# TECHNICAL AND ECONOMIC POTENTIAL OF MICROGRIDS IN CALIFORNIA

By

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A Thesis Presented to

The Faculty of Humboldt State University

In Partial Fulfillment of the Requirements for the Degree

Master of Science in Environmental Systems: Energy, Technology, and Policy

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May 2017

ABSTRACT

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Microgrids are being investigated across the U.S. as a solution to support greater reliability, resiliency, and security of electricity supply. This thesis evaluates the potential of developing technically feasible and economically viable microgrids for selected customer categories in California.

Customer categories selected for this study are deemed suitable for microgrid applications by previous studies. For a customer to be technically suitable for microgrid adoption, this study defined a minimum energy requirement threshold. In order to determine the economically viable potential, a benefit-cost analysis was done to assess microgrid benefits compared to the base case of exclusive reliance on grid electricity. The fraction of the technical potential that was found to clear the benefit-cost analysis was considered as the economic potential.

A total of 1,224 sites in California with a cumulative microgrid hosting capacity of 7,480 MW were found to be economically feasible. The study also found that customers with one MW or more peak load are economically viable for hosting a microgrid. Availability of external funding can make microgrids economically feasible

for more customer groups, even for customers with peak load less than one MW, which otherwise are currently at the margin.

It is acknowledged that the customer categories selected in this study represent a subset of the possible customer categories. The cost of microgrid development, and especially the cost of microgrid controller, is highly uncertain as microgrids are a relatively new market. Hence, the emphasis of this thesis was to demonstrate a methodology for estimating of microgrid development potential in California rather than determining precise values.

ACKNOWLEDGEMENTS

I wish to express my gratitude to my supervisors, Dr. Arne Jacobson, Dr. Steve Hackett, and Dr. Charles Chamberlin for their support and guidance in conducting this research.

I thank Arne for providing mentorship throughout the degree program and for his ever helping attitude. His always smiling face oozed lot of positive thinking in my approach towards everything that I now do in life. In my two years in HSU, I always looked at him for any advice on educational, professional, and personal matters.

I express my gratefulness to Charles for his careful review and extremely thoughtful suggestions on the thesis. I especially thank him for his amazing promptness and thoroughness in responding to any requests, including the review of this thesis work. Interactions with Charles in the last two years have made me analytically better, detail oriented, and a logically improved person. Not taking any class from Charles while in HSU will be a lifelong regret.

I had the sheer pleasure to closely interact with Steve in the courses that he taught me. Steve, whom I believe, has one of the best humor senses, provided me insightful guidance from the early stages of my thesis. He helped me to visualize the research questions and break it down into smaller tasks. I thank him for recognizing the value of this work and for his constant encouragement.

My appreciations go to Schatz Energy Research Center (SERC) for providing me wonderful project opportunities to learn about microgrids. While I enjoyed interacting

with everyone at SERC, the notable mentions include Dr. Peter Lehman, Dr. Charles Chamberlin, David Carter, Jim Zoellick, and Douglas Saucedo. These are the people with whom I closely worked with at SERC. The constant faith shown in my abilities, and keeping me intimately involved in the project activities provided me excellent learning opportunities.

I thank my dear friend Jim for always listening to me when I wanted to be heard. The laughter and stories that we shared, bocce ball and tennis that we played, made this leg of my life's journey worth remembering.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

## LIST OF APPENDICES



## LIST OF APPENDIX TABLES



## LIST OF APPENDIX FIGURES

ABBREVIATIONS

Readers may find helpful the following list of abbreviations used in the thesis.

| | |
|---|---|
| ADR | Auto Demand Response |
| BCR | Benefit Cost Ratio |
| BESS | Battery Energy Storage System |
| BIP | Base Interruptible System |
| CAIDI | Consumer Average Interruption Duration Index |
| CAISO | California Independent System Operator |
| CEC | California Energy Commission |
| CHP | Combined Heat and Power |
| CIGRÉ | Conseil International des Grands Réseaux Electriques |
| CPUC | California Public Utilities Commission |
| DER | Distributed Energy Resource |
| DG | Decentralized Generation or Distributed Generation |
| DERCAM | Distributed Energy Resources Customer Adoption Model |
| DOE | U.S. Department of Energy |
| DR | Demand Response |
| EIA | Energy Information Administration of United States |
| EPA | Environment Protection Agency of United States |
| EPRI | Electric Power Research Institute |
| GTM | Green Tech Media |
| HOMER | Hybrid Optimization of Multiple Energy Resources |
| ICE | Interruption Cost Estimate |
| IEC | International Electrotechnical Commission |
| ITC | Investment Tax Credit |
| kW | Kilo Watt |
| kWh | Kilo Watt Hour |
| LBNL | Lawrence Berkeley National Laboratory |
| LCOE | Levelized Cost of Energy |
| MDT | Microgrid Design Toolkit (MDT) |
| NEM | Net Energy Meter |
| NPV | Net Present Value |
| NREL | National Renewable Energy Laboratory |
| NYSERDA | New York State Energy Research and Development Authority |
| ORNL | Oakwood Ridge National Laboratory |
| PCC | Point of Common Coupling |
| PG&E | Pacific Gas and Electric |

| | |
|---|---|
| SAIDI | System Average Interruption Duration Index |
| SAIFI | System Average Interruption Frequency Index |
| T&D | Transmission and Distribution |
| TMY | Typical Meteorological Year |
| WACC | Weighted Average Cost of Capital |

# INTRODUCTION

The traditional electricity distribution system was primarily designed to provide electricity supply in one direction, wheeling electricity from large centralized generation sources to customers via networks of transmission and distribution (T&D) lines. This structure often known as “grid” or “macrogrid” was hugely successful for decades in meeting the electricity requirement of customers. However, with aging infrastructure, diminishing economies of scale, and proliferation of distributed energy resources (such as solar, wind, battery storage, etc.), the traditional electricity supply model is under stress. The addition of distributed energy resources (DERs), especially resources that are connected “behind the meter,” raises a variety of concerns for the traditional grid. One choice is to modernize the existing grid, but a question arises if this is the only option or if other alternatives are available.

Microgrids are emerging as solutions that can supplement the macrogrid or serve as a stand-alone power system. A microgrid is a system in which DERs serve loads in a local area using smart automation and communication schemes in a way that is compatible and coordinated with the existing “macrogrid" infrastructure. Microgrids represent a concept that is quickly gaining momentum in the utility sector. Several states in the US are working on a number of microgrid research, demonstration and development projects (LBNL, 2007). The US armed forces have more than 120 microgrids in operation and are pursuing a security-driven strategy to maximize their

energy independence (ACORE, 2014). In general, microgrids provide a unique opportunity for utilities to rethink the way they build their infrastructure.

In order to meet the ambitious target of 80% reduction in GHG emissions under the California Global Warming Solutions Act of 2006 (AB 32), the state has mandated achievement of 50% renewable energy (RE) penetration in the grid by 2030. Among several other solutions that can potentially support integration of distributed renewable energy resources, microgrids are also being seen as one of the promising solutions. With the help of demonstration projects, some studies are done to identify and quantify benefits from individual microgrid projects in California. However, no study exists in the public domain that has quantified the market deployment potential of microgrids. The diversity of microgrid characteristics complicates this problem. The purpose of this thesis is to estimate the potential of technically feasible and economically viable microgrids in the state of California. The scope of the research and analysis covers two distinct objectives as mentioned below:

1. Determination of the technical potential (in # of sites, MW capacity) of microgrid adoption with a focus on 'early adoption' application potential. The research will focus only on existing customers with energy requirements greater than a certain minimum threshold. This threshold is defined in the methods section.

2. Determination of the economic potential (in # of sites, MW of capacity) of microgrids in California. Economic potential is the fraction of the technical potential that is cost-effective to build. Microgrids will be economic to those customers that are currently being serviced from the macrogrid but can be substituted by microgrids in

future, in whole or part if cheaper. In addition to cost savings by substituting macrogrid with microgrids, any additional services that microgrids can facilitate and are easily quantifiable are included in the revenue stream of microgrids.

The diversity of microgrid types, size, design features, and ownership models were some of the key challenges experienced by the author while conducting this study during the study. Throughout the thesis, the author made attempts to define and standardize terms that are assumed for the purpose of this study.

The literature review section provides a relevant overview of the microgrids. The section provides a description of microgrids types, microgrid controllers, ownership types, and benefits generated by microgrids. This provides a useful background for establishing methods for conducting the study. The approach and method are described in the methods section of the thesis. The results and discussion section presents the findings conducted using the methods adopted for the study. This section also presents the implications of the findings. The thesis concludes by providing areas of improvements and further investigations needed.

# LITERATURE REVIEW

This section provides a description of microgrids types, microgrid controllers, ownership types, and benefits generated by microgrids. Microgrid researchers have developed a number of definitions and criteria, and the two noteworthy definitions are mentioned below.

## Microgrids Definition

U.S. Department of Energy Microgrid Exchange Group defines a microgrid as:

> "A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode" (Dan & Smith, 2013).

Conseil International des Grands Réseaux Electriques (CIGRÉ), the Council on Large Electric Systems, is an international non-profit association for promoting collaboration with experts from all around the world. The CIGRÉ C6.22 Working Group on Microgrid Evolution Roadmap defines that:

> "Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded" (CIGRE, 2010).

In neither definition there is there reference to the type of DER technologies involved, nor is there any guidance on the size of microgrids. The focus of the two definitions mentioned above is on the following two features:

1. Microgrids are locally controlled systems.

2. Microgrids can function both connected to the macrogrid or as electrical islands.

The ability to disconnect from the macrogrid and provide autonomous power either intentionally or under forced events, such as during power outages or other emergencies, is one of the distinguishing features of a microgrid. Other features are described below.

## Microgrids Features

Lack of a consistent definition and clearly specified desired characteristics of microgrids are issues that have perplexed the industry. For the purposes of this thesis, a microgrid is considered as a conglomeration of small generation source(s) and/or energy storage device(s), and load(s) that operate as a coherent system and connects to macrogrid as a single point load. The fundamental features of microgrids that are used in this thesis can be stated as follows:

1. Area: The beneficiaries or customers are confined in a small geographic footprint. To give a perspective, typically the size should not exceed the size of a university campus or a small town.
2. Criteria: The microgrid should have more than one DER under normal operation. A DER could be a renewable or non-renewable based generation source or an energy storage technology. If generators are used for back-up power purpose only, then they will not be counted as a DER towards meeting this criterion.

3. Operation: The system can operate in two modes: 1. normal mode where micro-grid and macro-grid are synchronized in operation, 2. island mode where micro-grid is working autonomously due to planned or unplanned outage of the macro-grid. These modes are described in the next section.
4. System Management: The microgrid has a control system to coordinate interaction between the microgrid and the macrogrid and to operate DERs in an integrated, stable, economic, and environment friendly fashion.
5. Load Control: The microgrid control system has the ability to enable prioritization of electricity supply to critical (essential) services and de-prioritization of non-critical services in case of an emergency.
6. Grid Interface: The microgrid has a point of common coupling (PCC) with the macrogrid. For the macrogrid, the microgrid is seen as a single controlled entity. A switch that separates the microgrid from the macro-grid automatically or manually is used to allow the micro-grid to function independently of the grid (Figure 1).

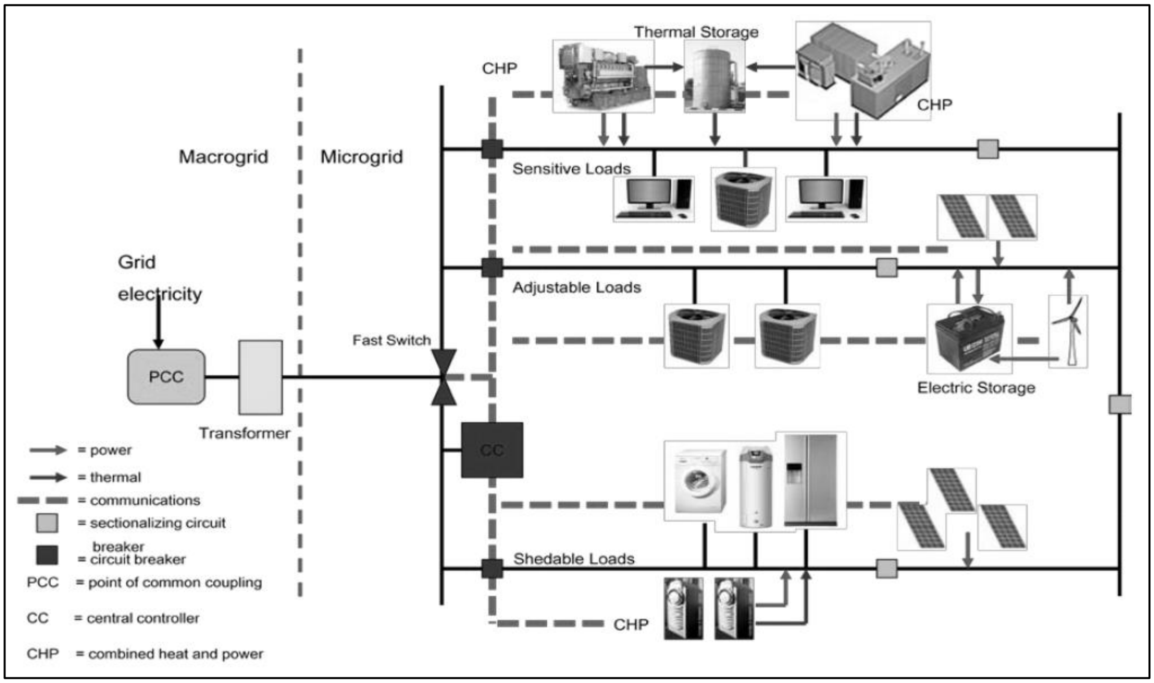



Figure 1. Schematic of a microgrid. The schematic shows the distributed energy resources, the point of common coupling with the macrogrid, and central controller. Source: (NYSERDA, 2010)

Some optional features not covered in the list described above but that could be characteristics of microgrids are as follows:

1. Microgrids could be single-user or multi-user based. This thesis covers both.
2. The DERs in a microgrid could be renewable based or non-renewable based or a mix of both. This thesis is focused on renewable DERs.
3. Microgrids could provide electrical energy as well as thermal energy to loads depending on the type of DERs used. However, this thesis is focused on electrical loads only.

Microgrids can work in two distinct modes or states depending on the status of the grid availability or a deliberate choice of the operator. The two operation modes are described below.

## Microgrids Operation Modes

Grid connected mode: This mode reflects the normal business-as-usual condition where the microgrid is connected to the main grid and uses grid electricity and onsite generation in parallel. In this mode, there is a possibility for the power to flow in both directions, i.e., from the utility grid into the local microgrid system (import) and from the local microgrid system back into the utility grid (export). The decision regarding functioning of the microgrid is orchestrated by a microgrid controller.

Island or Stand-alone mode: This mode is used when the utility grid is not available. The function of the island mode is similar to back-up power. The grid unavailability could be temporary (nuisance outage) or could continue for an extended period (emergency outage). These interruptions could be due to a planned maintenance activity on the grid or could be a result of an unplanned event. The controller coordinates the transition from grid tied mode to island mode, reconnects the islanded microgrid with the grid when it is available, and chooses the operation of the DERs.

The motive for developing microgrids in the past was to act as stand-alone power systems for locations that are geographically separated from macrogrid. While microgrids continue to be in use for electrically remote locations and new ones are developed for

isolated locations, these days microgrids are also considered as a supplemental source of energy for locations that are already grid connected. Classification of microgrids into various types is discussed below.

## Microgrid Classification

The purpose behind grid connected microgrids development is to reduce reliance on the traditional grid system, lower energy costs, provide reliable power to critical loads, and enable island operation during grid disruption. As per Lawrence Berkeley National Laboratory (LBNL), microgrids can be distinguished into the following two key types (LBNL, 2016a):

1. Customer microgrids or true microgrids are self-governed and are usually downstream of a single point of common coupling (PCC). Many of the most well-known demonstrations of microgrid systems are of this type. Just as a traditional customer has considerable leeway in the operation of the power system on its side of the meter, so the restrictions on the nature of a microgrid are relatively loose. For this reason, much of the early deployment of microgrid technology is of this type.
2. Utility or community microgrids involve a segment of the regulated grid. While, technically, they may not be different from microgrids, they are fundamentally different from a regulatory and business model perspective because they are integrated into utility networks.

Bloomberg’s research group divides microgrids into five categories (BNEF, 2017) shown below that are used in this thesis for analysis.

1. Commercial or Industrial: Such microgrids serve single users and are typically deployed by commercial and industrial customers. Single users include facilities like data centers, hospitals, airports, etc.
2. Campus or Institutional: These microgrids aggregate existing on-site generation with multiple loads that are co-located in a campus or institutional setting. Examples include university and corporate campuses, industrial parks, prisons, etc.
3. Community or Utility: Such microgrids serve multiple customers or services within a community. Examples include municipal utilities, water districts, and small sized load- serving entities. It is possible that such microgrids are integrated into utility networks rather than located behind a customer’s meter. In case of utility microgrids, it is also likely that the utility controls the system, and the distributed energy resources are subject to utility regulation.
4. Military: These microgrids are deployed with a focus on both physical and cyber security for military facilities to assure reliable power without relying on the macrogrid. Examples included installations of the U.S. Department of Defense (Navy, Air Force, etc.).
5. Off-grid or Remote: These microgrids are never connected to a utility network. Examples include power systems for islands, remote sites, and other unconnected locations.

Regardless of the classification, microgrids are typically managed by a smart controller often known as the microgrid controller. The sophistication and cost of the microgrid controller depends on the types of functions it is engineered to deliver.

## Microgrid Controllers

A microgrid controller, which serves as the heart of a microgrid, is responsible for optimally managing the distributed energy resources, energy storage systems, and responsive demand and for ensuring the microgrid is being operated in an efficient, reliable, and resilient way (ORNL, 2016). The controller is also a medium to consolidate all the monitoring, control, and communications of the microgrid. Since the industry is at a nascent stage, the controllers available in the market are not off-the-shelf products. Also, due to the absence of a recognized standard for such controllers, microgrid controllers provided by vendors have a range of functionalities. The functionalities are customized as per the type of services expected from the microgrid system. The following are the fundamental features expected from a microgrid controller system:

- Match load with generation in grid connected and island mode
- Maintain stability and reliability of the system by managing frequency and voltage
- Manage intentional and unintentional transitions between grid connected mode and island mode
- Monitor system operation and performance

- Activate alarm and event management activities in case of failures and faults

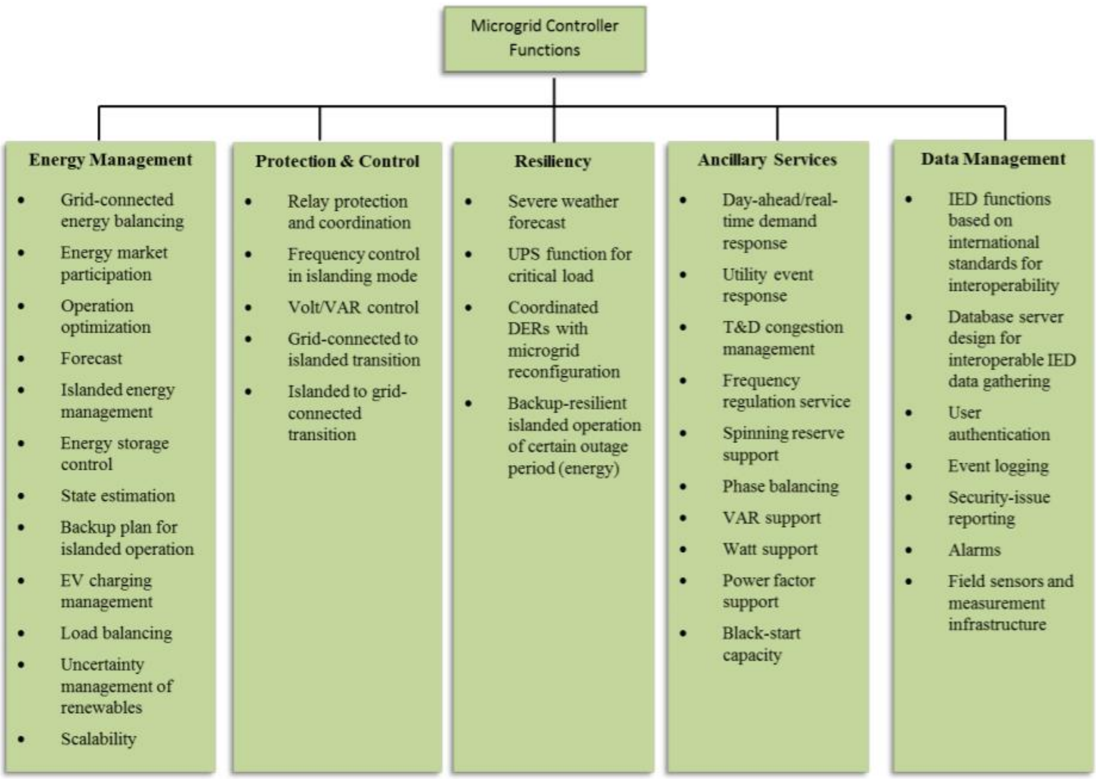
The following features listed for a microgrid controller are optional:

- Ability to segregate critical and non-critical loads
- Predictive and forecasting features for demand, generation availability, etc.
- Optimized operation based on an individual objective or a combination of economic and environment objectives
- Grid ancillary services such as demand response, voltage regulation, frequency regulation, and black-start support

ORNL has categorized microgrid controller functions into the following five major groups (ORNL, 2016), briefly described below.

- Energy Management: Balances power in steady state.
- Protection and Control: Provides voltage and frequency control.
- Resiliency: Aims to increase survivability of a microgrid under disturbances or severe weather conditions.
- Ancillary Services: Supports the interaction with the local utility or distribution system operator.
- Data Management: Addresses interoperability and data management.

Detailed functions or services included in these groups are shown in Figure 2, however these functions are not described in detail since the focus of this report is not on microgrid controllers.

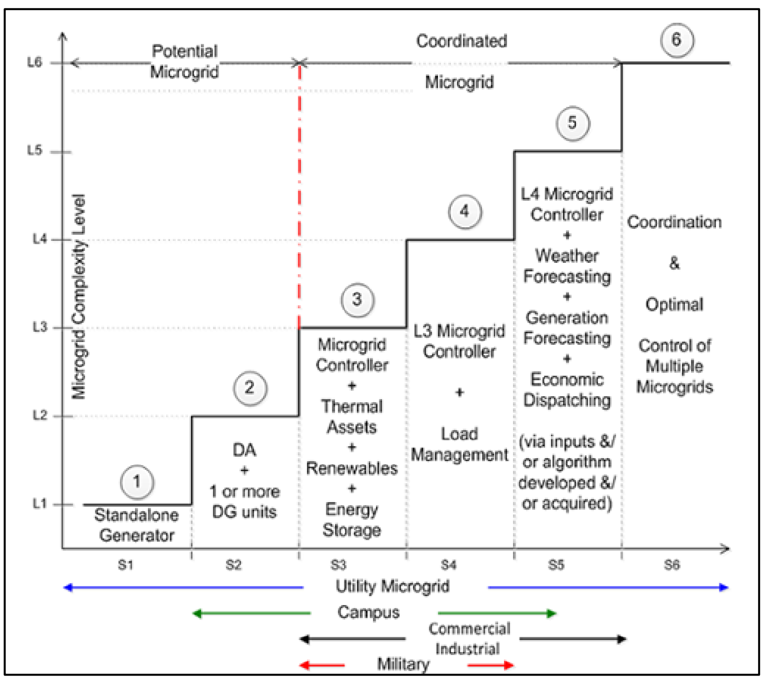



DER = distributed energy resource, EV= Electric Vehicle, IED = intelligent electronic device, T&D = transmission and distribution, VAR = volt-ampere reactive

Figure 2. Functions of a microgrid controller shown for illustration purpose. The functions are categorized into five broad groups—energy management, protection and control, resiliency, ancillary services, and data management. These functions include several sub-functions or services as shown in the figure. Source: (ORNL, 2016)

The functions illustrated in Figure 2 represent the entire plethora of functions that microgrid controllers could provide. It is evident that a customer may not seek every function, hence different levels of microgrids exist. Figure 3 shows the different levels of microgrids identified by S&C Electric

(https://microgridknowledge.com/microgrid-cost). The simplest level (L1) has a stand-alone generator, and the most advanced microgrid (L6) has multiple forms of generation, energy storage, sophisticated controller capabilities and even the ability to coordinate multiple microgrids (Figure 3). The L6 type microgrids are under development whereas microgrids of L3 through L5 are commonly referenced in literature and website sources. The fundamental features explained for a microgrid in the previous pages can be satisfied by a L3 controller. However, a customer would need a L5 controller if the optional features are also required. While evaluating the deployment potential of microgrids in California, this thesis has focused on the functions that can be provided by controllers of L3 through L5.




DA = distributed assets, DG = distributed generators or decentralized generators

Figure 3. Six levels of microgrid controllers based on complexity. L1 is the most basic controller with limited functions while L6 is the most complicated. Source: (S&C Electric as available on https://microgridknowledge.com/microgrid-cost)

Due to less information available in the public domain (business sensitive), it is hard to assess the current state of the industry. A survey conducted by the Microgrid Knowledge Center (microgridknowledge.com/) has identified the popular brands of controllers as perceived by the respondents (Figure 4). The top four brands are Siemens, Schneider Electric, ABB, and GE in decreasing order of popularity.

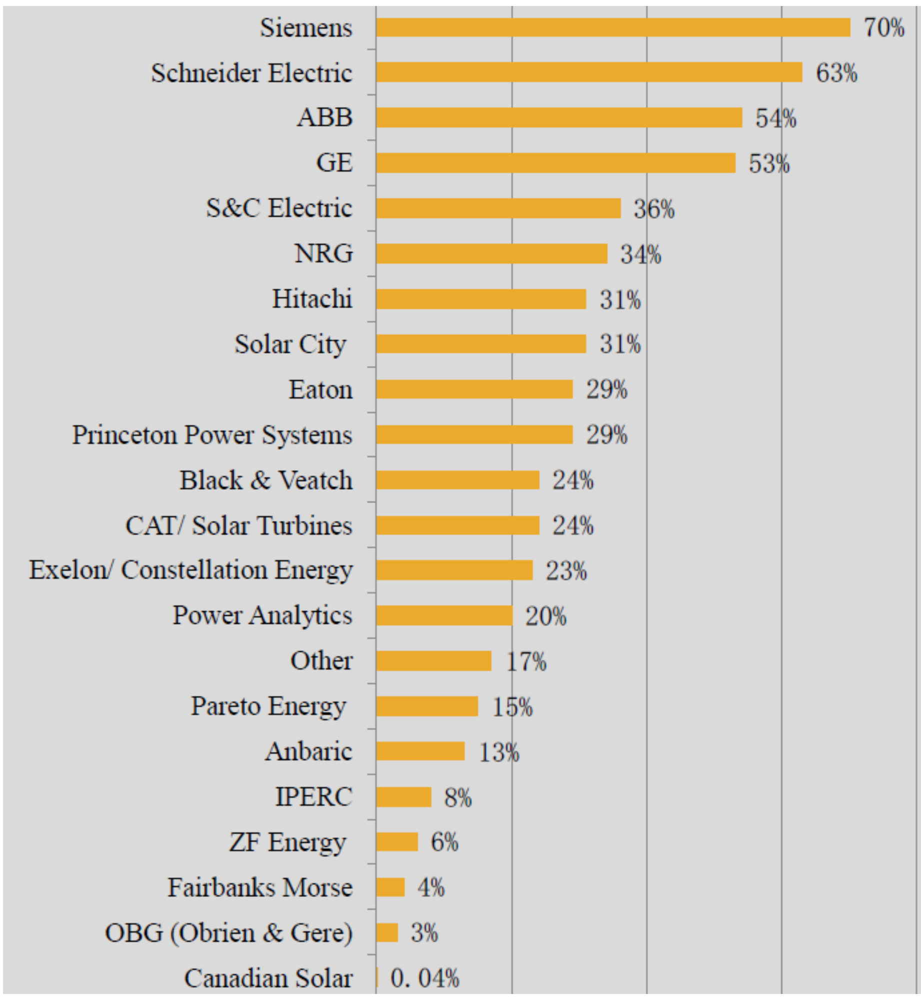



Figure 4. Brands that people associate most with microgrids. Siemens topped the list. Schneider was second and ABB third. The findings are based on an online survey conducted in 2016. Source: (Microgrid Knowledge Center, 2016)

For the purpose of economic potential estimation of microgrids development, which is the objective of this thesis, the author did a research on the top brands to gather information about estimated costs for microgrid controllers. A comparative analysis of the controller features offered by the top four brands is presented in Table 1. The information is compiled based on the author's understanding of controller information that is available publically. While vendors have laid claims to providing all functions (already developed or can be developed), a true comparison of the ability of a microgrid controller to perform these actions can only be demonstrated in real microgrid installations or in laboratories suitable for microgrids testing [Prabakar et. al, 2015].

Table 1. Comparison of functions of microgrid controller offered by top brands based on author's research of publically available information

| | **Siemens** | **Schneider Electric** | **ABB** | **GE** |
|---|---|---|---|---|
| **Product Name** | Spectrum Power™ MGMS | Advanced Microgrid Solutions | Renewable Microgrid Controller (MGC600) | Grid IQ™ Microgrid Control System |
| **Controller Level*** | L3 through L5 | L3 through L5 | L3 through L5 | L3 through L5 |
| **Information available** | Sufficient | Insufficient | Reasonable | Reasonable |
| **Energy Management** | Yes | Yes | Yes | Yes |
| **Protection and Control** | Yes | Yes | Yes | Yes |
| **Resiliency** | Yes | Could not be determined | Yes | Yes |
| **Ancillary Services** | Yes | Could not be determined | Yes | Could not be determined |
| **Data Management** | Yes | Yes | Yes | Yes |

* L3 has the capability to control multiple DERs; L4 in addition to the capabilities of L3, brings load management or load control options; L5 has the potential to do load forecasting, generation forecasting and economic dispatch or operation.

The generation constituents of microgrids could be of any technology, be it biomass, solar PV, diesel genset, natural gas based generation, storage, to name a few. However, a combination of solar and storage (solar-plus storage) is becoming attractive due to the declining prices of PV systems and energy storage technologies. While solar plus storage may not be the perfect solution for a microgrid, its versatility and scalability make it ideal for many facilities.

## Solar-Plus Microgrids

In their Clean Energy Group report, Seth Mullendore and Lewis Milford noted:

> "With steadily dropping costs in both solar and energy storage technologies, solar plus storage has become a viable and more neutral, reliable choice for emergency power. Not only do solar plus storage systems have the ability to provide power indefinitely when the grid is unavailable, they can also cut costs and generate revenue the other 99.9% of the time when the grid is functioning normally." (Mullendore and Milford, 2015).

A solar-plus microgrid refers to a topology where solar PV and storage technology are deployed behind the meter and satisfy the requirements of being a microgrid (Figure 5). With this logic, a utility-scale energy storage system deployed at a substation to manage solar variability of a PV plant is not a solar-plus microgrid, since the system will not support islanded operation of solar.

Solar-plus microgrids can experience stability issues in islanded mode due to low power system inertia of inverter based systems. Power system inertia is defined as the ability of a power system to oppose changes in system frequency due to resistance provided by rotating masses (Ørum et al. 2013). Inertia is dependent on the amount of

kinetic energy stored in rotating masses (of conventional generators) connected to the system. The stored inertia helps slows the decline in frequency when there is a sudden change in the generation or load of the system. PV solar and battery energy storage are connected to the system through power inverters which do not provide any inertia to the rest of the system. Hence, the control of frequency becomes a challenge, especially in an islanded mode compared to a grid-tied mode. However, with the evolution of microgrid controllers and fast response storage technologies, inverters can support stand-alone operation if the battery is properly sized. A storage unit can provide functionality similar to that of the inertia of a synchronous generator by absorbing temporary mismatches between power generation and demand. A detailed explanation of the challenges associated with microgrids was considered beyond the scope of this thesis.

PV = photovoltaic

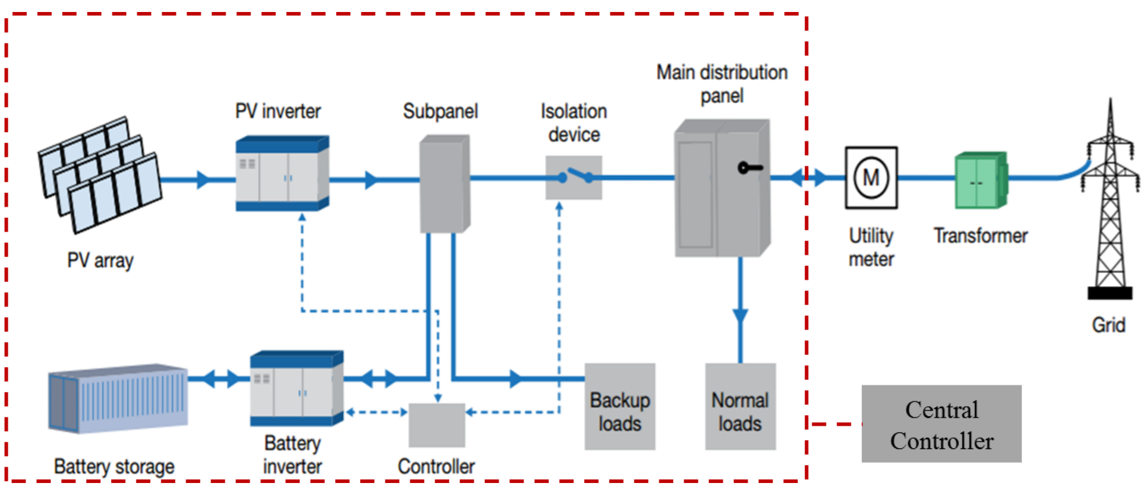



Figure 5: Illustrative schematic of a Solar-Plus microgrid that shows PV array and battery storage deployed behind the utility meter. The schematic also shows central controller to manage the control and operation of the microgrid. Source: (Mullendore and Milford, 2015). The image has been modified by the author to show a central controller.

The perspective taken in this thesis is one of technology neutrality. However, solar-plus microgrid is considered in this thesis for all illustration purposes. Solar-plus microgrids may not be the perfect solution for all customer types due to space availability and low system inertia, but the versatility, scalability, and modularity of PV and battery systems can make it ideal for many facilities.

The U.S. microgrid market is increasing and different ownership models have evolved as described below.

## Microgrids Ownership

- End-User owned: The microgrid is invested in by the customer or facility owner, and the operation and maintenance after the project completion are responsibility of the owner. The owner may have contracts with other parties such as with a utility for providing certain services.
- Utility owned: The utility invests in, owns, and maintains the microgrid assets. The utility may have contracts with a facility owner to avail certain services.
- Municipality or Community owned: The microgrid is owned by a municipality or a community. It is also likely that the utility controls the system. The owner may have contracts with utility for providing certain services.

- Third-Party owned: A party other than the customer or the utility owns the microgrid assets and sells energy and other services to the customer and/or utility.
- Multi-Stakeholder owned: Under this ownership model, multiple stakeholders type come together and invest in the system. It is possible that this type of microgrid can serve multiple customers, multiple customer meters, or multiple facilities. The earned revenues are shared among the investors.

Earlier, a majority of the microgrids were developed based on the End-User model. Figure 6 shows a trend in the U.S. installed microgrid capacity by ownership type. The end-user ownership dominated the mix until 2016 when other ownership models have also become popular. The reason for popularity of utility owned models is that utilities see microgrid as opportunities to replace their aging system and get the cost recovered through their rate base. Mixed ownership models are popular when long term power purchase agreements are attractive.

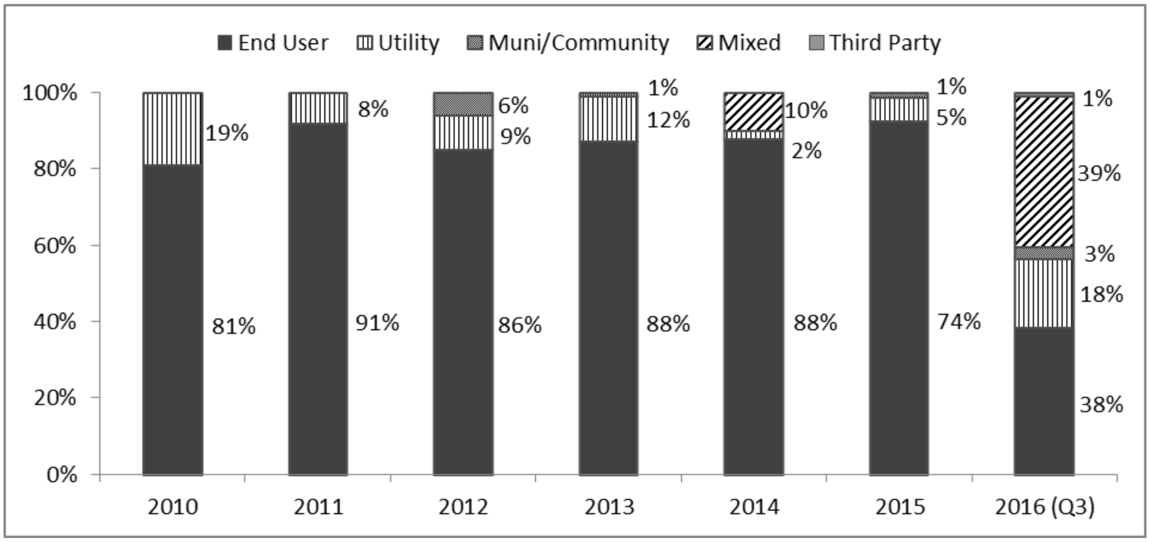
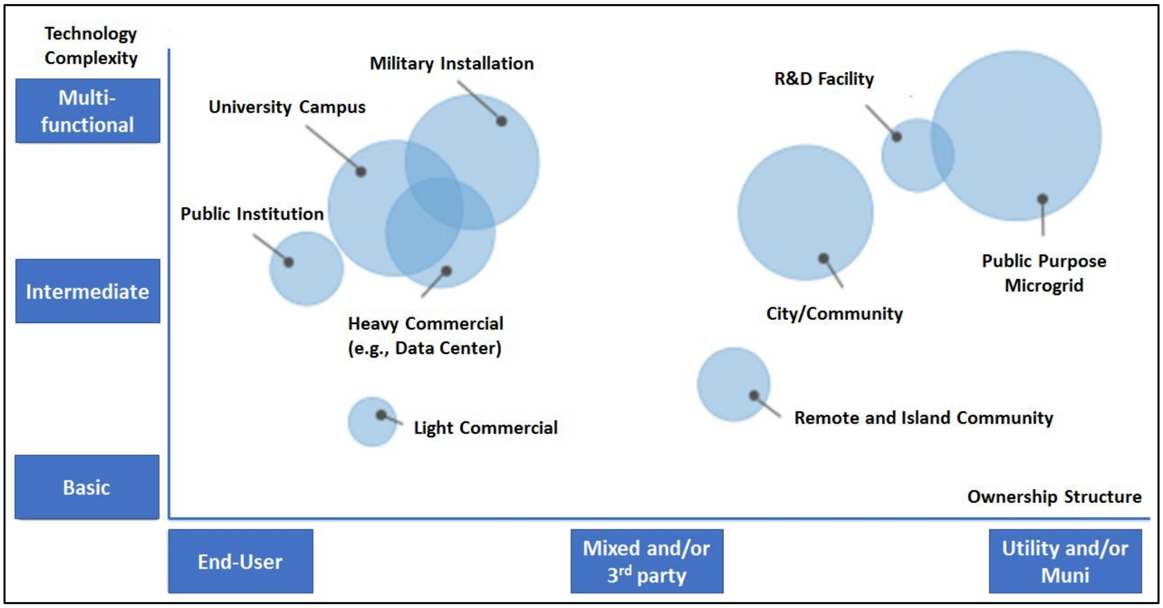



Figure 6: Trends in microgrid capacity by ownership type in the U.S. A majority of the microgrids were developed based on the end-user ownership model. Source: (GTM Research, 2016a)

Figure 7 represents the ownership of the microgrid according to the complexity and the type of microgrid till 2015 as per the GTM research (GTM Research, 2016a). Amongst other things, this figure shows that most of the microgrids implemented till date have a complexity level between intermediate and advanced (multi-functional). The size of the circles in the figure indicates average microgrid capacity. A bigger circle represents greater average capacity. In terms of ownership, the majority of the microgrids are end-user based or utility/municipality based. Currently, more than two-thirds of microgrids are owned by end-users (GTM Research 2016a). As described in detail in the methods section of this thesis, the author has mainly focused on end-user owned microgrids and for installations where average capacity is relatively bigger.




Note: bigger circle indicates greater average capacity

Figure 7: Ownership by microgrid complexity for microgrids in the U.S. Source: (GTM Research, 2016a)

Microgrids can provide host of benefits depending on microgrid's design and operation features. The benefits can accrue to stakeholders based on their interest in the microgrid and involvement in using the microgrid. The benefits are described as follows.

## Microgrid Benefits

The conceivable stakeholders of a microgrid project could be:

- Customers: These are end-users of energy generated by a microgrid.
- Utilities: These are load serving entities that purchase and/or generate power and supply it to the customers. They invest in generation, transmission, and

distribution systems and recover the investment from customers by providing energy services.

- Ratepayers: These are the customers of the utility to which the microgrid is connected. Such customers may not have any direct contractual agreement with the microgrid owner or microgrid customer.
- Society: These are any individual or entity that might be affected by microgrid externalities.
- Owners: These are entity which have invested in the microgrid and are responsible for operating the microgrid to meet contractual obligations. An owner could be different than a customer or a utility as described in the Microgrids Ownership section.

Microgrids may be operated in a way that benefits multiple stakeholders with a single project. Microgrids generate direct and indirect benefits. Direct benefits are the benefits that can be transacted or accounted through a financial/contractual arrangement. For example, the benefits experienced by customers, utilities, rate payers, and owners are direct benefits. Indirect benefits are broader benefits generated due to the positive externalities of a microgrid. These benefits are occasionally unformulated and can be difficult to quantify despite having far-reaching impacts. Examples of indirect benefits include a reduction in the physical footprint of centralized power stations, a reduction of reliance on external fuel sources, and creation of employment in the locality of the

microgrid (Morris, 2012). Compared to a traditional macrogrid, the potential benefits of microgrids are classified into four broad categories in this thesis as shown below.

1. Energy: The benefits that are generated due to change in power demand (kW) and energy consumption (kWh) as a result of onsite DERs.
2. Economic: The benefits that result from an increase in service reliability, not just for the microgrid customers, but also for the macrogrid. The load control features of microgrids make them ideal for demand response services. Creation of employment in the locality of the microgrid contributes to local economy growth.
3. Environment: The benefits generated as a result of reduction in emissions of greenhouse gasses and other pollutants.
4. Emergency: The benefits experienced by stakeholders on account of resilient power supply. For example, in times of emergencies or long-term outages, it can act as an island of refuge while the macrogrid is restored.

The following things should be considered while identifying benefits from a microgrid project:

1. Microgrid benefits depend on the DERs included in the system. Depending on the combinations of power generation, energy storage technologies, and controlled loads utilized, benefits type can vary. It is evident that the extent or scale of benefits will depend on the size of the system.

2. Benefits also depend on the type of microgrid controller deployed. A complex controller such as a Level 5 controller can provide additional revenue streams in comparison to a Level 3 controller. This is due to the more sophisticated hardware and software capabilities of a Level 5 controller. For example, a Level 5 controller can provide generation and load forecasting, capabilities that a Level 3 controller cannot provide (please refer to Figure 3 on Page 14).
3. Benefits depend on the electrical back-up infrastructure already existing. If the facility already has an onsite backup diesel generator, it is already immune to the power outage risks up to a certain extent. In such a case, the incremental reliability benefits due to addition of other microgrid components will be less.
4. Benefits depend on the location of a microgrid. A microgrid deployed in a location that experiences frequent outages or is vulnerable to outages will generate more economic and emergency benefits for the customer. The values are also dependent on the location within a grid. For example, the benefits and the primary beneficiaries will vary depending on whether the microgrid is deployed behind the meter at a customer site or in a utility's distribution system.
5. Benefits also depend on the ownership of microgrid and the contractual agreement(s) in place for sale of energy and other services. In a similar way as location compatibility, ownership also constrains the list of possible services to be accessible to the project. Harvesting one benefit type by a customer may preclude realization of some other benefits if the operational requirements

have an overlap. For example, if a microgrid is owned by a utility, the energy generated by the microgrid will influence the utility's cost of energy procurement but may not affect the customer's energy bill. Similarly, if a customer owns a microgrid, the energy generated is likely to affect the customer's energy and demand charges. If a customer chooses to consume the onsite generated energy for its own consumption, then it will reduce the microgrid's ability to provide grid energy services and other grid services. The bottom-line is that same electricity generated cannot be used in more than one service stream for monetization during the same time period. In such conflicting situation, where participation in one service prohibits participation in the other, contractual obligations will have to be honored first. If there are no contractual constraints, then the service providing highest value is typically preferred.

Table 2 illustrates the benefits generated by a customer-owned microgrid to different stakeholders. The benefits are shown for three stakeholders: customers, ratepayers, and society. Reason being, for a customer-owned microgrid, customers are the obvious beneficiaries as they reap the benefits of onsite generation. Additionally, ratepayers will experience the spillover benefits of microgrids and society will be affected by any positive externalities generated by the microgrid project. The table represents a comprehensive list of benefits. As discussed above, microgrids benefits are dependent on many factors such as DER mix, project location, controller complexity,

size, ownership, etc. It is to be noted that not all benefits shown in the table may be applicable to a single project.

Table 2. Possible benefits to different stakeholders from a customer-owned microgrid

| Benefit to | Customers | Rate payers | Society |
|---|---|---|---|
| **1. Energy benefits** | | | |
| Demand charge reduction | $Y_{D,E}$ | - | - |
| Energy cost reduction | $Y_{D,E}$ | - | - |
| Deferred T&D network addition | - | $Y_{D,H}$ | $Y_{I,H}$ |
| Energy Arbitrage | $Y_{D,E}$ | - | - |
| Deferred generation capacity | - | $Y_{D,H}$ | $Y_{I,H}$ |
| Ancillary services to macrogrid | $Y_{D,H}$ | $Y_{D,H}$ | - |
| **2.Economic benefits** | | | |
| Increased service reliability | $Y_{D,E}$ | $Y_{D,H}$ | $Y_{I,H}$ |
| Demand response service | $Y_{D,E}$ | $Y_{D,E}$ | $Y_{I,H}$ |
| Local jobs creation | - | - | $Y_{D,E}$ |
| **3. Environmental benefits** | | | |
| Reduced greenhouse gas emissions | $Y_{D,E}$ | - | $Y_{I,E}$ |
| Reduced smog emissions | - | - | $Y_{I,H}$ |
| **4. Emergency benefits** | | | |
| Emergency refuge services | - | - | $Y_{I,H}$ |

Source: NYSERDA, 2010 and information collected by the author from private sources
Y indicates benefits applicable to a stakeholder type
Subscript “D” indicates direct benefit; “I” indicates indirect benefit
Subscript “E” indicates easy to quantify; “H” indicates difficult to quantify due to data unavailability and absence of methodology

A brief description of the benefits realized by the customer in a customer-owned microgrid shown in Table 2 is provided below:

- **Demand charge reduction**: Onsite power generation results in a reduction in power or kW demand of the customer. This is a direct benefit and can be quantified based on the customer’s monthly energy bill.
- **Energy cost reduction**: Analogous to demand charge reduction, onsite generation results in energy or kWh consumption of the customer. This is also

a direct benefit and can be quantified through the customer's monthly energy bill.

- **Energy arbitrage**: If a customer is exposed to a time-of-day tariff (electricity rates that vary by the time of day and climatic season), then the microgrid controller can allow the customer to purchase more energy when grid prices are low, store the energy in battery system, and discharge the battery to meet onsite loads at a time when the grid prices are higher. This arrangement is called energy arbitrage. Benefits are reflected in customer's monthly energy bill.
- **Ancillary services**: A grid microgrid can strengthen the grid by providing ancillary services to the grid. These services include providing support for voltage and frequency regulation, synchronized reserve, black-start capabilities, voltage support, and similar assistance by injecting power into the grid when required by the grid. Participation in the ancillary service market can provide additional revenues to the microgrid customer. However, the ability of a microgrid to provide ancillary services depends on the size of the onsite generation technology (smaller systems may be inadequate) and the type of technology (e.g., dispatchable generators are flexible and thus suitable for ancillary services, while non-dispatchable generators are not). It is worth reiterating here that participation in other services concurrently (demand reduction, energy arbitrage, etc.) may prohibit the microgrid to provide ancillary services. Based on discussions with some experts, the author

concludes that the market for ancillary services is competitive, and that projects of the size and type that are typical for microgrids may have a comparatively small chance of submitting a qualifying bid. Quantification of ancillary services benefits becomes difficult due to this overlap and the market-based price of ancillary services. In light of this consideration, this thesis does not attempt to quantify the potential benefits of providing this service. LBNL is researching publically available information sources to summarize historical price trends of ancillary services by product type and market and to provide summary statistical analyses for some U.S. markets (LBNL, 2017).

- **Demand Response (DR)**: DR refers to changes in electric usage by end-use customers from their normal consumption patterns in response to:
  - Changes in the price of energy over time; or
  - Incentive payments designed to induce lower electricity use when electricity prices are high or system reliability is in jeopardy.

When grid supply is constrained, a customer can shed low-priority loads to support the grid in maintaining grid supply reliability during regular supply times. Intentional participation in load shedding schemes helps the customer earn income as the customer is paid to shed loads by the utility or the system operator. The microgrid's ability to demarcate critical and non-critical load enables it to make money though demand response schemes. Loads that are less critical become a good candidate for providing demand response when load shedding is

needed. A brief theoretical explanation on demand response programs is discussed in the methods section.

- **Reliability benefits**: Microgrids allow end users to become autonomous in their energy provision and hence can reduce the impact of energy interruption on the end-user. Microgrids can also provide enhanced power quality (e.g. voltage fluctuation, harmonics) compared with the wider grid that will be useful in critical applications such as hospitals and computer server-farms. The average cost of power interruption for broad customer categories has been estimated by a LBNL study (Sullivan, Schellenberg, & Blundell, 2015) as shown in Table 3 through Table 5. The costs are based on a meta-dataset of customer's willingness to pay/accept for interruption. The meta-dataset includes 34 different datasets from surveys fielded by 10 different utility companies between 1989 and 2012, totaling over 105,000 observations. In total, the meta-dataset includes 44,328 observations for medium and large C&I customers, 27,751 observations for small C&I customers and 34,212 observations for residential customers. The Table 3 through Table 5 show variation in customer interruption costs by average interruption duration, customer type, and size. The interruption cost is based on:
    - Cost per event (cost for an individual interruption for a typical customer);
    - Cost per average kW (cost per event normalized by average demand); and
    - Cost per unserved kWh (cost per event normalized by the expected amount of unserved kWh for each interruption duration).

If, for a customer, the number of outages experienced in a year, average demand unserved during the outage, and average consumption unserved during the outage are known, then the cost of unreliable power can be calculated for that customer. Reliability benefits for a microgrid can be calculated based on the change in the number of outage events, average kW, and unserved kWh subsequent to microgrid implementation. It is an assumption for this analysis that during a major outage, the distribution network within the microgrid is wholly invulnerable to service interruptions. It should be noted, however, that this assumption neglects to consider that an outage due to extreme natural event may damage the microgrid as well.

Table 3. Estimated interruption cost for different interruption duration for medium and large commercial & industrial customers with annual electricity consumption of over 50,000 kWh (Source: Sullivan, Schellenberg, & Blundell, 2015)

| **Interruption Duration** | **Momentary** | **30 minutes** | **1 Hour** | **4 Hours** | **8 Hours** | **16 Hours** |
|---|---|---|---|---|---|---|
| Cost per event | $12,952 | $15,241 | $17,804 | $39,458 | $84,083 | $165,482 |
| Cost per average kW | $15.9 | $18.7 | $21.8 | $48.4 | $103.2 | $203.0 |
| Cost per unserved kWh | $190.7 | $37.4 | $21.8 | $12.1 | $12.9 | $12.7 |

Table 4. Estimated interruption cost for different interruption duration for small commercial & industrial customers with annual electricity consumption of under 50,000 kWh (Source: Sullivan, Schellenberg, & Blundell, 2015)

| **Interruption Duration** | **Momentary** | **30 minutes** | **1 Hour** | **4 Hours** | **8 Hours** | **16 Hours** |
|---|---|---|---|---|---|---|
| Cost per event | $412 | $520 | $647 | $1,880 | $4,690 | $9,055 |
| Cost per average kW | $187.9 | $237.0 | $295.0 | $857.1 | $2138.1 | $4,128.3 |
| Cost per unserved kWh | $2,254.6 | $474.1 | $295 | $214.3 | $267.3 | $258.0 |

Table 5. Estimated interruption cost for different interruption duration for residential customers (Source: Sullivan, Schellenberg, & Blundell, 2015)

| Interruption Duration | Momentary | 30 minutes | 1 Hour | 4 Hours | 8 Hours | 16 Hours |
|---|---|---|---|---|---|---|
| Cost per event | $3.9 | $4.5 | $5.1 | $9.5 | $17.2 | $32.4 |
| Cost per average kW | $2.6 | $2.9 | $3.3 | $6.2 | $11.3 | $21.2 |
| Cost per unserved kWh | $30.9 | $5.9 | $3.3 | $1.6 | $1.4 | $1.3 |

The interruption cost, in reality, varies for each individual customer. Nonetheless, the average costs shown in the figure provide a representative cost for planning purposes (Sullivan, Schellenberg, & Blundell, 2015). Figure 8 shows indicative comparison on how interruption costs can vary by customer type. A medical facility has critical loads (such as a respirator), but it can also have non-critical loads (such as an entertainment system). An office building may have no critical loads, but the computer systems could be important for business continuity. Residential dwellings usually have no high priority loads, although this is not true in all cases (IEC, 2014)). For example, sometimes residential customers have ventilators or oxygen machines to meet the health needs of residents.

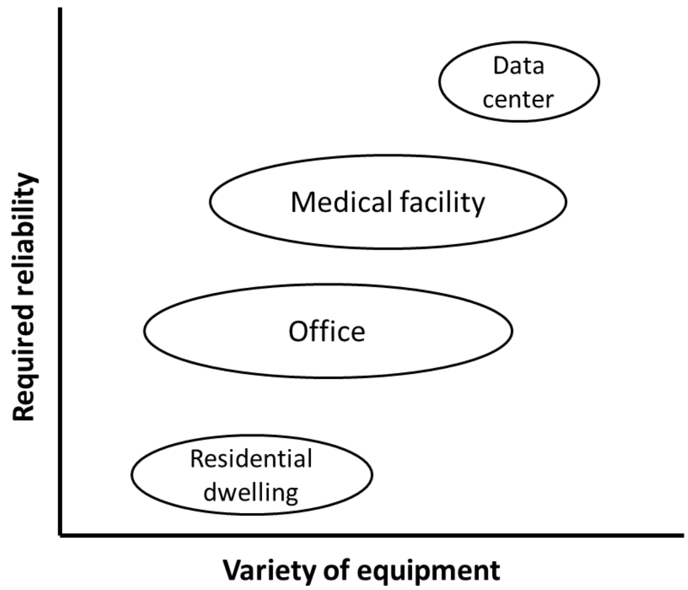



Figure 8. Typical required power system reliability for different customers. Data centers and medical facilities usually require highly reliable power supply compared to offices or residential dwellings. Source: (IEC, 2014)

There are several other benefits, realized by the rate payers and society, from a customer-owned microgrid as shown in Table 2 on page 27. For instance, any reductions in peak demand of the microgrid customer can potentiality free up transmission and distribution (T&D) capacity in the network. This may delay or avoid the need to build additional T&D network infrastructure and defer the cost of T&D network investment/upgrade costs. Since any network cost is recovered through the rate payers, microgrids provide potential benefits through the present value of money not spent. The same argument holds true for generation capacity avoidance. The benefits, in addition to cost avoidance or reduction, also come from avoidance or reduction in costs associated with land required for the installation of large generation plants and for building T&D infrastructure. Microgrids can also assist power systems to operate with significant

renewable electricity generation. Microgrids ease the challenge of controlling large numbers of distributed resources by making distributed generation control an internal process, operating within the microgrid (IEC, 2014). Each generator is managed internally to the microgrid, and the entire microgrid appears as only one single generator to the broader electricity system. Hence, microgrids are useful for renewable grid integration. With its single point of connection to the wider electricity system, microgrids appear as a large controllable resource from the grid's perspective. There are other benefits to microgrid deployment related to emissions reductions, reliability improvements, energy resiliency, a boost in local jobs and economic growth, etc. However, such benefits are not included in this thesis due to the following:

- For an economic analysis, it becomes necessary to quantify all benefits in monetary terms, however not all benefits are easily quantifiable. The methods section explains which of these benefits are included in the analysis of economic potential. For example, the monetary effect of reliability improvement and energy resiliency could not be determined by the author in the timeline of this study, and hence it is not included in the analysis.

The author has considered the benefits realized by the customers of a customer-owned microgrid as a basis for economic potential estimation of microgrids, as described in the methods section of this report. If a customer-owned microgrid project is economically favorable purely from the benefits realized by the customer, then the

project will certainly be economic if benefits to other stakeholders are accounted for. For calculation of microgrid benefits, the author has used several tools as described below.

## Analysis Tools

The benefits generated by a microgrid should be quantified in monetary terms to the extent possible, so that one can fully understand the benefits and make an economic comparison with other alternatives. A number of software packages have been developed that can aid in the techno-economic feasibility of a microgrid. The packages can identify the optimal economic configuration of a microgrid and optimize the interaction between the microgrid and macro grid to meet a specified objective, such as minimizing the cost. Several packages are proprietary and have been developed by engineering consulting companies, engineering, procurement, and construction companies, and project developers. An example of such a package is DNV GL's microgrid optimizer tool [https://www.dnvgl.com/energy/brochures/download/microgrid-optimizer-tool-brochure.html]. Use of these packages requires purchasing licenses. As discussed below, the three publically available tools for economic analysis that the author discovered are DERCAM, HOMER, and MDT. The tools can be used to size a microgrid optimally. If the size of the DERs is already identified, then the tools can calculate the optimum method of operating a microgrid to meet a specified objective, such as cost minimization or emissions minimization or a combination of both. A brief description of the three publically available tools is shown below:

- Hybrid Optimization of Multiple Energy Resources (HOMER) was developed initially by the US National Renewable Energy Laboratory (NREL), and the tool is currently marketed by HOMER Energy LLC. The tool is technically accessible to new users and available to demo freely. Using the tool, one can run simulations of specified microgrid configurations to identify the lowest lifecycle cost of the system.
- Distributed Energy Resources Customer Adoption Model (DER-CAM) was developed by the US Lawrence Berkeley National Laboratory (LBNL). This tool is used to minimize the cost of operating on-site generation and combined heat and power (CHP) systems, either for individual customer sites or microgrids. The model is freely available for academic and not-for-profit users.
- Microgrid Design Toolkit (MDT) is a decision support software tool for microgrid designers in the early stages of the design process. The software employs powerful search algorithms to identify and characterize the trade space of alternative microgrid design decisions in terms of user defined objectives. Common examples of such objectives are cost, performance, and reliability. The tool provides a variety of performance, reliability, and cost-related insights for candidate microgrid designs.

The author has used DERCAM tool for the calculation of benefits for the purpose of this thesis. Reason being, all functionalities of DERCAM are freely available. Moreover, the objective of this thesis is not to compare alternate microgrid designs but to

calculate benefits for a pre-selected microgrid design. HOMER and DERCAM are capable of calculating energy related benefits for a customer, but the benefits accrued to a customer extend beyond the energy benefits as shown in Table 2 of Page 27 which should be quantified. For quantification of economic, environmental, and emergency benefits, other tools will be required. Since this thesis is focused on benefits generated by a customer-owned microgrid, the following tools are used for calculation of the remaining benefits that cannot be estimated using DERCAM.

- Interruption Cost Estimate (ICE) Calculator is a tool designed by the US Department of Energy (DOE) for electric reliability planners at utilities, government organizations, or other entities that are interested in estimating interruption costs and/or the benefits associated with reliability improvements. The model estimates the benefits of avoiding outages based on average interruption costs determined through surveys. This tool is designed to estimate the costs of sustained interruptions lasting up to 16 hours. It is not meant to be applied to major outages or blackouts that last longer than 16 hours. The average interruption costs used in this model is based on the LBNL study shown in Table 3 through Table 5.

In addition to the above tools, the author developed a model in Microsoft Excel to calculate the environmental benefits and for collation of individual benefits. This is described in the methods section.

# METHODS

This section describes the approach and methodology executed to accomplish the research scope. The approach section, below, gives an overview of the sequence of activities adopted. A detailed description of the methodology, including data sources, modeling framework, and assumptions used, follows the approach section.

## Approach Outline

1. Defining scope and coverage: This section begins by establishing minimum size criteria for a customer for hosting or developing a microgrid. Thereafter, customer categories suitable for early adoption of microgrids are identified. The five categories of microgrids types (Commercial/Industrial, Utility/Community, Campus/Institutional, Military, Off-grid/Remote) are then mapped to these customer categories as per applicability. Out of four broad benefits categories (Energy, Economic, Environment, Emergency), the primary benefit for which microgrids will be preferred is identified for each customer category. For example, in case of military installations, the prime benefit is emergency power.

2. Technical potential estimation (in # of sites, MW capacity): Based on publically available information, a dataset of the total population of selected customer categories is prepared. The dataset is filtered for any inconsistency or gaps. For the technical potential of microgrids, minimum size criteria for hosting or developing a

microgrid are applied. If data for connected load (in kW) or annual energy consumption (in kWh) are available, then the data are used as is. Where load data or energy consumption data are not available, estimation for the same is done based on proxy indicators such as area, occupancy, average energy consumption, etc. The sites are classified as Small (less than 1 MW), Medium (between 1 MW and 5 MW), and Large (between 5 MW and 20 MW), depending on the peak energy load of the sites.

3. Economic potential estimation (in # of sites, MW capacity): For customers seeking microgrids primarily for emergency benefits, the entire technical potential is assumed to be economically viable since one human life saved is more valuable than any dollar benefits. The author recognizes that there could be a less expensive way to achieve the same emergency benefits which a microgrid can provide. However, for the sake of expedience this assumption was made and it could be an area for future work. For the remaining customer types, benefit cost analyses are done to determine the economic value generated by microgrids vis-à-vis grid electricity. The following steps are used for the economic potential analysis:

- Since customer size is a continuum, four discrete hypothetical size systems having peak loads of 0.25 MW, 1 MW, 5 MW, and 20 MW are considered to characterize the entire spectrum of customer sizes. These sizes represent the boundary conditions based on which microgrids sizes have been classified in this thesis.
- Representative electrical load shapes for the customer categories are obtained from previously conducted studies. The load shapes are scaled to generate

synthesized load curves that correspond to 0.25 MW, 1 MW, 5 MW, and 20 MW peak loads, respectively. These data are treated as the baseline grid consumption values in the Reference Scenario.

- Based on the ongoing time of day electric rates for the appropriate customer category, the cost of serving the baseline consumption is determined through spreadsheet models developed by the author. This cost is treated as the baseline cost in the Reference Scenario.
- For microgrids, a solar-plus microgrid system comprising of two DER technologies, a photovoltaic (PV) system and a battery energy storage system (BESS), are considered. A solar-plus microgrid system is taken for illustration purposes only, and it is not a prerequisite for any microgrid. A more comprehensive analysis would have analyzed other DER technologies as well, but, for computational simplicity, only PV systems are considered.
- Cost information is collected based on the pilot projects currently under implementation in California and future price projections made by market research agencies.
- Two scenario types are considered for microgrid analysis, namely Greenfield scenario and Brownfield scenario. The Greenfield scenario assumes that the customer currently does not have any power back-up infrastructure in place. In this scenario, a PV and a BESS system are installed for primary power generation, and a diesel generator (DG) is installed for back-up purposes, along with the installation of microgrid hardware. As opposed to the Greenfield scenario, the

Brownfield scenario assumes the existence of power back-up infrastructure but not microgrid hardware. In this scenario, a PV and a BESS system are installed for primary usage, along with the installation of microgrid hardware.

- Six benefit functions namely demand reduction, energy reduction, energy arbitrage, demand response, improved reliability, and emissions reduction, are developed based on use of the DERCAM model and author developed spreadsheet models. These benefits are direct in nature and less difficult to quantify (see Table 2 on Page 27). As an illustration of how a benefit function would work, suppose that a microgrid reduces the total greenhouse gas (GHG) emitted to the atmosphere by substituting 100 MWh of grid electricity with renewable electricity. If the GHG emissions factor of the grid electricity were 0.2 tonne/MWh and the market price of one kg of avoided GHG emissions is $10 per tonne, the emissions reduction benefit function would calculate the benefit to the customer as: 100 MWh* 0.2 tonne/MWh*10$/tonne= 200$. This example is for illustration purpose only, and the benefit functions used in the analysis are more complicated, as described in the methodology section.
- Keeping the customer load unchanged, the cost of delivering same level of service in the Microgrids Scenarios as in Reference Scenario is determined. The net gain or loss in the Microgrids Scenarios relative to Reference Scenario is found separately for a combination of four hypothetical customer sizes and different customer categories. As is done with the reference Scenario, the microgrid operation is simulated over a year's demand cycle and key performance metrics

are quantified. For all microgrids scenarios, the ownership of the system is assumed to rest with the customers of the microgrids.

- The economic viability of the investment is expressed using metrics such as simple payback period, levelized cost of energy (LCOE), and a benefit-cost ratio (BCR), as explained in the methodology section.
- A screening criterion based on market standards is defined to determine if a project is economic or not. If the values of metrics obtained from benefit-cost analysis are within the industry acceptable standards, then the investment is qualified as economically viable.

The economic analysis section concludes by applying a success percentage on the technically feasible potential to arrive at the economic potential.

## Detailed Methodology

The detailed methodology adopted in this study is described in this section.

### Minimum Criteria

Minimum criteria for hosting a microgrid can be defined in terms of the customer's energy requirement. As an appropriate method, size should be expressed in terms of parameters such as the peak load, average load, annual electricity consumption, or the number of customers served. These parameters may be used individually or in combination. For this study, the minimum requirement specified for microgrid suitability

is shown in Table 6. If a customer meets any of the thresholds mentioned in this table, it would be considered suitable for microgrid deployment. It is acknowledged that availability of physical space to build a microgrid should also be one of the criteria, but, given the difficulty to determine it without visiting individual sites, this aspect was not included.

Table 6. Minimum size requirement for microgrid suitability defined by the author for the purpose of this study

| **Particulars** | **Minimum Threshold** | **Unit** |
|---|---|---|
| Minimum Peak Demand | 250 | kW |
| Maximum Peak Demand | 20 | MW |
| Annual Energy Consumption | 2,000 | MWh |

Customer Categories

The customer categories selected for this study are based on the case studies of microgrids implemented in the US and made available by LBNL (https://building-microgrid.lbl.gov), microgrid projects funded by the California Energy Commission as part of the state's Electric Program Investment Charge (EPIC) program (http://www.energy.ca.gov/research/epic), and a primary survey conducted by IEEE and Zpryme (IEEE; Zpryme, 2012). This study was conducted by surveying 460 global smart grid executives in September of 2012. The survey findings are shown in Figure 9 and Figure 10. The top three benefits that customers expect from microgrids are to meet local demand (49%), to enhance grid reliability (36%), and to ensure local control of supply (30%). The customer categories most likely to deploy microgrids over the next five years

are hospitals (44%), military facilities (43%), government (non-military) facilities (40%), and utilities (39%).

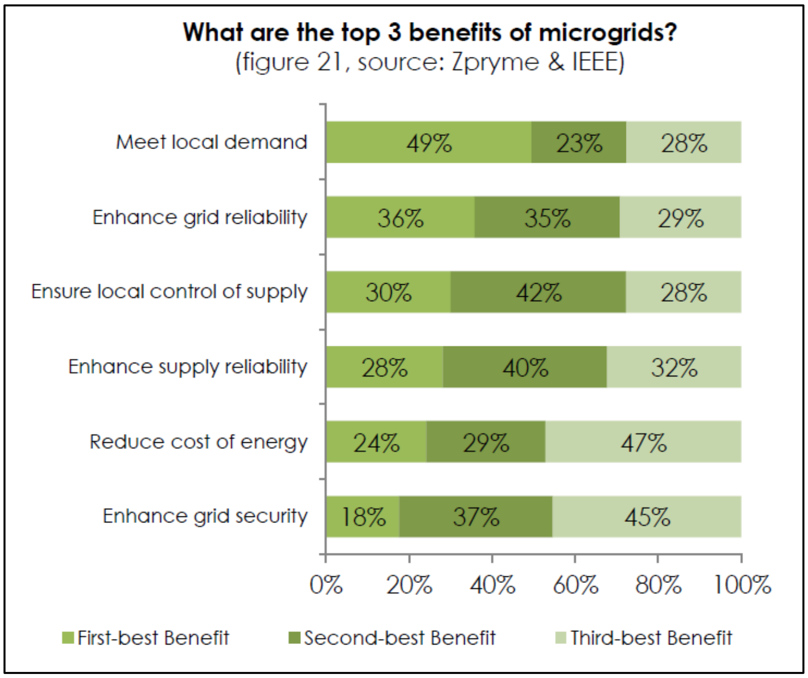



Figure 9. Results from the IEEE and Zpryme survey on microgrids. The top three benefits that the respondents expect from microgrids are meeting local demand, enhanced grid reliability, and ensuring local control of supply Source: (IEEE; Zpryme, 2012)

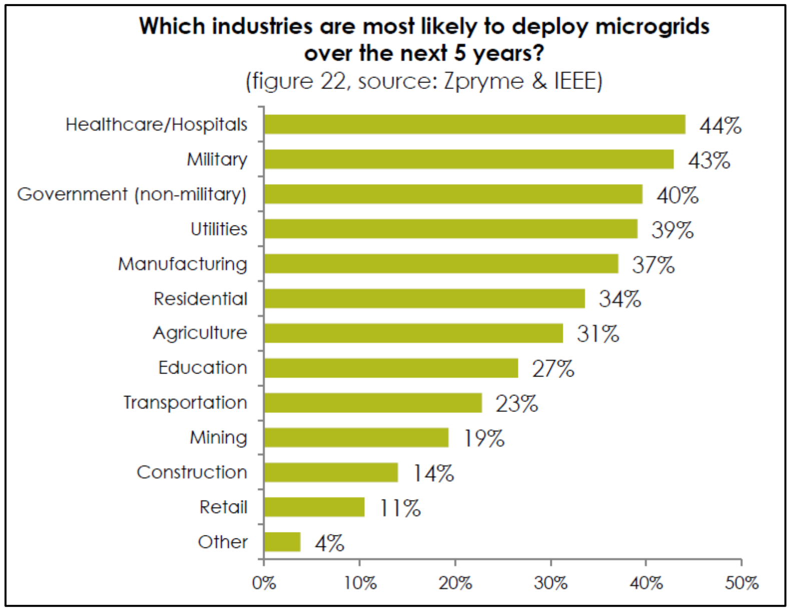



Figure 10. Results from the IEEE and Zpryme survey on microgrids showing the customer categories that are most likely to deploy microgrids over the next five years. Source: (IEEE; Zpryme, 2012)

Table 7 illustrates the list of customer types identified for analysis in this thesis. Based on the nature of the business activity of the customer types, a mapping of microgrids classification is done by the author. For example, airports and hospitals are classified into commercial/industrial type microgrids. The table also shows the top two benefits that these customers seek from a microgrid. The benefits mapping is done based on the author's understanding of the IEEE survey and the anecdotal evidences gathered from publically available case studies. In the table, "Economic" benefit indicates benefits on account of increased service reliability. The "Energy" benefit in the table indicates benefits on account of onsite generation of energy that can influence the cost incurred by customers on energy purchases. The "Environment" benefit shows customers' inclination

towards cleaner electricity. Additional clarity regarding the benefits type can be found in Table 2 on Page 27 of this thesis.

Table 7. Customer types selected for analysis

| **Microgrids classification** | **Potential Customers Type** | **Most Important Benefit** | **Second Most Important Benefit** |
|---|---|---|---|
| Commercial/Industrial | Airports | Economic | Energy |
| Commercial/Industrial | Data Centers | Economic | Energy |
| Commercial/Industrial | Hospitals | Economic | Energy |
| Commercial/Industrial | Native American Tribes | Energy | Economic |
| Commercial/Industrial | Red Cross Refuge Shelter | Emergency | Environment |
| Community/Utility | Utilities | Energy | Environment |
| Community/Utility | Cities | Energy | Environment |
| Campus/Institutional | Universities & Colleges | Energy | Environment |
| Military | Army, Navy, Air Force | Emergency | Energy |
| Off-grid / Remote * | Islands | Emergency | Energy |

* Technical and economic analysis of this category is not covered in this study

It is acknowledged that the customer categories shown in Table 7 represent a subset of the possible customer categories. Microgrid deployment opportunities exist for more customer categories, especially in the industrial and commercial space as per the IEEE survey. However, the data collection effort to obtain the necessary information would have posed significant challenges. Nonetheless, the customer categories selected in this thesis present opportunity for early adoption as found in the survey. The methodology for estimation of technical potential of microgrids is described below.

Technical potential

Based on the publically available information, a dataset of total population of the selected customer categories was prepared. The dataset was filtered for any inconsistencies or gaps. Wherever data for the connected load (in kW) or annual energy consumption (in kWh) was available, the data were used as is. Where load data or energy consumption data were not available, estimation was made based on proxy indicators such as area, occupancy, average energy consumption, etc. Once the technically feasible sites or customers were segregated from the data sets, the shortlisted sites were organized as per the microgrid size categories defined in Table 8.

Table 8. Microgrids classification by size for analysis purpose

| **Microgrids Classification** | **kW** |
| --- | --- |
| Small | >250 to <1,000 |
| Medium | >1,000 to <5,000 |
| Large | >5,000 to <20,000 |

The method for estimation of technical potential for the selected customer types is described in Table 9 through Table 17.

Table 9. Method for technical potential estimation of microgrids deployment at airports in California

| Particulars | Details |
|---|---|
| List of Airports Available? | Yes, data for commercial airports in California (The Airports Authority, 2016) |
| Energy Consumption Information Available? | No |
| Method for Potential Estimation | o The dataset contains information about airport size in a scale of one to five, with five indicating highest traffic airport.<br>o All airports with size equal or greater than 3 are assumed suitable for microgrid deployment. The premise for this assumption was based on the Arcata-Eureka airport, for which annual traffic data and annual energy consumption data are available. Arcata-Eureka airport is a size two airport and has a peak demand of ~20 kW which is less than the 250 kW peak load defined by the author as an eligibility criteria for hosting a microgrid. It was thus concluded that a size two airport does not meet the minimum criteria for microgrid deployment. The data for Arcata-Eureka airport was privately received by the author. |

Table 10. Method for technical potential estimation of microgrids deployment at data centers in California

| Particulars | Details |
|---|---|
| List of Data Centers Available? | No. A 2015 article published in Fortune magazine indicates that California is home to 800 data centers (Darrow, 2016) |
| Energy Consumption Information Available? | No |
| Method for Potential Estimation | o The "United States Data Center Energy Usage" report prepared by LBNL shows average energy consumption per data center in the US to be 330 kW (LBNL, 2016b).<br>o Since the minimum average power requirement for a customer to be able to host a microgrid is 250 kW (Table 6), it is assumed that all data centers sites are technically feasible. |

Table 11. Method for technical potential estimation of microgrids deployment at hospitals in California

| **Particulars** | **Details** |
|---|---|
| List of Hospitals Available? | Yes, data for hospitals in California (American hospitals directory, 2016) |
| Energy Consumption Information Available? | No |
| Method for Potential Estimation | o The dataset contains information about hospital size in terms of number of staffed beds available.<br>o The Energy Star benchmarking program of the US Environment Protection Energy (U.S. EPA) published statistics indicating that the median hospital size is 0.5 staff beds for 1,000 square feet of facility space (U.S. EPA, 2016a). This data set included numerous sites in California. Using these data, the size of hospitals in square feet is calculated.<br>o Energy Star statistics also show median energy consumption of hospitals to be 467 kBtu/sq ft, of which about 50% is electricity and the rest is fuel consumption. Using these values, electricity consumption of each hospital is estimated. Any facility with an average estimated load less than 250 kW was neglected. |

Table 12. Method for technical potential estimation of microgrids deployment at Red Cross centers in California

| **Particulars** | **Details** |
| --- | --- |
| List of Centers Available? | No |
| Energy Consumption Information Available? | No |
| Method for Potential Estimation | ○ 20 Red Cross chapters exist in California as per American Red Cross website (Red Cross, 2016). On the assumption that each chapter will have at least one refuge center, the number of refuge centers becomes 20.<br>○ The estimation is based on a number of assumptions starting from the assumption that each center can house 5,000 people, on average, and the average connected load is 0.1 kW per person. The assumption of 0.1 kW per person is based on an anecdotal example of the Blue Lake Rancheria (BLR). BRL is a designated Red Cross emergency shelter, and the total emergency load of the shelter is estimated at 200 kW. The shelter can accommodate around 2,000 people. This translates into 0.1 kW load per person. With an average connected load of 0.1 kW per person and capability to accommodate 5,000 people, the load per refuge center is found to be 500 kW. |

Table 13. Method for technical potential estimation of microgrids deployment at utilities in California

| **Particulars** | **Details** |
| --- | --- |
| List of Utilities Available? | Yes, list of all utilities in California (CEC, 2016). |
| Energy Consumption Information Available? | Yes, data for peak load, annual energy consumption, and number of customers for the year 2010 are available (CEC, 2016). |
| Method for Potential Estimation | This customer category is evaluated from the perspective of community microgrids. All utilities with peak demand less than 20 MW (upper threshold of microgrid) are assumed technical feasible. The dataset shows that a utility of nearly 20 MW demand has around 6,000 customers. |

Table 14. Method for technical potential estimation of microgrids deployment at cities in California

| **Particulars** | **Details** |
|---|---|
| List of Cities Available? | Yes, list of all cities in California (City-Data.com, 2016). |
| Energy Consumption Information Available? | No |
| Method for Potential Estimation | This customer category is evaluated from the perspective of community microgrids. The minimum population for a city to be eligible for microgrid deployment is found to be 66. This is calculated based on California's average electricity consumption per person of 557 kWh/month (U.S. EIA, 2015). The maximum population was kept at 6,000 to remain within the upper bound of 20 MW for a microgrid. |

Table 15. Method for technical potential estimation of microgrids deployment at universities and colleges in California

| **Particulars** | **Details** |
|---|---|
| List of Universities Available? | Yes, list of major universities and colleges in California (free-4u.com, 2016) |
| Energy Consumption Information Available? | No |
| Method for Potential Estimation | ○ The dataset contains information about universities in terms of number of enrolled students. In the absence of any data for average electricity consumption for universities in the state, energy consumption data for Humboldt State University (HSU) was taken as a reference. HSU's electricity consumption in 2015 was about 1,644 kWh per student based on the analysis of energy bills. Using this value, electricity consumption of each university is estimated. Any facility with average load less than 250 kW was neglected. |

Table 16. Method for technical potential estimation of microgrids deployment at military locations in California

| **Particulars** | **Details** |
|---|---|
| List of Military Installations Available? | Yes, list of defense locations obtained from United States Geological Survey (USGS, 2016) |
| Energy Consumption Information Available? | No |
| Method for Potential Estimation | Microgrid projects installed in military locations are, on average, in the order of 5 MW in size (e.g. Fort Carson at Colorado, Navy Yard in Philadelphia). Hence, 5 MW size was considered for every site as an assumption. |

Table 17. Method for technical potential estimation of microgrids deployment at American tribes in California

| **Particulars** | **Details** |
|---|---|
| List of Tribes Available? | Yes, federally recognized tribes in California (U.S. HHS, 2016) |
| Energy Consumption Information Available? | No |
| Method for Potential Estimation | o Research was used to confirm if tribes operate commercial facilities such as a casino or hotel. Data for casinos were available (500nations.com, 2016).<br>o All tribes with casinos are assumed suitable for microgrid deployment. The premise for this assumption was based on Blue Lake Rancheria (BLR), a northern California tribe that operates a casino. The average load of the casino at BLR is 400 kW, greater than the 250 kW minimum threshold required for a microgrid. |

The method adopted for determination of economic potential of microgrids is described below.

Economic Potential

For customers seeking microgrids primarily for emergency benefits, such as military and Red Cross centers, the entire technical potential is assumed economically viable since one human life saved is deemed more valuable than any dollar benefits. While alternatives cheaper than microgrids could be available that can provide the same emergency benefits (such as a diesel generator), the point being made here is that the emergency benefits provided by microgrids are strongly likely to exceed its costs. Ideally, life-saving value provided by a microgrid has to be ascertained based on probabilistic estimation of occurrence of severe natural disaster, likelihood of microgrid's contribution in lifesaving, and value of statistical life, etc. For brevity, the author made an assumption that all lifesaving microgrids are economic but this remains an area of future research. To give a viewpoint supporting the author's assumption, the U.S. EPA sets the value of human life at 7.4 million dollars (epa.gov/environmental-economics/mortality-risk-valuation). The other U.S. government agencies have also put up the value of human life between 6 and 9 million dollars (U.S. Food and Drug Administration, U.S.). If, over the course of its lifetime, a microgrid is able to save even one life, then the benefits will justify the investment notwithstanding the additional benefits occurring on energy, economic, and environmental grounds.

For the remaining customer types, benefit cost analyses are done to determine the economic value generated by microgrids vis-à-vis grid electricity. However, instead of conducting an economic analysis for each customer type, four customer types are

selected that are found representative of all categories in terms of most important benefit (Table 18). The analysis done for these four customers are extrapolated to the remaining customer types. For example, the main benefit for which airports, hospitals, and data centers are expected to deploy microgrids is for economic reasons. Hence, hospitals are selected for economic analysis and the results are applied to airports and data centers. This approach, which by no means is perfect, is found suitable for this thesis due to the unavailability of load shapes of all selected customer types (e.g. load shape of airport and data center are not available), homogeneity in the available interruption cost data (estimated interruption cost by LBNL is based on customer's size and not customer type), and acceptingly due to time limitation of the author. Table 18 shows the selected customer categories for assessment of economic analysis. The table also shows how the results from the selected categories will be applied to the rest of the customer categories.

Table 18. Selection of representative customer types for economic potential evaluation

| **Microgrid classification** | **Customer Type** | **First Best Benefit** | **Second Best Benefit** | **Economic Potential Conducted?** |
|---|---|---|---|---|
| Commercial or Industrial | Airports | Economic | Energy | Same as hospitals |
| Commercial or Industrial | Data Centers | Economic | Energy | Same as hospitals |
| Commercial or Industrial | Hospitals | Economic | Energy | Yes |
| Commercial or Industrial | Native American Tribes | Energy | Economic | Yes |
| Commercial or Industrial | Red Cross Refuge Shelter | Emergency | Environment | 100% economic |
| Community or Utility | Utilities | Energy | Environment | Same as cities |
| Community or Utility | Cities | Energy | Environment | Yes |
| Campus or Institutional | Universities & Colleges | Energy | Environment | Yes |
| Military | Army, Navy, Air Force | Emergency | Energy | 100% economic |

Representative electrical load shapes for the customer categories are obtained from the library of load shapes developed by Electric Power Research Institute (http://loadshape.epri.com/). The objective of the EPRI developed load shape library is to facilitate the collection, use and functionality of a library of representative electric load shapes by climate zone, geography or by utility. At the time of conducting this analysis, Load Shape Library 3.0 was available. Ideally, this analysis should be done on an annual hourly load profile (8760 data points for a year), but, due to data limitations, an annual average daily load shape is used in each analysis as available on EPRI's Load Shape Library. For a macro level study such as this one, this approach is reasonable. The annual daily average load shape shown in Figure 11 on the next page is representative of the city

of Los Angeles. For the tribes customer category, load shape was not available on EPRI's website, hence the author used privately obtained information from an individual tribe in California.

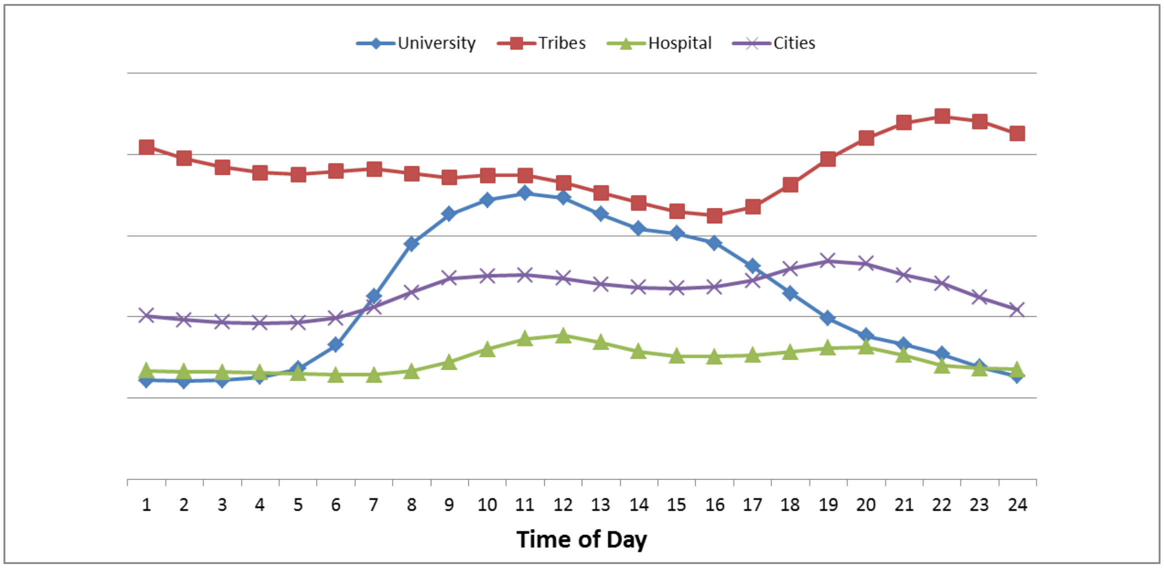



Figure 11. Representative annual average daily load shapes used for modeling. The load shapes are created using data from EPRI's load shape library for universities, hospitals, and cities. Source: (EPRI, 2016). Load shape data for tribes was obtained through private communication.

The load shape is scaled to create a synthesized (or designed) load curve for the four hypothetical systems (0.25 MW, 1 MW, 5MW, 20 MW) considered for the microgrids economic estimation analysis. Table 19 through Table 22 illustrate the synthesized data. The data shown in these tables are treated as baseline consumption data in the Reference Scenario. The minimum demand (also known as baseload demand) represents the minimum level of demand that exists for all hours during a day. The

minimum demand is about 70% of the average demand for tribes, hospitals, and cities, whereas the minimum demand is about 35% in case of universities.

Table 19. Baseline load data for the 0.25 MW customer peak load case

| | **Tribes** | **Hospitals** | **Universities** | **Cities** |
|---|---|---|---|---|
| Maximum Demand (kW) | 250 | 250 | 250 | 250 |
| Average Demand (kW) | 214 | 208 | 158 | 214 |
| Minimum Demand (kW) | 182 | 182 | 86 | 179 |
| Energy Consumption (MWh) | 1,874 | 1,821 | 1,388 | 1,876 |

Table 20. Baseline load data for the 1 MW customer peak load case

| | **Tribes** | **Hospitals** | **Universities** | **Cities** |
|---|---|---|---|---|
| Maximum Demand (kW) | 1,000 | 1,000 | 1,000 | 1,000 |
| Average Demand (kW) | 855 | 831 | 634 | 857 |
| Minimum Demand (kW) | 727 | 727 | 343 | 716 |
| Energy Consumption (MWh) | 7,494 | 7,283 | 5,550 | 7,505 |

Table 21. Baseline load data for medium size (5 MW) customer peak load case

| | **Tribes** | **Hospitals** | **Universities** | **Cities** |
|---|---|---|---|---|
| Maximum Demand (kW) | 5,000 | 5,000 | 5,000 | 5,000 |
| Average Demand (kW) | 4,277 | 4,157 | 3,168 | 4,284 |
| Minimum Demand (kW) | 3,635 | 3,635 | 1,714 | 3,582 |
| Energy Consumption (MWh) | 37,470 | 36,417 | 27,750 | 37,525 |

Table 22. Baseline load data for large size (20 MW) customer peak load case

| | **Tribes** | **Hospitals** | **Universities** | **Cities** |
|---|---|---|---|---|
| Maximum Demand (kW) | 20,000 | 20,000 | 20,000 | 20,000 |
| Average Demand (kW) | 17,110 | 16,629 | 12,671 | 17,135 |
| Minimum Demand (kW) | 14,541 | 14,538 | 6,858 | 14,326 |
| Energy Consumption (MWh) | 149,880 | 145,670 | 110,998 | 150,100 |

Once the baseline consumption data are established, the next step is to determine the baseline cost of serving loads using grid electricity. For this purpose, electricity rates are considered as shown in Appendix A. A customer can opt for one of the several available rate options. For simplicity, rate structures prevalent in PG&E territory are used. For tribes, hospitals, and universities, a commercial category time-of-day rate (E-19 schedule) is considered. For cities, a residential category time of day rate (E-6 schedule) is considered. The synthesized load shapes and applicable utility rates were provided in an author-developed spreadsheet model to determine the annual cost of serving the loads in the Reference Scenario.

Microgrids scenario

For the microgrid cases, two scenarios are analyzed as described below:

- Greenfield Scenario: This scenario assumes that the customer currently does not have any back-up infrastructure in place. In this scenario, a PV and a BESS system are installed for primary usage, a diesel generator is installed for back-up purpose, along with the installation of other necessary microgrid hardware.
- Brownfield Scenario: As opposed to Greenfield Scenario, this scenario assumes prior existence of back-up infrastructure (e.g. a diesel generator). In this scenario, a PV and a BESS system are installed for primary usage, along with the installation of the necessary microgrid hardware.

The methodology presented assumes PV and BESS technology for illustration purposes only. These technologies are not prerequisites for microgrids. The aim of the study is to focus on functionalities of a microgrid, preserving its generality, while considering representative cases. Table 23 shows the constituents of microgrids for the Greenfield Scenario. The constituents will be same for the Brownfield Scenario except that there will be no diesel generator set. The PV array is sized such that it matches with the peak load of the microgrid case that is analyzed. The rationale behind selection of a particular battery size is to support the stand alone (Island) operation of the system for one hour assuming peak load conditions. In many of the microgrids case studies available publically, similar trends for battery system sizing could be observed. For example, in case of Santa Rita jail microgrid in California, 1.5 MW of PV solar and 2 MW of battery systems are installed (LBNL, 2016c). Another example from the same information source is that of Borrego Springs microgrid in California where 700 kW of PV and approximately 550 kW of battery systems are installed. In practice, storage sizing for microgrids will depend on multiple factors and may vary from this assumption. Moreover, the initial attempt of the author was to determine the optimum size of PV array and battery systems using the DERCAM modeling tool instead of defining the size of the microgrid constituents using the assumptions described above. This approach failed to yield a feasible solution apparently due to the reason that the tool does not consider all type of benefits a customer can get from a microgrid. For example, reliability improvement related benefits were not getting captured. No combination of PV and battery system was found to be economic compared to the grid electricity in the absence

of any non-energy benefits. Due to this limitation, the author decided to provide the size of the microgrid constituents as an input data for the analysis rather than allowing the tool to determine the optimal size.

Table 23. Microgrid constituents in the Greenfield Scenario

| | **BESS (MWh)** | **PV (MWac)** | **Diesel Generator set (MW)** | **Microgrid Controller** |
|---|---|---|---|---|
| Case 1: 0.25 MW | 0.25 | 0.25 | 0.25 | 1 |
| Case 2: 1 MW | 1 | 1 | 1 | 1 |
| Case 3: 5 MW | 5 | 5 | 5 | 1 |
| Case 4: 20 MW | 20 | 20 | 20 | 1 |

The microgrid energy-flow model is shown in Figure 12 on Page 61 for illustration purposes. Although a diesel generator is shown in the Figure 12, it was not modeled for energy calculation purpose and it was assumed that the microgrid operates in the grid-connected mode.

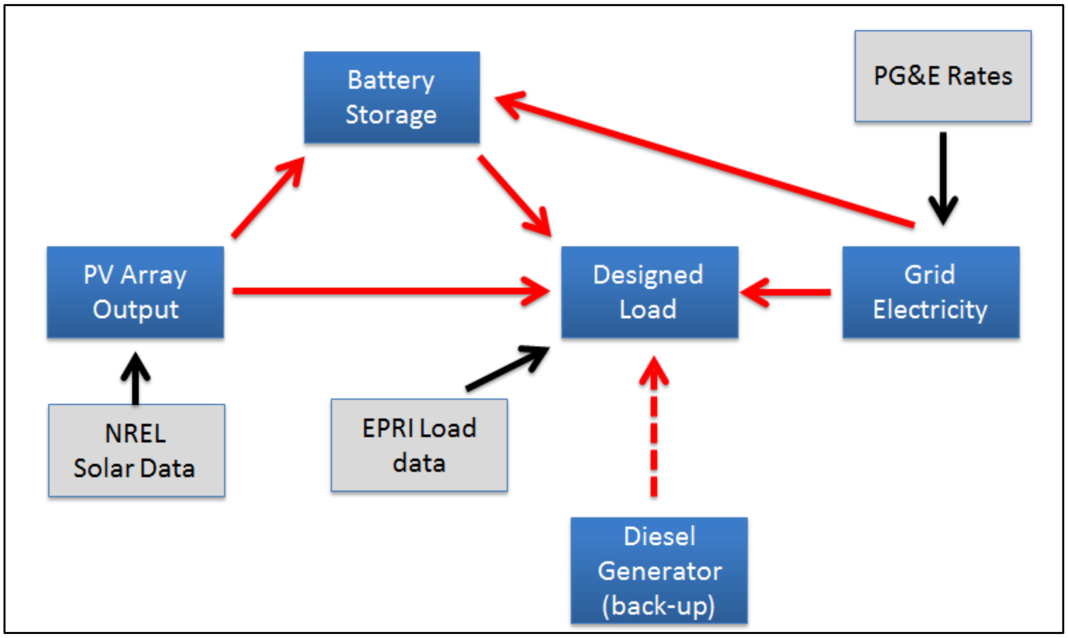



Figure 12. Schematic showing the microgrid energy flow model used in the analysis. The analysis was done to determine the least cost method of meeting the electricity requirement of the load while microgrid is operating in the grid connected mode.

The microgrid's controller decides the dispatch of generation sources based on availability of generated electricity, the grid situation, and price options. NREL's data for solar resources for a typical meteorological year (TMY 3 data), as available in the PV Watts model (http://pvwatts.nrel.gov/), were used in the modeling. For modelling of battery storage, certain inputs were provided as mentioned below. These inputs are generic and were assumed based on a CEC-funded microgrid project in California. This information was obtained via private communication and at the time of conducting this analysis, the data were not made available publicly.

- Minimum state of energy of battery storage system: The state of energy is defined as the available energy in a battery expressed as a percentage of its rated energy

capacity. In order to facilitate transition from grid connected mode to island mode and to also provide inertia (frequency control) to the islanded system in the absence of any rotational mass generator, certain minimum level of energy is desired to be always available in the battery. This minimum level was assumed at 10%.

- Round trip efficiency of battery storage system: The ratio of energy retrieved from a storage system (in kWh) to the energy put into the storage system (in kWh), expressed in percentage, is the round trip efficiency. This is also called as AC-to-AC efficiency. The higher the round trip efficiency, the less energy is lost due to storage. The round-trip efficiency was considered as 82%.

The next step in the economic analysis was to determine the cost of implementing a microgrid. This is discussed below.

Microgrids Cost

Similar to estimation of benefits, costs are difficult to generalize because each microgrid depends on the requirements and configuration of the user. While there are cost projections available for PV arrays and battery storage systems, the cost of the microgrid controller, communication system, and installation was difficult to obtain. Due to business sensitive information, the author's attempt to contact leading microgrid controller manufacturers for cost related information was not successful. Hence, attempts were made in two different ways to estimate the cost – a top down approach and a

bottom-up approach. Both methods had advantages and limitations, discussed below, and a mix of both approaches was considered for the final analysis. In the top down approach, a percentage break down of total cost by major cost categories was found as shown in Figure 13. The figure highlights cost break-up from some utility microgrids in North America. The cost of the microgrid controller is shown as 14% of the total cost, for example. The cost of the balance of system, controls, and electrical infrastructure combined is shown to be 52%. The report did not divulge cost breakup in absolute terms. Moreover, the data pertain to microgrids with conventional generation sources, thus less relevant for the microgrids scenarios identified in this thesis.

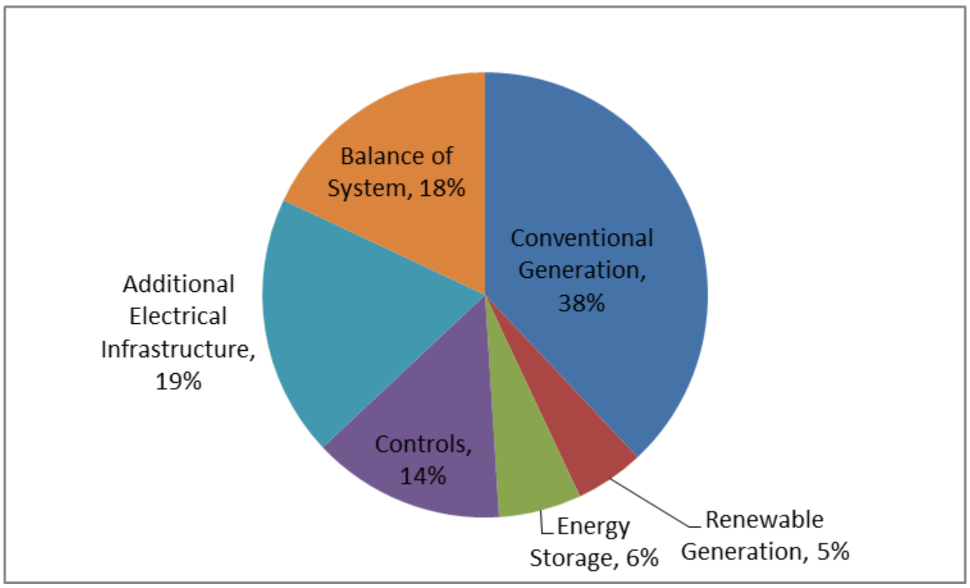



Figure 13. Percentage break-up of installed cost for distribution microgrids in North America. The cost break-up is shown for major cost categories. Source: (Cherian & Asmus, 2017)

The bottom-up analysis included identifying an inventory of equipment and components that constitutes a typical microgrid project. Table 24 summarizes the list of

components required in a microgrid in addition to generation and energy storage resources. This data is based on the report "Microgrids – Benefits, Models, Barriers and Suggested Policy Initiatives for the Commonwealth of Massachusetts" prepared by DNV KEMA in 2014 (DNV KEMA, 2014). The data and costs shown in this table pertain to a 5 MW microgrid. The cost of a microgrid controller is shown to be in the range of $150,000 to $500,000. The level of microgrid controller is not available from the report. The cost of communication represents about 40% to 50% of the total cost without considering any generation sources.

Table 24. Range of costs for microgrid equipment (Source: DNV KEMA, 2014)

| **Qty** | **Microgrid Equipment** | **Cost (lower range)** | **Cost (upper range)** |
|---|---|---|---|
| 1 | Main transfer switch | $50,000 | $100,000 |
| 1 | Master controller | $150,000 | $500,000 |
| 1 | Switchgear | $100,000 | $400,000 |
| 2 | Sectionalizing switchgear | $100,000 | $200,000 |
| 1 | Remote switchgear control | $70,000 | $110,000 |
| 1 | Automatic fault protection | $60,000 | $125,000 |
| 5 | Smart meters | $50,000 | $100,000 |
| 1 | Communication infrastructure | $500,000 | $1,000,000 |
| | **Total** | **$1,080,000** | **$2,535,000** |

Based on these two approaches, estimation of costs for a solar-plus microgrid for implementation in the year 2018 is done. Hardware prices components such as for PV system and batteries are based on forecasts, whereas soft costs for studies and project management are based on the two approaches shown above and anecdotal examples. Due

to confidential reasons, the source of the anecdotal examples cannot be disclosed. Price assumptions and references are shown in Appendix B. Since the customers are assumed to be already grid connected, no cost towards providing a distribution feeder was assumed. Also, it is worth mentioning here that no capital cost subsidy of any kind is assumed in the base case analysis. The impact of subsidy on microgrid economics is analyzed through sensitivity analyses presented later in this thesis. Table 25 and Table 26 summarize the cost assumptions.

Table 25. Capital cost of microgrids development assumed for analysis in the Greenfield Scenario

| **Particulars** | **0.25 MW Case** | **1 MW Case** | **5 MW Case** | **20 MW Case** |
|---|---|---|---|---|
| Studies and Approvals Costs | $100,000 | $100,000 | $200,000 | $500,000 |
| Hardware & Software Costs | $1,233,100 | $2,832,400 | $9,130,000 | $34,320,000 |
| Project Design, Management, and Commissioning Costs | $246,620 | $566,480 | $1,826,000 | $6,864,000 |
| Construction and Installation Costs | $246,620 | $566,480 | $1,826,000 | $6,864,000 |
| **Total Capital Cost** | **$1,826,340** | **$4,065,360** | **$12,982,000** | **$48,548,000** |

Table 26. Capital cost of microgrids development assumed for analysis in the Brownfield Scenario

| **Particulars** | **0.25 MW Case** | **1 MW Case** | **5 MW Case** | **20 MW Case** |
|---|---|---|---|---|
| Studies and Approvals Costs | $100,000 | $100,000 | $200,000 | $500,000 |
| Hardware & Software Costs | $1,183,100 | $2,632,400 | $8,130,000 | $30,320,000 |
| Project Design, Management, and Commissioning Costs | $236,620 | $526,480 | $1,626,000 | $6,064,000 |
| Construction and Installation Costs | $236,620 | $526,480 | $1,626,000 | $6,064,000 |
| **Total Capital Cost** | **$1,756,340** | **$3,785,360** | **$11,582,000** | **$42,948,000** |

For fixed annual operation and maintenance costs, the following costs were assumed based on the recent cost trends:

- PV system at $15/kW-year based on NREL's estimate of 2016 and some expected decline in future (nrel.gov/analysis/tech_lcoe_re_cost_est.html)
- BESS system at $20/kWh-year based on Lazard's estimate (Lazard, 2015).
- Diesel generator at $15/kW-year based on anecdotal examples.

Benefit functions

The benefits generated by microgrids can be viewed in terms of functions. These functions provide values to stakeholders based on the technical, economic, environmental, and social impacts that result from the characteristics and operation of the microgrids. The list of benefits illustrated in Table 2 (page 27) is a result of the microgrids functions. Six benefit functions reflecting customer's benefits in a customer owned model are proposed for assessment of microgrids economics. It is acknowledged that the six functions detailed here are believed by the author to comprise a set of the most significant functions, but they are by no means complete. Microgrids can provide additional functions, such as ancillary services and load control features that would potentially generate additional benefits. However, quantification of such benefits will require additional data, otherwise several assumptions will have to be made in their calculation. In the interests of technical simplifications and brevity, such functions were not considered in this study, and the analysis was confined to the six functions. It is also acknowledged that many types of microgrid controllers are available in the market, and the actual benefits realized are dependent on the various characteristics of the controller. This study has assumed a Level 5 controller with consistent features for all customer

categories. Of the six functions discussed below, only the reliability function will yield different results for the Greenfield and Brownfield Scenarios. This is because existence of a diesel generator set in the Brownfield Scenario already provides a better level of reliability level than the Reference Scenario where no back-up power is considered. With a microgrid that involves storage in place, the reliability will be further enhanced as the transition to the island state will be instantaneous in case of any grid interruption. Table 27 through Table 30 describe the six benefit functions.

Table 27. Description of the method used for modeling improved reliability benefit function

| Particulars | Details |
|---|---|
| Benefit Function Description | Microgrids can reduce the impact of macrogrid outages experienced by a customer through the use of a BESS and/or diesel generator for emergency power. If the macrogrid is having power quality issues, then the microgrid can isolate from the macrogrid and provide reliable supply. |
| Quantification Methodology | Monetary valuation of improved reliability is customer dependent, and usually relies on contractual arrangements or market value. In this study, US Department of Energy's (DOE) Interruption Cost Estimate (ICE) calculator tool is used. This tool is designed for electric reliability planners at utilities, government organizations, or other entities that are interested in estimating interruption costs and/or the benefits associated with reliability improvements. The tool takes grid reliability indices as inputs. The grid reliability indices used in the tool are:<br>**System Average Interruption Frequency Index (SAIFI):** SAIFI is the average number of sustained interruptions per consumer during a year.<br>**System Average Interruption Duration Index (SAIDI):** SAIDI is the average duration of interruptions per consumers during the year.<br>**Consumer Average Interruption Duration Index (CAIDI)**: It is the ratio of the total duration of interruptions to the total number of interruptions during the year. CAIDI = SAIDI/SAIFI |
| Input Parameters | For the Reference Scenario, average reliability index values for SAIFI, SAIDI, and CAIDI for California were provided as inputs (CPUC, 2016). For the Microgrids Scenarios, reliability indices were assumed based on the expected performance of the BESS and diesel generator in the case of the Greenfield Scenario and performance of the diesel generator in the case of the Brownfield Scenario. |
| Output | Cost of interruption with breakdown of cost per interruption event, cost per kW unserved, and cost per kWh unserved |

Table 28. Description of the method used for simultaneous modeling of three benefit functions related to demand charges reduction, energy cost reduction, and energy arbitrage.

| **Particulars** | **Details** |
|---|---|
| Benefit Function Description | Internal generation sources allow customers to avoid energy purchases from the grid. Depending on at what time of the day energy is generated and consumed for self-consumption, there will be reductions in demand (kW) and consumption (kWh) from the grid. The microgrid controller can allow energy to be purchased or stored in BESS when prices are low and sold when prices are high. This is called energy arbitrage. These three functions reduce the total cost of meeting the customer's loads. The benefits are reflected in the customer's monthly energy bill. |
| Quantification Methodology | LBNL's Distributed Energy Resources Customer Adoption Model (DERCAM) was used for this analysis. This model calculates the least cost of meeting a customer's electricity demand by optimally selecting the timing and quantity of onsite generation, onsite storage, and grid electricity based on optimized hourly dispatch decisions. The model algorithm identifies opportunities for demand charge reduction, energy cost reduction, and energy arbitrage. |
| Input Parameters | Generation profile of solar electricity<br>• Solar resource profiles vary by location. For simplification, the solar profile of Los Angeles, CA was used from NREL's database [http://pvwatts.nrel.gov/].<br><br>BESS parameters were used based on anecdotal data from a CEC funded project.<br>• Minimum state of energy (10%)<br>• Roundtrip efficiency (82%) |
| Output | Demand Charges and Energy Charges |

Table 29. Description of the method for modeling the demand response benefit function

| Particulars | Details |
|---|---|
| Benefit Function Description | DR activities are called upon by the system operator (such as CAISO) or by the power utility (such as PG&E), and participating customers are compensated. Utilities run several types of DR programs, and customers have the option to choose which one they would prefer to participate in. The two programs mentioned below are run by PG&E and are considered in the benefit function analysis as an illustration.<br>**Base Interruptible Program (BIP)**: BIP is intended to provide load reduction on PG&E's system on a "same day" basis when the California Independent System Operator (CAISO) issues a curtailment notice. Customers enrolled in the program are required to reduce their load down to or below their pre-defined Firm Service Level (FSL). This level is decided and declared by participating customers.<br>**Automated Demand Response (ADR) Program**: ADR provides incentives for customers investing in energy management controls that also enable DR.<br>Appendix C provides a brief explanation of demand response fundamentals and specifics about the two programs mentioned above. |
| Quantification Methodology | An author-developed spreadsheet model was used for this study. The model performs the calculation based on below mentioned formula.<br>For BIP events:<br>• Annual DR revenue (in $) = DR quantity (in kW) * contract price ($/kW/month) * 12 months/year<br>For ADR events:<br>• Annual DR revenue (in $) = DR quantity (in kW) * contract price ($/kW/event)* number of events in a year |
| Input Parameters | BIP event<br>• Minimum contract price which is $8/kW/month. (PG&E, 2016a)<br>• Firm Service Level (assumed 50% of average load). This assumption is based on the synthesized load shape of the four selected customer types shown in Table 19 through Table 22. The minimum demand or baseload demand of tribes, hospitals, and cities is 70% of the average demand. To demonstrate voluntary load reduction for demand response, a 20% reduction potential was assumed from the baseload demand level that will supposedly be achieved by shedding non-critical loads. For consistency, similar FSL was considered for universities.<br>ADR event<br>• Minimum contract price which is $200/kW/event. (PG&E, 2016b)<br>• Number of annual events (assumed as five as a conservative assumption; the number of price responsive or bidding based events in 2016 in PG&E was more than ten (PG&E, 2017) |
| Output | Revenue from demand response programs |

Table 30. Description of the method used for modeling emissions reduction benefit function

| Particulars | Details |
|---|---|
| Benefit Function Description | Microgrids will substitute a portion of grid electricity consumption. If the microgrid's generation sources are renewable, then the self-generation may reduce greenhouse gas emissions that otherwise would have been emitted if loads were grid supplied. On behalf of customers, power distribution utilities purchase carbon allowances or credits, and the cost of such allowances is embedded in the electricity bill. Any reduction in the electricity consumption due to the microgrid's onsite generation will reduce the cost of carbon allowances required by the customer if the onsite generation is based on renewable energy. This will be partially true if the generation mix includes a combination of renewable sources and diesel generation. In cases where diesel generator is a used as a back-up source, there will be emissions generated by the microgrid, and the net emissions reduction compared to a grid electricity alternative should account for these emissions. Since the benefits analysis in this thesis is for grid connected mode, emissions due to diesel generation are not considered. |
| Quantification Methodology | An author-developed spreadsheet model was used for this study. The model performs a simple calculation for grid connected situation. The emissions due to operation of diesel generator in island mode were neglected as the expected hours of operation of diesel generator was felt to be considerably lesser.<br>• Emissions reduction = (RE generation from microgrids in kWh) * (Grid emissions factor in $kgCO_{2e}$/kWh) |
| Input Parameters | • PG&E grid emissions factor (PG&E, 2016c) and analysis for future emissions factor projection (Appendix D). It is acknowledged that the PG&E emissions factors may not be reflective of the entire California grid. PG&E has a lower emissions factor than the other investor owned utilities in California.<br>• Carbon allowance market price of $CO_{2e}$ is assumed constant at $12/tonne for all years. This assumption is based on the median price of $12.73/tonne carbon allowance in California for the auction carried out in August 2016 (CARB, 2016). |
| Output | Avoided costs of carbon credits (allowances) due to avoided GHG emissions |

The benefit functions listed above are applied to the four selected customer categories for the four hypothetical microgrid sizes. The benefit functions are computed for the Reference Scenario, Greenfield Scenario, and Brownfield Scenario. It is again

highlighted that the economic analyses do not incorporate any government incentives, whether capital cost related, financing related, or any tariff rebate related. The costs are reflective of the market costs in the absence of any government intervention. Figure 14 illustrates how input parameters used in the modeling affects the benefit functions.

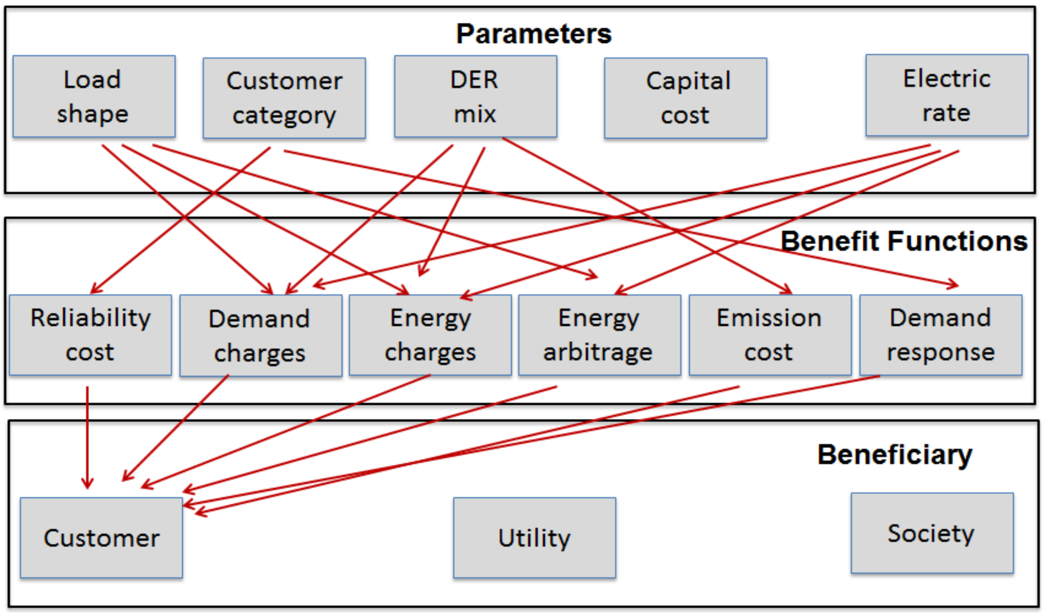



Figure 14. Visual representation of the relationship between inputs parameters and benefit functions. This highlights that the benefit functions are dependent on the data used and assumptions made for different parameters.

Metrics for Benefit-Cost Analysis

The primary reason for evaluating benefit functions is to determine the net gains microgrids are expected to provide to customers relative to the reference scenario. Several metrics could be used for such types of analysis, such as pay-back period, net-present value (NPV), internal rate of return (IRR), and levelized cost of energy (LCOE). This thesis being a macro level study and not a project level assessment, the author's view is that NPV and IRR values may not be required. Hence, the thesis has focused on the following metrics:

- Benefit-Cost Ratio (BCR): This metric evaluates if an investment is cost effective as a resource option over the life cycle of the project.

  *BCR = (Present value of customer benefits in dollars) / (Present value of customer costs in dollars)*

- Simple Payback Period: This metric determines the number of years it takes for an investment to be recovered through benefits generated. Any benefit after the cost recovery is true gain.

  *Simple payback period in years = (Investment in dollars) / (Annual benefits in dollars)*

- Levelized Cost of Energy: This metric evaluates the net present value of the unit cost of electricity in \$/kWh over the lifetime of a generating asset. It gives an indication of the minimum price that the project must receive to break even.

  LCOE in \$/kWh = {*(Present value of customer costs in dollars) - (Present value of customer benefits in dollars)*}*/* (*Annualized generation in kWh)*

Table 31 lists the assumptions used for calculation of these metrics.

Table 31. Financing Assumptions for Benefit-Cost Analysis

| Particular | Value | Remarks |
|---|---|---|
| Project Life (yrs) | 20 | Assumption |
| Debt-Equity mix | 60%, 40% | Lazard, 2015 |
| Nominal Interest Rate | 8% | Lazard, 2015 |
| Post Tax ROE | 12% | Lazard, 2015 |
| Effective Tax Rate | 40% | 35% Federal, 7% State |
| Calculated Weighted Average Capital Cost (WACC) | 7.7% | Based on Debt-Equity mix and Tax Rate |
| Annual escalation in grid electricity price | Nil | For simplicity |

Once the metrics are calculated, screening criteria, discussed below, are applied to determine what fraction of the technical potential is cost-effective. The criteria are shown in Figure 15. Discussion of these criteria follows the figure.

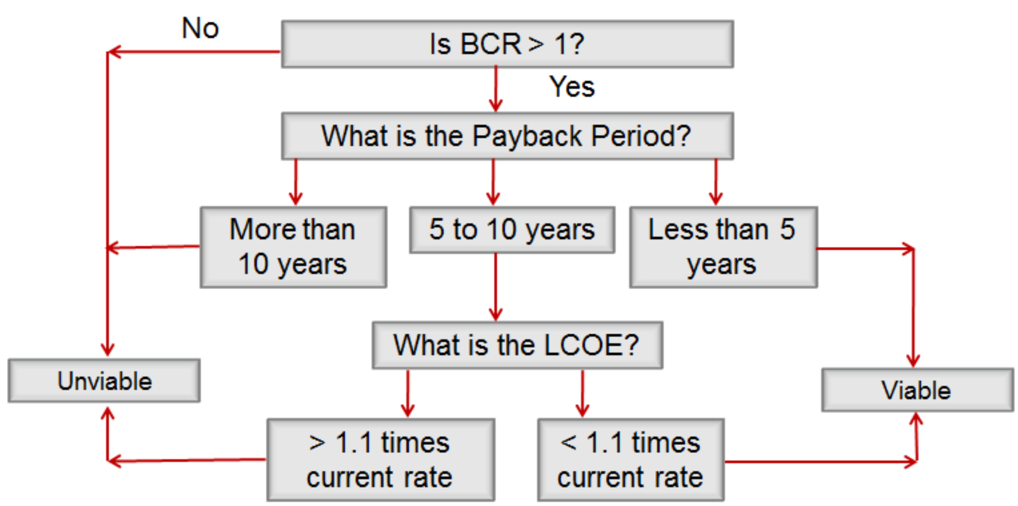



Figure 15. Screening criteria for economic potential estimation

- Step 1: If the BCR is less than one, the project is economically infeasible. If the BCR is greater than one, then further screening is required as mentioned in Step 2.

- Step 2: A simple payback period of 10 years is defined as the upper limit for a microgrid project to be considered as an attractive investment. The basis for the 10-year period originates from a customer survey conducted in the US that found a 10 year payback period as a cut-off criterion for customers to self-invest in a distributed generation project (Hedman & Hampson, 2010). The survey also found that less than 10% prospective customers expressed a willingness to invest in a distributed generation project if the payback period was between 6 to 10 years. Hence, the author of this thesis assumed that projects having a payback period of less than 5 years are economically feasible. If the payback period is between 5 and 10 years, the project could still be attractive, however the impact on the cost of serving electricity is to be analyzed. Hence, a third metric was introduced in the screening criteria as described below.
- Step 3: If the LCOE in the microgrid scenario is not more than 10% of the rate customers currently pay in the Reference Scenario, the project is considered economically feasible.

# RESULTS AND DISCUSSION

This section presents the analyzed results that were obtained based on the method as described in the previous section. The section also includes findings of sensitivity analyses.

## Technical Potential

The technical potential of microgrids in California for the customer categories selected in the study is shown in Table 32. In total, the study found that 2,171 sites or customers have the potential to host a microgrid, which is about 83% of the total population of 2,569 candidate sites in the state. The cumulative microgrid potential capacity is about 7,825 MW which is about 9.8% of the 2015 installed generation capacity in California (CEC, 2017). Small-sized microgrids present 46% of the potential sites, but this size category represents just 5% in terms of MW capacity.  On the contrary, large-sized microgrids represent 29% of the potential sites, but 76% in terms of potential MW capacity. All data centers, emergency refuge centers, and defense sites are found technically feasible sites for microgrids. Cities category represents the largest technical potential of microgrid deployment at 5,104 MW (65% of total technical potential) followed by hospitals at 1,467 MW (19% of total technical potential).

Table 32. Estimated technical potential of microgrids in California

| | Total probable sites in California (# sites) | Potential for Small-Size microgrid (# sites) | Potential for Small-Size microgrid (in MW) | Potential for Medium-Size microgrid (# sites) | Potential for Medium-Size microgrid (in MW) | Potential for Large-Size microgrid (# sites) | Potential for Large-Size microgrid (in MW) | Total Potential for all sizes combined (# sites) | Total Potential for all sizes combined* (in MW) |
|---|---|---|---|---|---|---|---|---|---|
| Airports | 145 | 15 | 15 | 3 | 15 | 2 | 40 | 20 | 70 |
| Data Centers | 800 | 800 | 264 | - | - | - | - | 800 | 264 |
| Tribes | 96 | 47 | 18 | - | - | - | - | 47 | 18 |
| Emergency Refuge Center | 20 | 20 | 10 | - | - | - | - | 20 | 10 |
| Utilities | 56 | 2 | 2 | 5 | 17 | 11 | 151 | 18 | 170 |
| Defense | 88 | | | | | 88 | 440 | 88 | 440 |
| Hospitals | 310 | 21 | 15 | 164 | 507 | 118 | 945 | 303 | 1,467 |
| Universities | 259 | 62 | 31 | 39 | 91 | 21 | 160 | 122 | 282 |
| Cities | 795 | 36 | 31 | 331 | 840 | 386 | 4,233 | 753 | 5,104 |
| **Total** | **2,569** | **1,003** | **386** | **542** | **1,470** | **626** | **5,969** | **2,171** | **7,825** |
| **Percentage of total potential for all sizes (# sites)** | **-** | **46%** | **-** | **25%** | **-** | **29%** | **-** | **100%** | **-** |
| **Percentage of total potential for all sizes (MW)** | **-** | **-** | **5%** | **-** | **19%** | **-** | **76%** | **-** | **100%** |

Please note: The author calculated the MW potential for sites (# 2,171) that are evaluated as technically feasible for microgrid deployment. For the total number of probable sites (# 2,569), estimation of MW was not done. Thus total technical MW potential of microgrid as a percentage of total MW of probable sites cannot be ascertained.

## Grid Electricity Consumption in the Reference Scenario and Microgrid Scenarios

Table 33 through Table 36 depicts the change in grid demand and grid electricity consumption for the four hypothetical microgrid size cases chosen for the study. In the case of universities, grid energy consumption reduces by 31% from the Reference Scenario while the reduction is in the order of 23% for other customer categories. The reduction in grid consumption is due to the PV generation in the microgrid. The reduction in consumption would have been more had the energy arbitrage function not been considered. In order to improve the economics, the BESS system charges itself when grid electricity price is low and discharges when price is high. Although, there is an energy loss of 18% in the charging and discharging process, the economics are still favorable due to differences in time of use rates. More details on this are provided in the benefit-cost analysis section. Due to the energy arbitrage function, there is an increase in the maximum demand. However, the increase in demand charges is minimal compared to savings in energy charges. The consumption pattern shown in Table 33 will be identical for the Brownfield Scenarios.

Table 33. Grid electricity consumption in the Reference and the Microgrid Scenario for the 0.25 MW case

| | **Tribes Reference** | **Tribes MG** | **Hospitals Reference** | **Hospitals MG** | **Universities Reference** | **Universities MG** | **Cities Reference** | **Cities MG** |
|---|---|---|---|---|---|---|---|---|
| Grid Energy Consumption (MWh) | 1,873 | 1,448 | 1,821 | 1,395 | 1,387 | 961 | 1,876 | 1,450 |
| % change | - | -23% | - | -24% | - | -31% | - | -23% |
| Grid Maximum Demand (kW) | 250 | 275 | 250 | 255 | 250 | 245 | 250 | 275 |
| % change | - | +10% | - | +2% | - | -2% | - | +10% |
| Grid Average Demand (kW) | 214 | 165 | 208 | 159 | 158 | 110 | 214 | 166 |
| % change | - | -23% | - | -24% | - | -30% | - | -22% |

* MG abbreviated for Microgrid Scenario

Since the load shape is assumed to be the same for all microgrid size cases, there is no difference in the pattern of the results across the different microgrids sizes except that the demand and energy consumption figures are scaled according to the ratio between the respective microgrid sizes and the 0.25 MW case. The percentage changes in grid energy consumption, maximum demand, and average demand remain same for same customer categories across all the microgrid sizes. For Tribes, there is no site with greater than 1 MW demand, hence the 5 MW and 20 MW cases were not computed.

Table 34. Grid electricity consumption in the Reference and the Microgrid Scenario for the 1 MW case

| | **Tribes Reference** | **Tribes MG** | **Hospitals Reference** | **Hospitals MG** | **Universities Reference** | **Universities MG** | **Cities Reference** | **Cities MG** |
|---|---|---|---|---|---|---|---|---|
| Grid Energy Consumption (MWh) | 7,494 | 5,790 | 7,283 | 5,580 | 5,550 | 3,846 | 7,505 | 5,801 |
| % change | - | -22% | - | -24% | - | -31% | - | -23% |
| Grid Maximum Demand (kW) | 1,000 | 1,100 | 1,000 | 1,021 | 1,000 | 980 | 1,000 | 1,100 |
| % change | - | +10% | - | +2% | - | -2% | - | +10% |
| Grid Average Demand (kW) | 855 | 661 | 831 | 637 | 634 | 439 | 857 | 662 |
| % change | - | -23% | - | -24% | - | -30% | - | -22% |

* MG abbreviated for Microgrid Scenario

Table 35. Grid electricity consumption in the Reference and the Microgrid Scenario for the 5 MW case

| | **Tribes Reference** | **Tribes MG** | **Hospitals Reference** | **Hospitals MG** | **Universities Reference** | **Universities MG** | **Cities Reference** | **Cities MG** |
|---|---|---|---|---|---|---|---|---|
| Grid Energy Consumption (MWh) | - | - | 36,417 | 27,898 | 27,750 | 19,230 | 37,525 | 29,005 |
| % change | - | - | - | -24% | - | -31% | - | -23% |
| Grid Maximum Demand (kW) | - | - | 5,000 | 5,106 | 5,000 | 4,899 | 5,000 | 5,499 |
| % change | - | - | - | +2% | - | -2% | - | +10% |
| Grid Average Demand (kW) | - | - | 4,157 | 3,185 | 3,168 | 2195 | 4,284 | 3,311 |
| % change | - | - | - | -24% | - | -30% | - | -22% |

* MG abbreviated for Microgrid Scenario

Table 36. Grid electricity consumption in the Reference and the Microgrid Scenario for the 20 MW case

| | **Tribes Reference** | **Tribes MG** | **Hospitals Reference** | **Hospitals MG** | **Universities Reference** | **Universities MG** | **Cities Reference** | **Cities MG** |
|---|---|---|---|---|---|---|---|---|
| Grid Energy Consumption (MWh) | - | - | 145,670 | 111,591 | 110,998 | 76,919 | 150,100 | 116,021 |
| % change | - | - | - | -24% | - | -31% | - | -23% |
| Grid Maximum Demand (kW) | - | - | 20,000 | 20,426 | 20,000 | 19,597 | 20,000 | 21,996 |
| % change | - | - | - | +2% | - | -2% | - | +10% |
| Grid Average Demand (kW) | - | - | 16,629 | 12,739 | 12,671 | 8,781 | 17,135 | 13,244 |
| % change | - | - | - | -24% | - | -30% | - | -22% |

* MG abbreviated for Microgrid Scenario

Results of Benefit Functions

Table 37 presents the simulation results for the 0.25 MW case. The numbers in top row correspond to the Greenfield Scenario, and numbers in the bottom row correspond to the Brownfield Scenario as written in the parenthesis.

Table 37. Annual electricity service cost for the Reference Scenario and the Microgrid Scenario for the 0.25 MW case

| | **Tribes Reference** | **Tribes MG** | **Hospitals Reference** | **Hospitals MG** | **Universities Reference** | **Universities MG** | **Cities Reference** | **Cities MG** |
|---|---|---|---|---|---|---|---|---|
| A1.Grid Energy Cost (Greenfield) | $172,596 | $126,199 | $170,408 | $124,011 | $132,617 | $86,220 | $456,111 | $332,991 |
| A2.Grid Energy Cost (Brownfield) | $172,596 | $126,199 | $170,408 | $124,011 | $132,617 | $86,220 | $456,111 | $332,991 |
| B1. Grid Demand Charge Cost (Greenfield) | $67,019 | $57,071 | $70,684 | $55,490 | $70,017 | $45,215 | - | - |
| B2. Grid Demand Charge Cost (Brownfield) | $67,019 | $57,071 | $70,684 | $55,490 | $70,017 | $45,215 | - | - |
| C1. Demand Response Revenue (Greenfield) | - | $31,653 | - | $30,764 | - | $23,441 | - | $31,699 |
| C2. Demand Response Revenue (Brownfield) | - | $31,653 | - | $30,764 | - | $23,441 | - | $31,699 |
| D1. Cost of Unreliability (Greenfield) | $13,146 | $85 | $12,961 | $84 | $11,329 | $75 | $13,156 | $85 |
| D2. Cost of Unreliability (Brownfield) | $6,688 | $85 | $6,581 | $84 | $5,647 | $75 | $6,693 | $85 |
| E1. Cost of Emissions (Greenfield) | $4,496 | $3,474 | $4,370 | $3,348 | $3,330 | $2,308 | $4,503 | $3,481 |
| E2. Cost of Emissions (Brownfield) | $4,496 | $3,474 | $4,370 | $3,348 | $3,330 | $2,308 | $4,503 | $3,481 |
| **Total Annual Electricity Service Cost (Greenfield) (A1+B1+D1+E1-C1)** | **$257,258** | **$155,176** | **$258,423** | **$152,168** | **$217,293** | **$110,376** | **$473,769** | **$304,857** |
| **Total Annual Electricity Service Cost (Brownfield) (A2+B2+D2+E2-C2)** | **$250,800** | **$155,176** | **$252,043** | **$152,168** | **$211,611** | **$110,376** | **$467,307** | **$304,857** |
| **% change in total annual electricity service cost compared to reference (Greenfield)** | **-** | **-40%** | **-** | **-41%** | **-** | **-49%** | **-** | **-36%** |
| **% change in total annual electricity service cost compared to reference (Brownfield)** | **-** | **-38%** | **-** | **-40%** | **-** | **-48%** | **-** | **35%** |

From Table 37, the following things can be observed for the 0.25 MW case:

- The total annual cost of meeting electric service is lower in both the Greenfield and Brownfield Scenarios for all customer categories. The annual electricity service costs reduce by 40% for tribes, 41% for hospitals, 49% for universities, and 36% for cities in the Greenfield Scenario. In case of the Brownfield scenario, the annual electricity costs are about 1% to 2% lower than the Greenfield Scenario for all customer categories.
- A reduction in energy charges and an increase in revenues from demand response are two primary reasons for reduction in the overall electricity service cost for the microgrid scenarios. Together, they approximately contribute towards 75% of the total cost reduction. Revenues from demand response roughly contribute towards one third of the dollars saved.
- In the absence of a microgrid, i.e. in the Reference Scenario, the cost of unreliability is higher in case of Greenfield compared to Brownfield cases. This is due to the fact that presence of a diesel generator already provides some level of reliability to Brownfield sites. With microgrid in place, Greenfield Scenarios lead to greater improvement in reliability (e.g. $13,061 for tribes) compared to Brownfield Scenarios ($6,603 for tribes). Pre-existence of diesel generators in the Brownfield Scenario reduces the additional gains of reliability improvement. The pattern is same for other customer types. The cost of unreliability is same in case of scenarios with Greenfield and Brownfield microgrids case (e.g. $85 for tribes). The obvious reason for same unreliability cost is that both the systems become similar after implementation of a

microgrid (the sites differ in pre-microgrid situation). The reason for non-zero cost of reliability is due to the non-seamless, albeit better than a diesel generator, nature of changeover that batteries facilitate while transitioning from grid connected mode to island mode.

- Since residential customers are not exposed to demand charges, savings in electricity bill for the cities category is through a reduction in energy charges only.
- The cost of emissions changes in the order of approximately $1,000 for all customer types. This is due to substitution of about 24% grid electricity with onsite renewable generation for tribes, hospitals, cities and 31% substitution of grid electricity in case of universities. It is worthwhile repeating that the cost of emissions was considered at $12/tonne of $CO_{2e}$ which is the market price of the allowance in California's cap and trade scheme in 2016. Since the analysis exclusively focused on grid connected mode of operation, there was no difference observed in the cost of emissions between Greenfield and Brownfield scenarios.
- Given that the objective of the study is to determine the economic potential based on benefit-cost analysis, in the interest of brevity it is not considered worthwhile to describe the results of other microgrid sizes in this section. The results of the different microgrids sizes are similar in pattern and the costs are scaled according to the ratio between the respective microgrid sizes and the 0.25 MW case.

## Results of Economic Screening

In order to ascertain if the investment will be sufficiently profitable to justify a given level of savings, benefit-cost analyses are performed and the results are shown in Table 38 through Table 41. The reduction in annual energy service costs (as shown in Table 37 in the previous subsection) can be credited as savings from microgrids which is then compared with the cost of implementing microgrids.  The screening criteria illustrated in Figure 15 of page 74 are applied to determine the economic viability. Numbers in the top row correspond to the Greenfield Scenario, and those in the bottom row correspond to the Brownfield Scenario.

Table 38. Results of the benefit-cost analysis and the economic feasibility screening for the 0.25 MW case

| | **Tribes MG** | **Hospitals MG** | **Universities MG** | **Cities MG** |
|---|---|---|---|---|
| Benefit-Cost Ratio (Greenfield) | 0.56 | 0.59 | 0.59 | 0.96 |
| Benefit-Cost Ratio (Brownfield) | 0.54 | 0.57 | 0.58 | 0.94 |
| Simple payback period (Greenfield) (year) | 17.9 | 17.2 | 17.1 | 10.8 |
| Simple payback period (Brownfield) (year) | 18.4 | 17.6 | 17.3 | 10.8 |
| Ratio of LCOE to current rate (Greenfield) | 1.28 | 1.26 | 1.31 | 1.01 |
| Ratio of LCOE to current rate (Brownfield) | 1.29 | 1.27 | 1.31 | 1.01 |
| Economically feasible? (Greenfield) | NO | NO | NO | MAY BE* |
| Economically feasible? (Brownfield) | NO | NO | NO | MAY BE |

* MAY BE indicate the marginal cases where economic screening criteria are missed by a narrow margin.

Table 39. Results of the benefit-cost analysis and the economic feasibility screening for the 1 MW case

| | **Tribes MG** | **Hospitals MG** | **Universities MG** | **Cities MG** |
|---|---|---|---|---|
| Benefit-Cost Ratio (Greenfield) | 0.94 | 0.98 | 1.00 | 1.66 |
| Benefit-Cost Ratio (Brownfield) | 0.97 | 1.02 | 1.04 | 1.74 |
| Simple payback period (Greenfield) (year) | 10.6 | 10.2 | 10.0 | 6.3 |
| Simple payback period (Brownfield) (year) | 10.3 | 9.8 | 9.6 | 5.9 |
| Ratio of LCOE to current rate (Greenfield) | 1.02 | 1.01 | 1.00 | 0.87 |
| Ratio of LCOE to current rate (Brownfield) | 1.01 | 0.99 | 0.98 | 0.86 |
| Economically feasible? (Greenfield) | MAY BE | MAY BE | MAY BE | YES |
| Economically feasible? (Brownfield) | MAY BE | YES | YES | YES |

Table 40. Results of the benefit-cost analysis and the economic feasibility screening for the 5 MW case

| | **Tribes MG** | **Hospitals MG** | **Universities MG** | **Cities MG** |
|---|---|---|---|---|
| Benefit-Cost Ratio (Greenfield) | - | 1.48 | 1.51 | 2.54 |
| Benefit-Cost Ratio (Brownfield) | - | 1.63 | 1.67 | 2.82 |
| Simple payback period (Greenfield) (year) | - | 6.7 | 6.6 | 4.1 |
| Simple payback period (Brownfield) (year) | - | 6.1 | 6.0 | 3.7 |
| Ratio of LCOE to current rate (Greenfield) | - | 0.89 | 0.86 | 0.81 |
| Ratio of LCOE to current rate (Brownfield) | - | 0.87 | 0.83 | 0.79 |
| Economically feasible? (Greenfield) | - | YES | YES | YES |
| Economically feasible? (Brownfield) | - | YES | YES | YES |

Table 41. Results of the benefit-cost analysis and the economic feasibility screening for the 20 MW case

| | **Tribes MG** | **Hospitals MG** | **Universities MG** | **Cities MG** |
|---|---|---|---|---|
| Benefit-Cost Ratio (Greenfield) | - | 1.56 | 1.59 | 2.69 |
| Benefit-Cost Ratio (Brownfield) | - | 1.75 | 1.79 | 3.02 |
| Simple payback period (Greenfield) (year) | - | 6.4 | 6.3 | 3.9 |
| Simple payback period (Brownfield) (year) | - | 5.7 | 5.6 | 3.4 |
| Ratio of LCOE to current rate (Greenfield) | - | 0.88 | 0.84 | 0.80 |
| Ratio of LCOE to current rate (Brownfield) | - | 0.85 | 0.82 | 0.79 |
| Economically feasible? (Greenfield) | - | YES | YES | YES |
| Economically feasible? (Brownfield) | - | YES | YES | YES |

Following observations can be made from Table 38 through Table 41:

- Microgrids of 0.25 MW size are not economic at present based on the assumptions used in the analysis. They did not achieve the target values for any of the listed criteria. The cities category missed the target for the benefit-cost ratio and payback period criteria marginally (indicated as MAY BE in Table 38). The benefit-cost ratio was 0.96 (target: > 1.0), and the payback period was 10.8 years (target: < 10 years). The economics could change in the future as equipment prices and energy costs change. It is worth reminding that no incentives or subsidies were considered in the analysis. With some incentives, microgrids in cities may become economic. One of the limitations in the study was consideration of same interruption cost for all customer types. Remember that LBNL's estimate for interruption cost as shown previously in Table 3 through Table 5 was dependent on the size (annual energy consumption) of the customer and not customer types. In reality, different customer types will have different costs of outage which is not reflected in this analysis.
- The 1 MW microgrid in the Greenfield Scenario is economic for the cities category. For other customer categories, the economic criteria targets are missed by a narrow margin, especially for the universities category. In case of the Brownfield Scenario for 1 MW microgrids, all customer types clear the target values except for the tribes category. Moreover, it is unlikely that hospitals, universities, and tribes will be greenfield customers. All hospitals have back-up power provisions (mostly diesel generators) in place; many tribes operate casinos that have back-up power to avoid commercial loss and for cyber security reasons. Since Brownfield microgrids are

economic for hospitals and universities, it is reasonable to conclude that they are economically feasible. For microgrids at tribes to be economic, the screening criteria would have to be narrowly relaxed or they can automatically become economic if equipment prices decline or if energy prices escalate in future.

- Microgrids of 5 MW and 20 MW are economic for all applicable categories. These microgrids have demonstrated a high BCR of more than 1.5, a payback period of about 6 years, and a levelized cost of energy cheaper by 2 cents per kWh for hospitals and universities. For cities, the benefits are very positive with a payback period of less than 4 years, and a cost of energy less expensive by 5 cents per kWh compared to the Reference Scenario.

## Economic Potential

Based on the results from economic screening, the economically feasible potential of microgrids is summarized in Table 42. In total, 1,224 sites with a cumulative microgrid hosting capacity of 7,480 MW are found to be economically feasible. The estimated potential includes the marginal ‘MAY BE” cases where the author defined economic screening criteria were missed by an extremely narrow margin. There are 36 “MAY BE” sites with a combined potential of 31 MW.

Compared to the technical potential established previously in this study, the economic potential represents 56% and 96% in terms of number of technically feasible

sites and technically feasible capacity, respectively. Other observations from the table are:

1) The medium and large size sites make up almost 96% of the economically feasible sites in terms of the number of sites. In terms of MW capacity, they make up almost 100%.

2) There are more large sized sites that are economically feasible than medium sites, although the difference (84 sites) in number is not much. However, the economically feasible potential MW capacity of large sized sites is about 4,500 MW more than the medium sized sites.

4) Cities and hospitals make up 84% of the economically feasible sites and 87% of the economically feasible MW capacity.

5) Utilities, universities, and defense make up a second tier in both number of sites and MW capacity.

Table 42. Estimated economic potential of microgrids in California

| Economic Potential | Potential for Small-Size microgrid (# sites) | Potential for Small-Size microgrid (in MW) | Potential for Medium-Size microgrid (# sites) | Potential for Medium-Size microgrid (in MW) | Potential for Large-Size microgrid (# sites) | Potential for Large-Size microgrid (in MW) | Total Potential for all sizes combined (# sites) | Total Potential for all sizes combined (in MW) |
|---|---|---|---|---|---|---|---|---|
| Airports | 0 | 0 | 3 | 15 | 2 | 40 | 5 | 55 |
| Data Centers | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Tribes | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Emergency Refuge Center | 20 | 10 | 0 | 0 | 0 | 0 | 20 | 10 |
| Utilities | 0 | 0 | 5 | 17 | 11 | 151 | 16 | 168 |
| Defense | 0 | 0 | 0 | 0 | 88 | 440 | 88 | 440 |
| Hospitals | 0 | 0 | 164 | 507 | 118 | 945 | 282 | 1,452 |
| Universities | 0 | 0 | 39 | 91 | 21 | 160 | 60 | 252 |
| Cities | 36 | 31 | 331 | 840 | 386 | 4,233 | 753 | 5,104 |
| **Total Economic Potential* (A)** | **56** | **41** | **542** | **1,470** | **626** | **5,969** | **1,224** | **7,480** |
| **Total Technical Potential (from Table 32) (B)** | **1,003** | **386** | **542** | **1,470** | **626** | **5,969** | **2,171** | **7,825** |
| **Percentage of technical potential that is economic (A/B)** | **6%** | **11%** | **100%** | **100%** | **100%** | **100%** | **56%** | **96%** |
| **Percentage of total economic potential for all sizes combined (# sites)** | **4.6%** | **-** | **44.3%** | **-** | **51.1%** | **-** | **100%** | **-** |
| **Percentage of total economic potential for all sizes combined (MW)** | **-** | **0.5%** | **-** | **19.7%** | **-** | **79.8%** | **-** | **100%** |

*The economic potential includes the marginal "MAY BE" cases. There are 36 such sites with a combined potential of 31 MW.

## Sensitivity Analysis

Since the analysis required making assumptions, the author conducted a series of simple sensitivity analyses. In these analyses, which involve keeping everything constant as per values in the base case analysis except the single parameter that is to be varied in order to understand its impact on microgrid economics. The resulting impact of the change in microgrid economics on the economic potential for microgrid development in California due to change in a parameter was not quantitatively evaluated, but insights were provided regarding the direction in which the economic potential would shift as a result of such changes.

The analysis conducted for this thesis involved several parameters. Several assumptions and proxies were also made. Ideally, a comprehensive sensitivity analysis should try to untangle the impact of all assumptions made, but for computation and reporting ease, the author has identified five key parameters for sensitivity analysis. These parameters all have a high degree of uncertainty and are perceived by the author to have greater influence on the results than other parameters. Further, for simplification in calculation and ease of interpretation, the sensitivity analyses are conducted for the 0.25 MW brownfield microgrids for the hospitals category only. This size has been identified in the study as an economically infeasible site for hosting a microgrid based on the assumptions made in the analysis. The selection of hospitals for the sensitivity analyses is an arbitrary choice for demonstration purposes, and the insights from the analyses may be applied to other customer types. The rationale behind selection of brownfield microgrids

is that most potential microgrids sites are likely to fall in this category. The parameters selected for sensitivity analysis are:

1. Change in PV cost and battery cost: The original run did not consider any capital cost subsidy for PV solar despite the availability of federal investment tax credits (ITC) on solar. For projects commencing construction till 2019, 30% ITC is available. The ITC then gradually reduces every year, 26% in 2020, 22% in 2021, and then reaches 10% after 2021 (SEIA, 2017). The reason for non-consideration of the ITC in the original run was due to the declining credits and also due to its non-applicability to organizations that do not have federal tax liability. The cost of battery storage for implementation in the year 2018 was assumed at $300/kWh. The cost of battery storage is declining rapidly, and many believe that the cost projections for future pricing will be achieved earlier. The cost of solar has declined over the years and is projected to decline further. Hence a sensitivity analysis was conducted to analyze the impact of change in the cost of PV and battery systems on the overall economics. This parameter will impact the metrics used in the economic screening criteria.
2. Change in microgrid controller cost: Today’s microgrid controllers are not plug and play type systems. The cost of the controller varies by both sophistication of the functions provided and the project complexity. A sensitivity analysis is warranted due to the lack of controllers’ cost data in the public domain. This parameter will impact the metrics used in the economic screening criteria.

3. Change in grid electricity rates: The price of grid electricity is a main determinant in the economics of the microgrids. In the original run, the author assumed PG&E's E-19 rate plan for non-residential customers and E-6 rate plan for residential customers (Appendix A), although not all customers are expected to utilize this rate category. The rates were also kept constant over the life cycle, contrary to the fact that the electricity prices are inherently variable. Also the time of use periods may change in future due to the duck curve effect. So the peak hours, non-peak, and off-peak times may be quite different than what is considered in the analysis. However, to keep things simplified, only the sensitivity of change in prices was analyzed and not the change in time of use periods. This parameter will impact the annual electricity service cost calculations.
4. Change in discount rate: A 7.7% post tax weighted average cost of capital was used in the base case. In contrast to solar PV systems, which have become a credible investment, microgrids are new technologies and may have a greater risk perception. A sensitivity analysis was used to understand the impact of the discount rate. This parameter will impact the metrics used in the economic screening criteria.
5. Change in emissions cost: The cost of emissions comprised less than 5% of the total annual electricity service cost (see Table 37 to recapitulate). Nonetheless, emissions costs considered for analysis needed further investigation for two reasons: 1) The base case run assumed a market price of carbon allowances of $12/tonne based on the carbon auction price of California (CARB, 2016). The

carbon allowance price was kept constant by the author for all future years in the analysis, whereas in reality it is reasonable to expect that the prices are likely to go upwards. 2) The social cost of carbon has been pegged much higher. The social cost of carbon estimates the benefit society will gain, represented in monetary value, by avoiding the damage caused due to carbon dioxide (or other greenhouse gases) released into the atmosphere. Scientists from Stanford University have estimated the social carbon cost at $220/tonne (Moore & Diaz, 2015) . The U.S. EPA estimate for social cost of carbon for the year 2020 is $42/tonne (2007 real dollars) for an average scenario and $123 (2007 real dollars) for high impact scenario (U.S. EPA, 2016b). Hence a sensitivity analysis was done to understand the impact of change in carbon prices on the economic feasibility of microgrids. The carbon price used in the analysis was conservatively kept at $50/tonne. This parameter will impact the annual electricity service cost calculations.

6. Change in price of demand response events: The revenues from demand response activities contributed about one-third of the total savings. While the assumption regarding the number of demand response events was conservative, the incentive or price for participation in each event was kept constant over the life cycle according to the current price offered. Hence a sensitivity analysis was warranted. This parameter will impact the annual electricity service cost calculations.

Table 43 shows the parameter values used in the sensitivity analysis. The results of the sensitivity analysis are shown in Table 44.

Table 43. Parameter values used in sensitivity analysis

| | **Sensitivity 1: Change in PV and Battery Cost** | **Sensitivity 2: Change in microgrid controller cost** | **Sensitivity 3: Change in grid electricity cost** | **Sensitivity 4: Change in discount rate** | **Sensitivity 4: Change in emissions cost** | **Sensitivity 5: Change in demand response price** |
|---|---|---|---|---|---|---|
| Values used in base case | PV at $1.5/W, BESS at $300/kWh | $700,000 | E-19 rate of PG&E | 7.7% | 12$/tonne | $200/kW/event |
| Values used in sensitivity analysis | 10% reduction | 10% reduction | 10% reduction in all charges | 7.2% (6.5% reduction) | 50$/tonne (317% increase) | $100/kW/event (50% reduction) |

Table 44. Results of sensitivity analyses conducted on 0.25 MW Brownfield hospitals case

| | **Base case: 0.25 MW Brownfield MG** | **Sensitivity 1: Change in PV and Battery Cost** | **Sensitivity 2: Change in microgrid controller cost** | **Sensitivity 3: Change in grid electricity cost*** | **Sensitivity 4: Change in discount rate** | **Sensitivity 4: Change in emissions cost*** | **Sensitivity 5: Change in demand response price** |
|---|---|---|---|---|---|---|---|
| Capital cost of microgrid | $1,756,340 | $1,688,706 | $1,658,340 | $1,756,340 | $1,756,340 | $1,756,340 | $1,756,340 |
| Annual electricity service cost | $152,168 | $152,168 | $152,168 | $189,007 | $152,168 | $162,769 | $162,561 |
| Benefit-Cost Ratio | 0.57 | 0.59 | 0.60 | 0.49 | 0.59 | 0.59 | 0.50 |
| Simple payback period (years) | 17.6 | 16.9 | 16.6 | 20.2 | 17.6 | 17.0 | 19.6 |
| Ratio of LCOE to current rate | 1.27 | 1.25 | 1.23 | 1.29 | 1.24 | 1.24 | 1.31 |
| Whether Economically feasible? | NO | NO | NO | NO | NO | NO | NO |

*The author re-evaluated the reference scenario without a microgrid to calculate the cost of annual electricity services occurring due to the change in electricity cost and emissions cost as proposed in the sensitivity analyses. For the same costs assumptions, annual electricity costs of the 0.25 MW hospitals under Brownfield microgrid scenario were calculated. The revised reference scenario and Brownfield scenario were then compared for calculation of the economic metrics that are presented in the table. This approach was not needed for other sensitivity analyses because the parameters varied for analysis had no impact on the annual electricity service cost of reference scenario.

Following can be concluded from the sensitivity analysis:

- A 10% reduction in PV and battery cost improves the economics, but the project remains economically unviable. In order for the project to be economically viable (qualifying all three metrics), the capital cost has to decline by about 42% or $750,000. While the federal investment tax credit on PV solar and batteries can help reduce the cost by about $150,000 (30% of the capital cost incurred towards PV and batteries), and delaying the investment by few years may help achieve further cost reduction of $70,000, the microgrid will remain uneconomic. Solar incentives, in conjunction with a reduced controller cost, may make the smaller sized microgrids economic. If the microgrid controller cost can be reduced to 25% of the cost assumed (lower down to $200,000 from the base case estimate of $700,000), the project will clear the economic screening criteria.
- An increase in the grid electricity cost and an increase in the emissions cost both worsen the economics as reflected by the increase in the annual cost of electricity service. This is due to the fact that the selected size combination of solar and batteries provide roughly a quarter of the electricity requirement and the rest is grid supplied.
- A change in the discount rate has a moderate effect on the project economics. For the small size microgrids to clear the economic screening criteria, the discount rate would need to be less than 4.5% as opposed to the 7.7% considered in the base case. A lower discount rate could be achieved through a higher leverage of debt and accessing debt at lower interest rates.

- A change in demand response pricing affects the annual electricity cost drastically. High sensitivity of project economics to demand response revenues may bring uncertainty in the microgrid deployment.

# CONCLUSION

The study finds that customers with peak loads that exceed 1 MW are economically viable for hosting microgrids. Availability of external funding can make microgrids economically feasible for more customer groups, including even customers with peak loads below 1 MW which otherwise are currently at the margin. The findings of this research can be utilized by policy makers and power utilities to make a policy and business case, respectively, for the development of microgrids. It is acknowledged that the customer categories selected in this thesis represent a subset of the possible customer categories. Nonetheless, the customers considered in the study represent possibilities for early adoption. It is also admitted that the costs and benefits are difficult to generalize because each microgrid depends on the requirements and configuration of the user. The findings of this thesis are not definitive. The emphasis of this thesis was on demonstration of a methodology for estimation of the overall potential for microgrid development in the state rather than a calculation of costs and benefits for specific cases. The following considerations can improve the results of the study:

- The study focused on potential estimation for the existing customer population. With economic growth, a new population of customers will be added for every customer type. By considering a growth rate in the population of customers, new customers can also be covered in the analysis.
- In the study, four discrete size bands of microgrids were selected for computational ease. For microgrids up to 1 MW in size, it will be good to identify

the critical size threshold beyond which a microgrid project will be economic. This can be done by including more scenarios of microgrids size up to one MW (e.g. 0.5 MW, 0.75 MW).

- This study defined a minimum size of 250 kW peak load for any site to become eligible for microgrids deployment. This was done for convenience sake with a preconceived notion that customers with energy requirements less than 250 kW peak load may not be suitable, both technically and economically for microgrids. The data for trends in microgrid development in North America also supported this hypothesis. However, a few pilot projects to demonstrate small sized microgrids are already underway or in conception stage for customers with smaller electrical loads such as fire stations and gas stations.
- The study selected four customer types and the analysis done for these four customer types were extrapolated to the remaining customer types. This approach, which by no means is perfect, is found suitable for this thesis due to the unavailability of load shapes of all selected customer types. Future work could focus on analyzing each of the customer types individually.
- The study did not consider any form of incentives, whether capital subsidy or performance based incentives. Research on the effect of external funding opportunities will improve the economics and thus may bring more projects into the feasibility ambit.
- The analysis assumed that the entire state had a common set of characteristics for key parameters. The customer load shape and solar resource profile represented

Los Angeles; electric reliability indices represented the state average; utility electric rates were for PG&E; PV and BESS were analyzed as local generation sources; and the cost of emissions was based on California's cap & trade allowance prices. Future work could focus on making these assumptions geographically consistent and creating more scenarios to cover technological and geographical diversity.

- The study considered cities of less than 6,000 people and smaller sized utilities with less than 20 MW peak load are identified as candidate sites. It will be interesting to understand the regulatory and institutional challenges associated with implementation for these cases.
- The benefit functions used in the analysis did not include ancillary services that can provide additional value to customers. In addition, quantification of utility level benefits and societal benefits will provide insights for making a policy case for microgrid development. Calculating such benefits should be an area for future research.
- This study focused on customer-owned microgrids. If the microgrids were to be funded through rate payers, then there are additional societal benefits that will become a part of the microgrid value stream. The potential of deployment will change based on the ownership model.
- The study assumed that microgrids designed for emergency purposes are by default economic since a human life saved exceeds any dollar benefit. Quantifying this benefit remains an area of future research.

- One of the limitations in the study was consideration of same interruption cost for all customer types. In reality, different customer types will have different costs of outage which did not get reflected in this analysis.
- A significant limitation in the study was non-availability of adequate information regarding data centers in California. The information regarding the total population of data centers was obtained through a news article, while no data could be found related to the size-wise distribution of the population. The load shape information was not available, and the assumption regarding energy consumption per site was based on an average number. Intuitively, one would imagine data centers as ideal candidates for microgrids. They largely rely on back-up power to maintain highest reliability of power service. Also, they are critiqued for their high energy and water consumption. Hence, there are economic, energy, environment, and branding considerations for data centers to adopt microgrids that may make microgrids economically attractive for them.
- Finally, a study of this kind also covers assessment of market potential for a technology. Market potential is the fraction of the economic potential that is attainable in near future given the infrastructure, societal, and market limitations. For microgrids per se, customers with combined heat and power (CHP) technology and/or net-energy-metered (NEM) solar could act as early adoption possibilities. This study could be expanded to include evaluation of market potential.

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# APPENDIX A. ELECTRICITY RATES USED IN THE ANALYSIS

Table A.1-A.2 show the electricity rate plan used in the analysis. Figure A.1 shows time of use periods and seasons defined for the purpose of electricity rate plan. The rate plan is for PG&E territory.

Table A.1. E-19 rate for commercial customers applicable to tribes, hospitals, and universities. The rates are for PG&E territory for Jan 2016. Source: (PG&E, 2016d)

| | **Peak period demand charge ($/kW)** | **Part-peak period demand charge ($/kW)** | **Maximum demand charge ($/kW)** | **Peak period electricity charge ($/kWh)** | **Part-peak period electricity charge ($/kWh)** | **Off-peak period electricity charge ($/kWh)** |
|---|---|---|---|---|---|---|
| Summer months | $16.68 | $4.57 | $12.59 | $0.137 | $0.098 | $0.074 |
| Winter months | $0.000 | $0.150 | $12.59 | - | $0.093 | $0.080 |

Table A.2. E-6 rate for residential customers applicable to cities. The rates are for PG&E territory for the month Oct 2016 Source: (PG&E, 2016e).

| | **Peak period electricity charge ($/kWh)** | **Part-peak period electricity charge ($/kWh)** | **Off-peak period electricity charge ($/kWh)** |
|---|---|---|---|
| Summer months | $0.141 | $0.103 | $0.079 |
| Winter months | NA | $0.098 | $0.085 |

Months of the year and times of the day for the purpose of electricity rates as defined by PG&E are shown in Figure A.1.

Times of the year and times of the day are defined as follows:

| | | |
|---|---|---|
| SUMMER | Period A (Service from May 1 through October 31): | |
| Peak: | 12:00 noon to 6:00 p.m. | Monday through Friday (except holidays) |
| Partial-peak: | 8:30 a.m. to 12:00 noon AND 6:00 p.m. to 9:30 p.m. | Monday through Friday (except holidays) |
| Off-peak: | 9:30 p.m. to 8:30 a.m.<br>All day | Monday through Friday<br>Saturday, Sunday, and holidays |
| WINTER | Period B (service from November 1 through April 30): | |
| Partial-Peak: | 8:30 a.m. to 9:30 p.m. | Monday through Friday (except holidays) |
| Off-Peak: | 9:30 p.m. to 8:30 a.m.<br>All day | Monday through Friday (except holidays)<br>Saturday, Sunday, and holidays |

Figure A.1. Time of use definitions and seasons used in PG&E territory. Source: (PG&E, 2016d)

# APPENDIX B. COST ASSUMPTIONS USED IN THE STUDY

Table B.1 shows the capital cost assumptions used in the study. These assumptions were key inputs in determining the initial cost of microgrid installation. Figure B.1-B.2 show projected PV prices used in the study.

Table B.1. Capital cost assumptions used in the study

| **Particulars** | **Price ($)** | **Unit** | **Source** |
|---|---|---|---|
| Solar PV array with inverters | $1.06 for systems greater than 1 MW<br><br>$1.484 for systems up to 1 MW | $/kW$_{dc}$ | Based on GTM Research shown in Figure B.1. (GTM Research, 2016b) and SEIA report shown in Figure B.2. (SEIA, 2016) |
| Storage batteries with inverters costs | $300 | $/kWh | Mckinsey's price projection (Hensley, Newman, & Rogers, 2012) |
| Diesel Generator costs | $200 | $/kW | Product Catalogues |
| Microgrid controller costs | $700,000 for up to 1 MW<br>$800,000 for up to 5 MW<br>$1,000,000 for up to 20 MW | Lump sum | Cherian & Asmus, 2017; DNV KEMA, 2014; Privately received information |
| Studies and Approvals costs | 100,000 for up to 1 MW<br>200000 for up to 5 MW<br>500000 for up to 20 MW | Lump sum | Assumption based on general research |
| Project Design, Management, Commissioning costs | 20% of project cost | Lump sum | Assumption based on general research |
| Construction and Installation costs | 20% of project cost | Lump sum | Assumption based on general research |

The future PV for installation in 2018 was taken from the GTM research as shown in Figure B.1 on the next page. These prices are for utility scale solar i.e. for projects size greater than 1 MW.

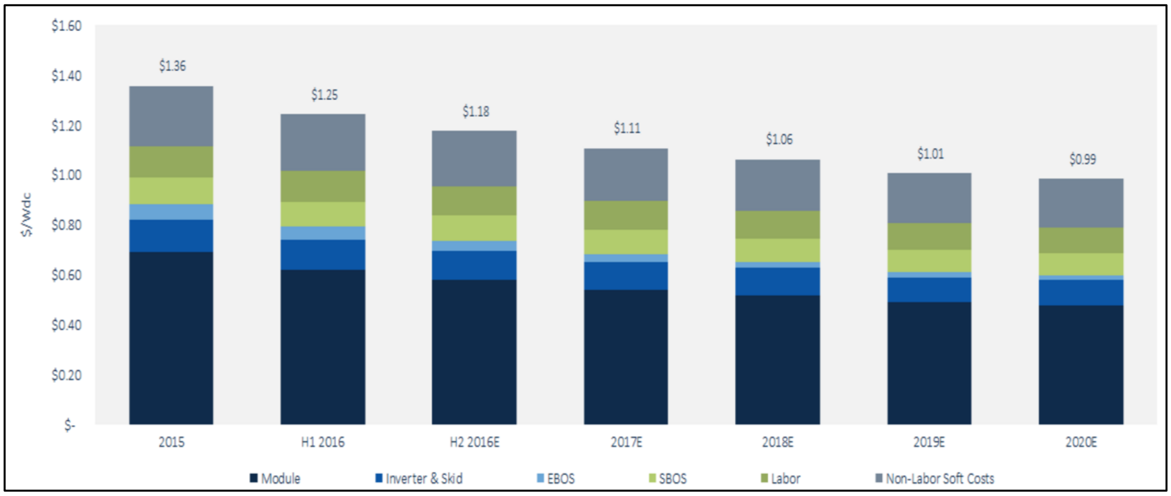


Figure B.1. Future price projection of utility scale PV. Source: (GTM Research, 2016b)

For commercial scale PV projects, i.e. for projects size up to 1 MW, price was calculated based on the historical trend of difference between utility scale and commercial scale solar. As shown in Figure B.2., commercial size solar is expensive by a factor of 1.4.

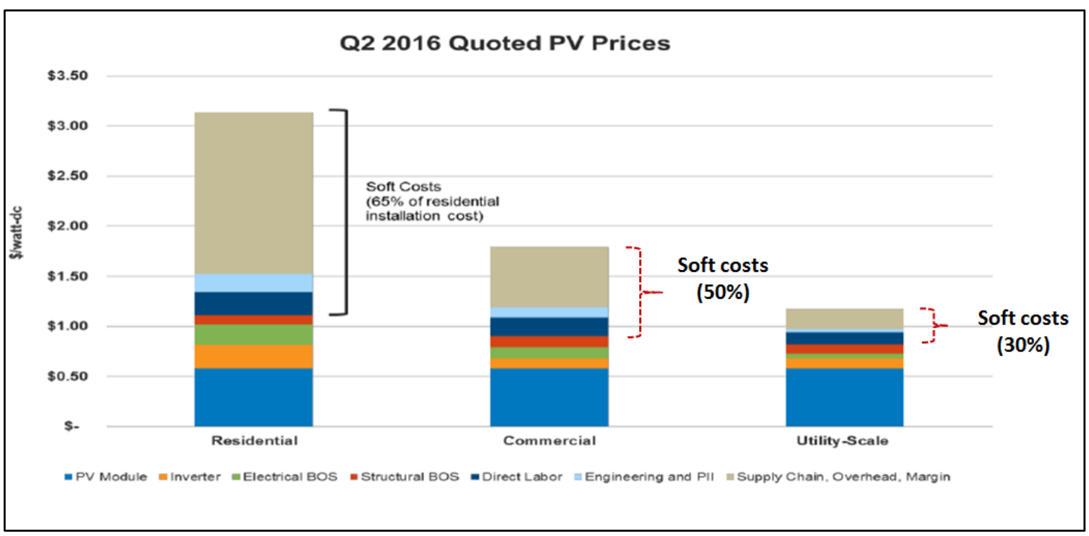


Figure B.2. Comparison of utility scale and commercial scale PV price. Source: (SEIA, 2016)

# APPENDIX C. BASIC INFORMATION ABOUT DEMAND RESPONSE PROGRAMS

Demand Response refers to changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of energy over time or to incentive payments designed to induce lower electricity use when prices are high or system reliability is in jeopardy. Figure C.1. shows that for a hypothetical illustration, in the event of no DR action, electricity peak demand would have exceeded 35 kW (12pm to 2 pm), however this was avoided with a DR event. The demand shifts to periods of relatively lower demand period (4pm to 10 pm). Hence, DR leads to change in kW demand may or may not lead to change in kWh consumption (total area under the curve may not change).

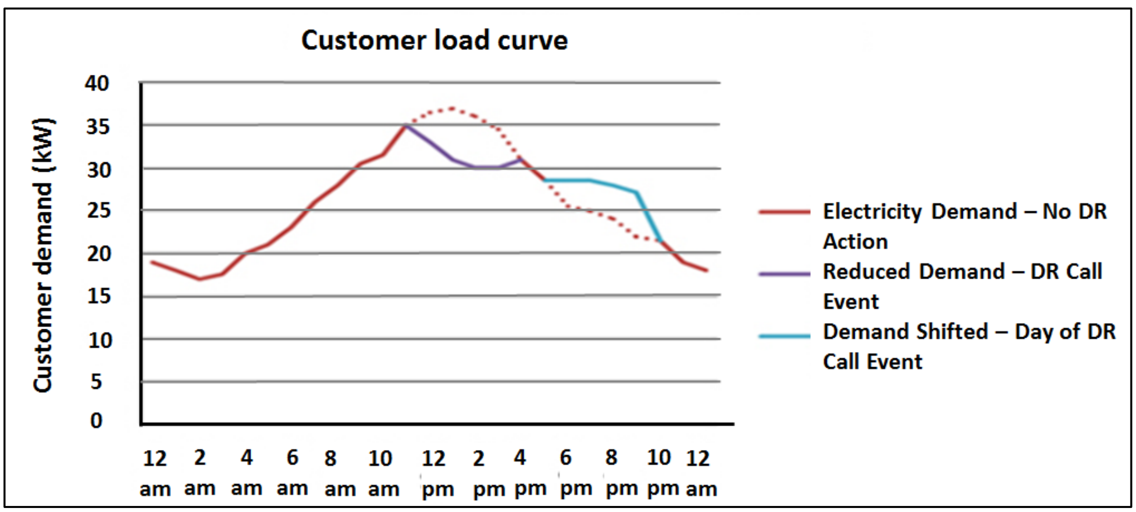


Figure C.1. Illustration of a Demand Response event. Source: (GreenBiz, 2016)

A brief explanation of the two demand response programs that are used in this thesis as an illustration for benefits calculation is provided below:

1. Base Interruptible Program (BIP): Under the BIP, customer declares a Firm Service Level (FSL) in kW which becomes a cap for maximum import from PG&E during the DR event. Once enrolled in the program, it becomes compulsory for the customer to participate and the customer has to pay a penalty if it exceeds the FSL during a DR event. BIP is a reliability based DR program initiated during the system emergencies. The notice to participate in a BIP program could be as short as 30 minutes. The number of DR events that PG&E can invite is limited to a maximum of one (1) event per day and four (4) hours per event. The BIP cannot exceed 10 events during a calendar month, or 180 hours per calendar year. More information about the program can be had from PG&E's program page at pge.com/en_US/business/save-energy-money/energy-management-programs/demand-response-programs/base-interruptible/base-interruptible.page.

2. Automated Demand Response (ADR): ADR encourages customers to expand their energy management capabilities by participating in DR programs using automated electric controls and management strategies. The objective of this program is to enable the execution of a sequence of steps at the facilities to curtail electrical load after receiving a communications signal from the utility.

More information about the program can be had from PG&E's program page at pge.com/en_US/business/save-energy-money/energy-management-programs/demand-response-programs/automated-demand-response-incentive/automated-demand-response-incentive.page.

# APPENDIX D. STEPS FOR DETERMINATION OF EMISSIONS FACTOR

This appendix shows calculations done by the author to estimate future emissions factors. The historical emissions factor till 2013 and projected emissions factor till 2020 for PG&E territory was available (PG&E, 2016c). It is acknowledged that the PG&E emissions factors may not be reflective of the entire California grid. PG&E has a lower emissions factor than the other investor owned utilities in California. However, the same was used for the sake of expedience. Using the historical data, a relationship between emissions factor and renewable penetration was derived by the author as shown in Figure D.1. Using the linear relationship established by the author, future emissions factors were projected considering California's goal of achieving 50% renewable by 2030. The projected emissions factors are shown in Table D.1.

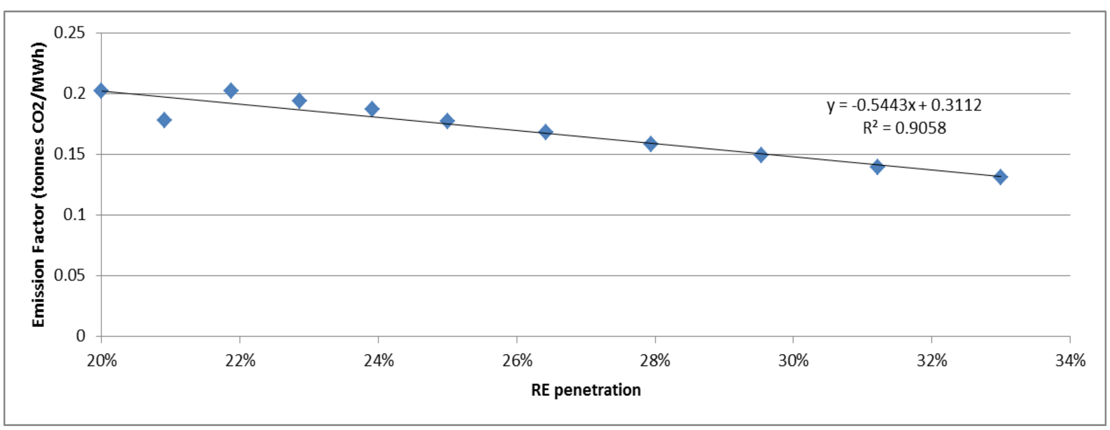


Figure D.1. Relationship between emissions factor and renewable penetration

Table D.1. Projection of emissions factor for California based on expected renewable electricity in the mix. The data till 2013 are actuals and data from 2014 to 2020 are forecasts (PG&E, 2016c). The data for 2021 to 2030 are author's projection.

| **Year** | **Renewable percentage in electricity** | **Emissions Factor (Metric tons $CO_2$/MWh)** |
|---|---|---|
| 2010 | 20% | 0.202 |
| 2011 | 20.9% | 0.178 |
| 2012 | 21.9% | 0.202 |
| 2013 | 22.9% | 0.194 |
| 2014 | 23.9% | 0.187 |
| 2015 | 25% | 0.177 |
| 2016 | 26.4% | 0.168 |
| 2017 | 27.9% | 0.158 |
| 2018 | 29.5% | 0.149 |
| 2019 | 31.2% | 0.139 |
| 2020 | 33% | 0.131 |
| 2021 | 34.4% | 0.124 |
| 2022 | 35.9% | 0.116 |
| 2023 | 37.4% | 0.108 |
| 2024 | 39.0% | 0.099 |
| 2025 | 40.6% | 0.090 |
| 2026 | 42.3% | 0.081 |
| 2027 | 44.1% | 0.071 |
| 2028 | 46.0% | 0.061 |
| 2029 | 48.0% | 0.050 |
| 2030 | 50% | 0.039 |