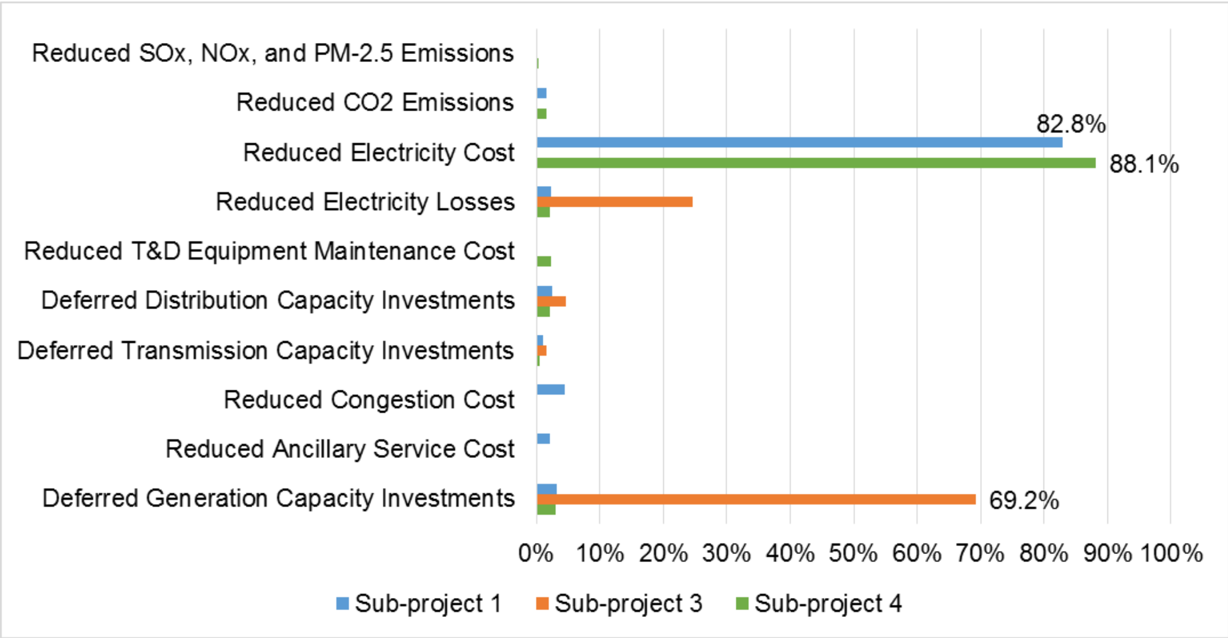


Figure 10 Distribution of benefits in each Sub-project

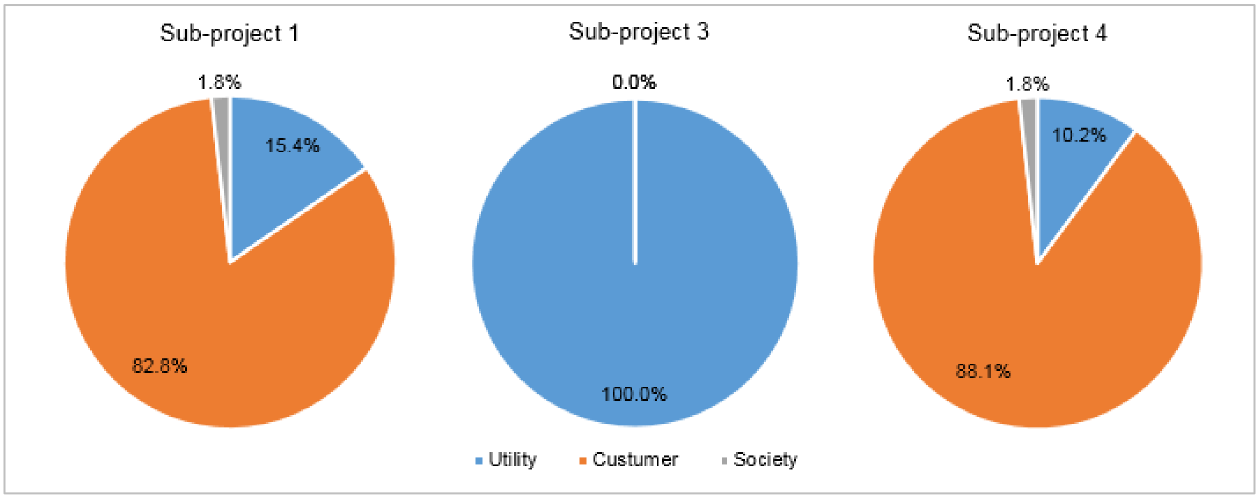


Figure 11 Distribution of benefits to stakeholders in each Sub-project

4.3. Sensitivity Analysis

Figure 12 compares the cumulative net present benefits of Sub-project 1 with and without energy storage technologies and also heat pumps. Heat pump is the second expensive technology in the project, listed after energy storage technologies (see Appendix). As can be seen, net benefits are improved when the energy storage technologies are excluded from the analysis with or without heat pump. However, they are still negative throughout the computation horizon. In addition, the results showed that the B/C ratio increased to 0.2 when only energy storage technologies are excluded, and 0.3 when energy storage technologies and a heat pump are together excluded, which are still very low to be an economically positive demonstration project.

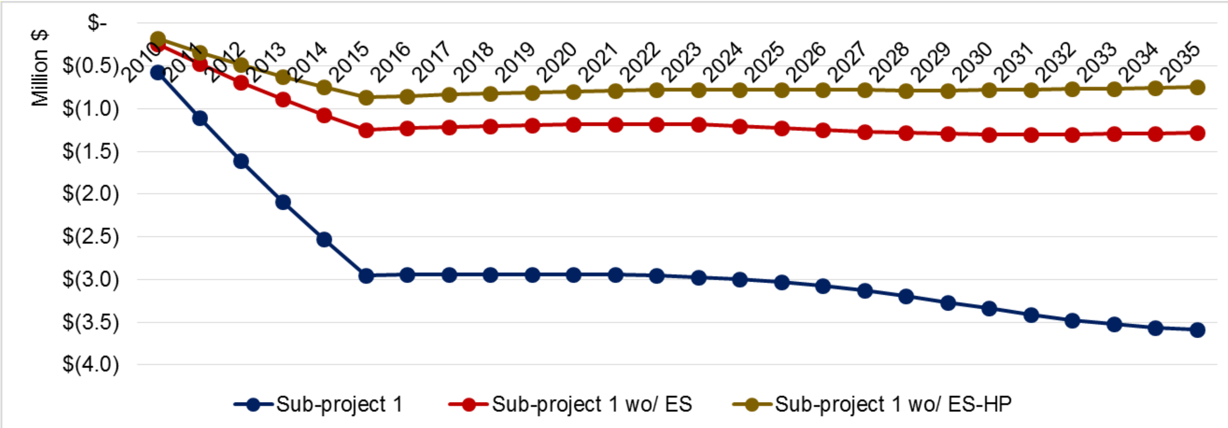


Figure 12 Cumulative net present benefits of Sub-Project 1 compared to the scenarios 'without Energy Storage Technologies' and 'without Energy Storage Technologies and Heat Pump'

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

The sensitivity of 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, since costs are incurred predominantly at the beginning of the scenario while benefits may be sustained over the long-term. Figure 10 and Table 7 illustrate the sensitivity of each case Sub-project to discount rate. Naturally, the results show that the higher the discount rate, the lower the NPV. Nonetheless, note that results are fairly robust and all NPVs are negative and all Sub-project 1 B/C ratios are close to zero regardless of the discount rate, while Sub-Projects 3 and 4 always generate positive NPVs and B/C ratios above breakeven.

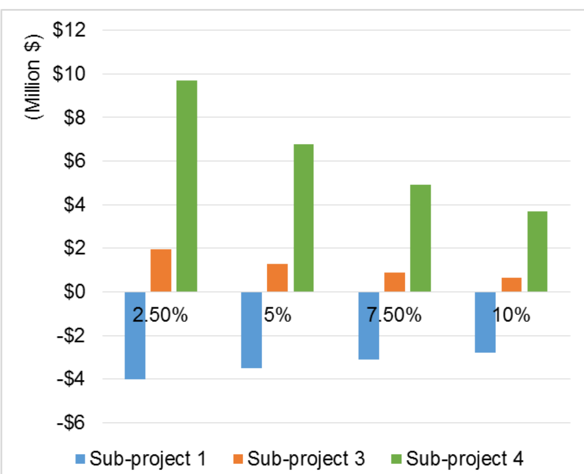


Figure 13 Sub-project NPVs with varying discount rates

Table 7 B/C ratios with varying discount rates

	2.5%	5%	7.5%	10%
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	14.42	12.94	11.00	9.61

5. Discussion

This example case analysis and the other international work summarized below show the SGCT has only limited ability to effectively compare B-C analysis results of international smart grid demonstration projects.

5.1. General limitations of the SGCT

Some of the functions identified are not necessarily mapped to the benefits listed in the SGCT as mentioned earlier. For example, the tool lists *Optimized Generator Operation* as a benefit from the *Distributed Production of Electricity* function for Sub-project 1. While distributed generation assets such as PV panels might allow utilities to remotely operate distributed generation systems to dispatch a more efficient mix of generation (Navigant, 2011), this seems unlikely in practice. Similarly, the *Automated Voltage and VAR Control* function is never linked to *Reduced Electricity Cost* benefit, while field experiments show a notable potential decrease in electricity bills, and the results in Section 5 reflect this large benefit. The NPV of Sub-project 4 is about $7M, and 88 % of it comes from *Reduced Electricity Cos*t. Similarly, there may be some other benefits that are not listed but should be included in a thorough B-C analysis. For example, batteries are not allowed to generate a reliability benefit, when their provision of emergency power is clearly one of their desirable features. In other words, that the set of available benefits incorporated in the SGCT is necessarily limited causes a *de facto* bias, that is, the set is likely to be incomplete.

The SGCT is intended to be generally applicable to highly diverse projects, and consequently it is inevitably too generic to address the subtleties of any particular one. Variations in the nature and the scope of the ISGD project are not well considered, and indeed all projects are effectively evaluated on the same criteria set. Because the tool is locked and considered proprietary, no customization specific to a particular project is possible. This limitation places a heavy burden on the user to design exogenous analysis of any benefits and mechanisms whose exclusion is suspected to be a significant limitation, particularly so for international applications.

Among the other analysis limitations that emerged in the analysis of the ISGD project are the following:

- By including only the kW capacity of energy storage, the model overstates the value of capital deferrals for energy storage. Battery discharge cannot necessarily lower peak by the full discharge power because it may not store enough energy to sustain this reduction throughout high load periods. In other words, models should consider both the power and energy constraints of storage.
- Efficiency parameters for energy storage systems are not included in the model. Thus, the SGCT is not capable of tracking these losses.
- Tariff representation is basic, without time differentiation of energy or demand charges. This limitation can have a significant effect on the attractiveness of technologies. Customer benefits could be greater by including time-based rates.
- Treatment of uncertainty is limited, and notably does not allow sensitivity analysis on some key variables, such as project capital cost, and some project costs are not included at all, e.g. installed equipment maintenance and operational costs. Possible price reduction due to future technological change is also uncertain and not considered in the EPRI method or the SGCT.
- Modeling of costs is inadequate because no failure probability or equipment lifetime is possible.
- Nothing on scaling up of projects is provided; in other words, the project can be analyzed only in isolation without consideration of its likely merits in wider scale deployment.
- Categorization of benefits under stakeholders is not necessarily correct, although a correct allocation is a non-trivial task. The EPRI method treats some of the *Consumer* benefits as *Utility*

benefits, since they accrue initially to the distribution company. All cost reductions in operational, maintenance and capital investments are considered *Utility* benefits. Over time, as rates are adjusted to match the changing cost structure, customers may ultimately benefit, whether or not they are project participants.

- Nothing on possible reduction of benefits due to aging of physical infrastructure or software, or unexpected damage, is available.
- Calculation of emission reduction is based only on consumption reduction; however, there is also potential for emissions reductions by decreasing peak.
- The discount rate is constant. Some studies in the literature suggest using a lower rate to discount costs and benefits that accrue decades in the future.

Finally, it should be repeated that the balance between consistency and wide applicability is not easily struck, and any tool intended for such a wide range of projects included in the SGIG Program and the SGCP will necessarily not satisfy the detailed needs of any individual project.

5.2. Application of the SGCT to the Tianjin Eco-City

Smart Grid projects are being demonstrated worldwide, and this study has been conducted in the context of U.S.-China cooperation on energy and climate change. The U.S.-China Joint Announcement on Climate Change released on 21 November 2014 specifically mentions smart grid among the additional measures planned to strengthen and expand cooperation. Existing research vehicles, in particular the CCWG, the U.S.-China Clean Energy Research Center, and the U.S.-China Strategic and Economic Dialogue will be utilized to foster coordination and cooperation between the countries (White House, 2014).

> "**Demonstrating Clean Energy on the Ground**: Additional pilot programs, feasibility studies and other collaborative projects in the areas of building efficiency, boiler efficiency, solar energy and smart grids."

The 31 km^2 Tianjin Eco-city project, which is planned to ultimately accommodate 350,000 residents, was selected as one of the two demonstration projects from China to be part of the CCWG smart grid B-C analysis demonstration projects. The Sino-Singapore Eco-city is located in Binhai New Area, close to the Economic-Technological Development Area and the Port of Tianjin.

This project integrates renewable energy, automatic control, microgrid and energy storage systems, intelligent building, combined heating, cooling and power, geothermal heating, cool storage, and other smart grid technologies to achieve efficient use of energy. The CCWG Benefit Subgroup is collecting data to complete a B-C analysis of the Tianjin Eco-city project and compare benefits approaches and results for projects in China and the U.S. However, the SGCT is designed for assessing U.S. smart grid projects, and the assumptions are mainly based on the U.S. situation. International application of this approach will likely focus on using the EPRI method embodied in other modes, as the example below shows.

5.3. Application the EPRI Method by the Joint Research Center

The European Commission's Joint Research Centre (JRC) has more than 450 active smart grid projects with more than 3 billion EUR invested since 2002. In Europe, JRC proposed an assessment framework for smart grid projects which includes defining boundary conditions, identifying costs and benefits, and performing sensitivity analysis (Giordano et al., 2012). This guidance also includes the costs and benefits derived from broader social impacts such as security of supply, consumer participation, and improvements to market performance, etc. JRC adapted the EPRI method to the European context and made it more relevant by using project specific factors such as geography, typology of consumers, and regulations. A new report discussing the first application of B-C analysis to the City of Rome has recently been released (Vitiello et al., 2015).

Other international applications and comparisons would enable further in-depth discussion of the methods and tools for B-C analysis of smart grid projects, and approaches to result dissemination. The findings from doing such analysis and comparison will help to identify the best practices and industrial trends for implementing smart grid technologies and facilitate policy making to scale up smart grid deployment.

6. Conclusion

This exercise was conducted within a broader bilateral effort to compare the benefits of a two U.S. microgrid projects to Chinese cohorts, and to demonstrate the methods developed and applied in both countries. This first U.S. analysis is intended to demonstrate the capabilities of the SCGT via an example analysis of three ISGD subprojects, which are the type of ARRA project for which the tool was developed Initial results show significant benefits potential for two technologies, distribution voltage and VAR control and utility-scale batteries, while the third 22-residence ZNE home demonstration inspired by California's 2020 residential energy efficiency standard falls far short of economic breakeven at the current stage of costs and technology performance. It should be emphasized that the ZNE homes subproject was not based on economic objectives but was rather intended to be a technology demonstration. Consequently, the cost of the installed equipment was very high, and the energy savings, especially of natural gas use, are disappointingly small. Based on this limited experience, the strengths of the SGCT are its simplicity and explicit and transparent mappings, its clear definitions of technologies, and access to the formulas behind them in the literature. Its weaknesses are actually the other side of the same coin, namely its inflexibility and poor applicability to projects outside straightforward technology deployment or outside U.S. conditions. The model is locked and considered partially proprietary by Navigant Consulting Inc., which is a major impediment to its broad application, especially internationally.

Acknowledgements

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Appendix

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

Figure A 1 Smart grid assets and functions considered in the EPRI methodology and listed in the SGCT

Benefits			Fault Current Limiting	Wide Area Monitoring, Visualization, and Control	Dynamic Capability Rating	Power Flow Control	Adaptive Protection	Automated Feeder and Line Switching	Automated Islanding and Reconnection	Automated Voltage and VAR Control	Diagnosis & Notification of Equipment Condition	Enhanced Fault Protection	Real-Time Load Measurement & Management	Real-time Load Transfer	Customer Electricity Use Optimization	Storing Electricity for Later Use	Distributed Production of Electricity
			Functions														
Economic	Improved Asset Utilization	Optimized Generator Operation		•												•	•
		Deferred Generation Capacity Investments													•	•	•
		Reduced Ancillary Service Cost		•						•			•		•	•	•
		Reduced Congestion Cost		•	•	•									•	•	•
	T&D Capital Savings	Deferred Transmission Capacity Investments	•	•	•	•									•	•	•
		Deferred Distribution Capacity Investments			•								•	•	•	•	•
		Reduced Equipment Failures	•		•						•	•					
	T&D O&M Savings	Reduced T&D Equipment Maintenance Cost									•						
		Reduced T&D Operations Cost						•		•							
		Reduced Meter Reading Cost											•				
	Theft Reduction	Reduced Electricity Theft											•				
	Energy Efficiency	Reduced Electricity Losses				•				•			•	•	•	•	•
	Electricty Cost Savings	Reduced Electricity Cost													•	•	•
Reliability	Power Interruptions	Reduced Sustained Outages					•	•	•		•	•	•			•	•
		Reduced Major Outages		•					•				•	•			
		Reduced Restoration Cost					•	•	•		•	•	•				
	Power Quality	Reduced Momentary Outages										•				•	
		Reduced Sags and Swells										•				•	
Environmental	Air Emissions	Reduced CO_2 Emissions				•		•		•	•		•	•	•	•	•
		Reduced SO_x, NO_x, and PM-10 Emissions				•		•		•	•		•	•	•	•	•
Security	Energy Security	Reduced Oil Usage (not monetized)						•			•		•			•	
		Reduced Widescale Blackouts		•	•												

Figure A 2 Smart grid functions and benefits considered in the EPRI method and listed in the SGCT

Table A 1 Inputs used in SGCT calculations

Input Name		Source
Price of Capacity at Annual Peak	$50.17/kW-year	SCE, 2014
Ancillary Services Cost	$5/MWh	LBNL Assumption
Congestion Cost	$10/MWh	LBNL Assumption
Capital Carrying Charge of Transmission Upgrade	$310-370K/MVA	SCE expert opinion
Capital Carrying Charge of Distribution Upgrade	~$2.1M over 3 years/Distribution circuit	SCE expert opinion
Transmission Investment Time Deferred	1.5 (in baseline); 6 (in Test period)	LBNL Assumption
Distribution Investment Time Deferred	1.5 (in baseline); 6 (in Test period)	LBNL Assumption
Total Distribution Equipment Maintenance Cost	~$130K/year/new circuit ~$120K/year/new circuit	LBNL Assumption
Distribution Losses	4.8%	SCE expert opinion
Transmission Losses	2.7%	SCE expert opinion
Average Price of Wholesale Energy	$52.22/MWh	SCE expert opinion
Average Residential Electricity Cost	$0.17/kWh	SCE expert opinion
CO2 factor	0.28tCO2/MWh	2010 Carbon dioxide for WECC California (from eGRID; total output emissions rate)
SOx factor	0.000077tSOx/MWh	2010 Sulfur dioxide for WECC California (from eGRID; total output emissions rate)
NOx factor	0.000184tNOx/MWh	2010 Nitrogen dioxide for WECC California (from eGRID; total output emissions rate)
Value of CO2	$12/tCO2	California carbon price in 2014 (http://calcarbondash.org/)
Value of SOx	$520/tSOx	SGCT default data for Western Electricity Coordinating Council (Navigant, 2011)
Value of NOx	$3000/tNOx	SGCT default data for Western Electricity Coordinating Council (Navigant, 2011)
Efficiency of DBESS	90%	Based on SCE experts
Energy savings from DVVC	2.6%	Irwin and Yinger, 2015

Table A 2 Technology cost structure

Technology	Unit Investment Cost ($/unit)	Unit installation Cost ($/unit)	Incremental Cost Assumption	# of Assets Acquired	# of assets in the project
Energy Star Smart Refrigerator	$ 2,229.0	$ 706.4	40% of total cost* is used	23	21
Energy Star Smart Clothes Washer	$ 1,288.0	$ 706.4	40% of total cost* is used	22	20
Energy Star Smart Dishwasher	$ 1,357.0	$ 706.4	40% of total cost* is used	24	22
Programmable Communicating Thermostat	$ 118.0	$ 131.2		36	31
Home Energy Management System (home EMS)	$ 118.0	$ 808.6		27	22
In-Home Display	$ 118.0	$ 8,083.6		22	22
Central Air Conditioning Replacement (Heat Pump)	$ 4,200.0	$ 26,314.9		11	9
Lighting Upgrades	$ 1,262.5	$ 518.2	50% of the investment cost is used	700	700
Insulation	$ -	$ 1,666.7		9	9
Efficient Hot Water Heater	$ 2,000.0	$ 33,252.0	40% of total cost* is used	2	2
Domestic Solar Hot Water and Storage Tank	$ 2,000.0	$ 4,101.0		7	7
Solar Panels for Water heaters	$ 2,312.0	$ 5,591.0		7	7
Low Flow Shower Heads**	$ 118.0	$ 808.6		9	9
Plug Load Timers**	$ 118.0	$ 808.6		22	22
Community Energy Storage Unit	$ 22,865.1	$ 3,061.6		1	1
Residential Energy Storage Unit with Smart Inverter	$ 61,300.0	$ 5,358.8		18	14
CES By Pass Switch	$ 2,237.1	$ 3,061.6		1	1
CES - Intelliteam DEM Controller	$ 10,207.1	$ 3,061.6		1	1
3.2 – 3.6 kW Solar PV Panels	$ 18,486.8	$ 18,253.3		113	113
3.9 kW Solar PV Panels	$ 9,816.0	$ 9,692.0		108	108
DBESS and equipment	$ 642,477.0 (total unit cost)			1	1
DVVC license and equipment	$ 359,266.0 (total unit cost)			1	1

Source: SCE experts, *total cost = unit investment cost + unit installation cost, ** There was no available cost data. Costs of Home Energy Management System (home EMS) are repeated for Low Flow Shower Heads and Plug Load Timers

Table A 3 Technology lifetime

Measure Name	Lifetime (years)	Source
Energy Star Smart Refrigerator	14	Demesne, 2010
Energy Star Smart Clothes Washer	14	Demesne, 2010
Energy Star Smart Dishwasher	10	Demesne, 2010
Programmable Communicating Thermostat (PCT)	30	InterNachi, 2015
Home Energy Management System (home EMS)	10	LBNL Assumption
In-Home Display	10	LBNL Assumption
Central Air Conditioning Replacement (Heat Pump)	12	Zogg, 2014
Lighting Upgrades	13	BTP DOE, 2015
Insulation	whole project assessment time (i.e., 25 years)	Diez, 2014
Efficient Hot Water Heater	12	Lowe's, 2015
Domestic Solar Hot Water and Storage Tank (SHW)	30	Home Energy Saver, 2015
Solar Panels for Water heaters	20	Energy Star, 2015
Low Flow Shower Heads	30	InterNachi, 2015
Plug Load Timers	10	Mallery, 2013
Community Energy Storage Unit	10	Schoenung, 2011
Residential Energy Storage Unit with Smart Inverter	15	Schoenung, 2011
CES By Pass Switch (CES_b)	30	Mallery, 2013
CES - Intelliteam DEM Controller	15	InterNachi, 2015
3.2 – 3.6 kW Solar PV Panels	30	Strecker, 2011
3.9 kW Solar PV Panels	30	Strecker, 2011
DBESS and equipment	15	LBNL Assumption, based on Schoenung, 2011
DVVC license and equipment	15	SCE expert opinion