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A methodology for cooperation between electric utilities and consumers for microgrid utilization based on a systems engineering approach

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A METHODOLOGY FOR COOPERATION BETWEEN ELECTRIC UTILITIES AND CONSUMERS FOR MICROGRID UTILIZATION BASED ON A SYSTEMS ENGINEERING APPROACH

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Para quienes siempre me apoyan y confían en mí, incluso más que yo mismo: mi familia actual y futura.

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LIST OF ABBREVIATIONS

AMI: Advanced Metering Infrastructure

CEN: European Committee for Standardization

CENELEC: European Committee for Electrotechnical Standardization

DER: Distributed Energy Resources

DG: Distributed Generation

DoD: United States Department of Defense

ETSI: European Telecommunications Standards Institute

INCOSE: International Council on Systems Engineering

MRM: Microgrid Reference Methodology

NIST: National Institute of Standards and Technology (US)

PV: Photovoltaic

RES: Renewable energy sources

SE: Systems Engineering

SGAM: Smart Grid Architecture Model

SG-CG: Smart Grid Coordination Group

SoS: System of Systems

SoSE: System of Systems Engineering

GLOSSARY

Actor: An actor "is a social entity that has an interest in a system and/or has some ability to influence that system. An actor mostly is a group or organization, but important individuals can be considered as actors" (Enserink, 2015).

Business process: "a collection of interrelated tasks which solve a particular issue. There are at least three types of business processes: management and control processes, operational processes, and supporting processes" (Janssen, 2009, p. 117).

Cybersecurity: "The activity or process, ability or capability, or state whereby information and communications systems and the information contained therein are protected from and/or defended against damage, unauthorized use or modification, or exploitation" (National Initiative for Cybersecurity Careers and Studies, n.d.).

Microgrids: Localized grids that can operate autonomously when disconnected from the utility grid. They integrate distributed generation, load management, and storage in smart networks to provide ancillary, mitigation of disturbances, emergency back-up energy, and the improvement of energy efficiency, reliability, and resilience (Corum, 2015, p. 36)

Return on Investment (ROI): is "a performance measure used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments. […] To calculate ROI, the benefit (or return) of an investment is divided by the cost of the investment, and the result is expressed as a percentage or a ratio" (Investopedia).

ABSTRACT

Pacheco Chiguano, Franklin E. M.S., Purdue University, May 2016. A Methodology For Cooperation Between Electric Utilities And Consumers For Microgrid Utilization Based On A Systems Engineering Approach. Major Professor: Chris Foreman.

In recent years, the energy market has experienced important challenges in its structure and requirements of its actors, such as the necessity for more reliable electric service, energy efficiency, environmental care practices, and the incorporation of decentralized power generation based on distributed energy resources (DER). Given this context, microgrids offer several advantages to the grid and its actors. However, few microgrid projects have been implemented, and the participation of electric utilities is lower than the expected. Hence, this research explores how electric utility - customer interactions can accommodate mutual benefits for both parties through the proposal of a Microgrid Reference Methodology (MRM) that guides the cooperation of these actors for future microgrid projects.

For this research, an understanding of the microgrid system was imperative; hence, the interests and concerns of electric utilities and industrial customers were determined via questionnaires, interviews, and a literature review of specialized articles, books, and magazines. In addition, the MRM development was based on different frameworks and concepts from the fields of Systems Engineering, System of Systems, Management Science, and Infrastructure Architectures.

The proposed MRM uses a four-level microgrid system in which the δ (business) level is added to the other three levels that are traditionally analyzed in microgrid design

and modeling. The steps and processes necessary to determine the actors in the system and their interests, goals, criteria, and factors are exemplified with a generic case study, in which the proposed MRM evaluates the impact of different alternatives on the objectives of both parties. In addition, it was possible to identify external factors that can be influenced by other actors, such as regulators and government, to incentivize the implementation of microgrid projects.

CHAPTER 1. INTRODUCTION

This chapter states the problem addressed in this research, its scope, and significance. The chapter concludes by stating the assumptions, limitations, and delimitations of the research conducted.

1.1 Statement of the Problem

Microgrid technology is rapidly growing in the United States of America (USA), as well as in various other countries of the world. According to Saadeh (2015), it is "expected to grow the market opportunity by over 3.5 times between 2015 and 2020, to over $829 million annually" (para. 1). The main users of microgrids are industrial customers, such as factories, supermarkets, universities, governmental agencies, and the military.

In the recent years there have been considerable efforts to change the provision of electricity from a traditional model based in centralized big power plants to a decentralized model with more environmentally-friendly, distributed energy resources (DER). Furthermore, electricity consumers are generating their own electricity using solar panels and wind turbines, and feeding this power into the grid. Given this context, microgrid technology can help to increase power reliability, power quality, and power assurance of the grid, manage the intermittency of the DER, and control the peak demand cost. However, the utilization of microgrids introduces new issues, such as balancing supply and demand, managing utility-customer interactions, the need for proper planning, the need for simulation and management, the introduction of new implementation and maintenance costs, and cyber security concerns.

Most of the past and current research has focused on solving technical challenges. One important problem that has not yet been widely addressed is the interaction and cooperation between the actors in a microgrid project. Although it may seem trivial, this is very important for the successful adoption of microgrid initiatives. Currently, there is limited participation of electric utilities in microgrid projects. One reason is that utilities think their corporate profits would be threatened by microgrid participation. There are many actors with their own interests and different backgrounds: utilities, industrial/commercial customers, vendors, and regulators. Hence, the relationships and interactions between actors must be analyzed in order to understand the socio-technical complexity of microgrids and to propose solutions that benefit all the actors.

Current microgrid simulation and design tools consider the technical variables and manage the technical complexity of microgrid projects, but these tools do not consider some important non-technical aspects, which are even more critical in deciding whether or not to implement a project.

1.2 Scope

This is an exploratory study that aims to develop a methodology for future microgrid projects, especially with an existing infrastructure, and to handle the cooperation between utilities and customers. The methodology was implemented using a systems-thinking approach, which is often used to solve complex problems with different good alternatives rather than one optimal answer. According to Senge (1990), a systems thinking approach considers the whole rather than just the parts, and sees interrelationships rather than simply things. In addition, this study used the established framework and principles of engineering systems design and system of systems. It is necessary to analyze different system models and approaches in order to determine the best strategies to apply in the current scenario. Furthermore, the perspectives of electric utilities, vendors, and customers were important data for microgrid system modeling and strategizing.

This research includes a phase of obtaining data from secondary and primary sources. The secondary sources were journals, magazines, and reports regarding previous and current microgrid implementations in different U.S. states that mainly feature the perspectives of the electric utilities and customers. In addition, other important sources of information were conferences and webinars related to the future of electric utilities and Regulators in new energy markets. The primary information sources utilized were interviews and questionnaires to representatives from one utility company and one industrial customer to determine the necessities of every actor. Following this literature review and systems tool analysis, different procedures were proposed to define the methodology's architecture, the principle deliverable of this research. Finally, the methodology was tested in a case study to determine its validity and applicability for future scenarios. This case study was a generic microgrid project in its design phase.

1.3 Significance

The implementation of microgrid projects offers considerable benefits to the electrical grid in terms of system robustness, resilience, and security. Microgrid projects also deliver increased power security to critical loads, use renewable integration, and include emerging technologies instead of traditional fuel sources that negatively impact the environment.

Current U.S. microgrid projects are mainly developed by private initiatives founded by private companies in the electricity industry, or by states that are encouraging energy efficiency initiatives. Unfortunately, not all electric utilities are participating in microgrid projects because they see microgrids as potential threats to their incomes and the payoff as not as beneficial as possible. In addition, regulators have not created laws in favor of the new energy market. For example, in some states, companies that own a microgrid are not allowed to distribute or sell excess electricity to the grid, and there are no incentives to make utilities change their business models.

This research will guide the model of cooperation, implementation, operation, and maintenance of a microgrid and accommodate different stakeholders maximizing their payoffs. This research will help to manage risk and liability, determine an ongoing plan for utility/customer interaction and operation of the microgrid, thereby supporting the decision-making process and cooperation.

If this research project is not carried out, the proliferation of DERs and microgrid technologies may be compromised; utilities will continue using the traditional business model described by Corum (2015), in which new centralized power plants are used as loads increase and added to their rate bases.

1.4 Research Question

How to determine utility-customer interactions that accommodate mutual benefits from a microgrid project, while taking into account technical and non-technical variables?

This question includes the following sub questions:

- What kind of technical and economic benefits are commonly expected by utilities and customers?
- How can an existing local distribution grid be turned into a microgrid?
- How can the benefits and risks of a microgrid project be quantified to justify its implementation?
- How should the information and control be shared between the utility and its customers?
- How can cyber-security be implemented effectively?

This is a qualitative research and the hypothesis was developed as the research progressed. The goal of the research is to develop a new methodology for microgrid designs that incorporates the interests of utilities and customers and helps to handle their interactions for mutual benefits.

To validate the results and decide if the research question and sub questions were answered, a simulated case study was performed using face validity, as explained in the subsequent research methodology subsection.

1.5 Assumptions

The assumption made in this research include:

1. This research is limited to U.S. regulations and companies, specifically in the state of Indiana.
2. At the present time, the technology necessary to implement a microgrid project exists; therefore, this is not a limiting factor in cooperation projects.
3. There are no political restrictions for microgrid project implementation.

4. All stakeholders in a microgrid project are willing to participate; hence, there are no personal reasons that hinder collaboration.
5. The current regulatory norms, tariff structures, and market conditions regarding microgrids did not change during the development of this research.

1.6 Limitations

The limitations of this research include:

1. This project did not have funding from any organization; hence, the research was theoretical and utilized the Purdue University resources.
2. The research was performed with the data obtained from an Indiana utility company, and two industrial customers. In addition, the study examined reports and literature from other states.
3. The methodology provided strategies and recommendations for different microgrid project scenarios according to the stakeholders' requirements.
4. The methodology was evaluated in the planning stage of a generic microgrid project with different simulation scenarios because an actual microgrid installation was unavailable to validate this research.

1.7 Delimitations

The delimitations of this research include:

1. The deliverable of this research was not a software tool or a device. Instead, the deliverable is a documented methodology.
2. The methodology was not evaluated in a real microgrid project during this research.

1.8 Chapter summary

Chapter One introduced and justified the research explained in this thesis, and outlined the problem statement, research question, and significance. Additionally, this chapter noted the assumptions, limitations and delimitations of the research scope.

CHAPTER 2. REVIEW OF LITERATURE

This chapter provides a summary of research literature concerning microgrid systems, beginning with a theoretical basis and key concepts, then referencing the most relevant approaches and methods in order to analyze and model systems with some degree of complexity. This approach fosters a complete understanding of the current situation and establishes the research problem. Furthermore, the literature review supports the research methodology.

2.1 Introduction

Rapid world population growth and the modernization of society has led to a greater awareness of conservation, sustainability, and access to real-time information. These trends have increased the demand for electricity generated in a cleaner, efficient, more environmentally-friendly ways (Feisst, Schlesinger, & Frye, 2008). Currently, the electrical networks of most countries are unable to meet these new requirements because they were developed several years ago with the sole purpose of delivering electricity to consumers. For instance, U.S. power-grid transmission lines are, on average, 50-60 years old (Yang, Divan, Harley, & Habetler, 2006). These outdate electric grids need to be replaced and enhanced with new technologies. The microgrid is a popular option.

In order to effectively implement microgrids, a proper planning methodology is necessary to ensure maximum mutual benefits while mitigating risk and conflict. This scenario leads to the emergence of a smarter electric grid capable of automating the integration, control, and management of all systems and stages involved in the generation, transmission, and distribution of the electricity; secondly, this strong interaction with the consumer leads to better energy management. This approach requires the integration of Information and Communication Technologies (ICT) in two-way communication technology and computer processing.

Moreover, understanding the complete system involved in a microgrid project is crucial. This understanding defines policies and strategies for the decision making process and other stages of the project, such as planning, designing, implementing, and operating. Because microgrid technologies cover different areas of knowledge in technical, economical and sociological facets, the literature in this topic is varied. In this research, the literature review focuses on microgrids, modeling, simulation techniques, and articles related to cooperation between industrial customers and utilities.

2.2 What is a smart grid?

No single answer defines a smart grid. A smart grid is not just a single technology; rather, it is a complex infrastructure, a platform for various socio-technical factors. According to CEN/CLC/ETSI/TR (2011), a smart grid "is a supply network (principally electricity network) that intelligently integrates the behavior and actions of all users connected to it-- generators, consumers and those that do both-- in order to efficiently ensure a more sustainable, economic and secure electricity supply" (p.11). In *Figure 2.1*, Vijayapriya & Kothari (2011) display a model Smart grid set-up with subsystems and elements such as distributed energy sources, a central power plant, smart appliances, demand management, sensors, processors, a storage system, various customers (houses, industrial plants, office buildings), and the communication networks between these elements. This figure demonstrates that these connections are more complex than a traditional grid with sequential hierarchy and defined boundaries for generation, transmission, and distribution.

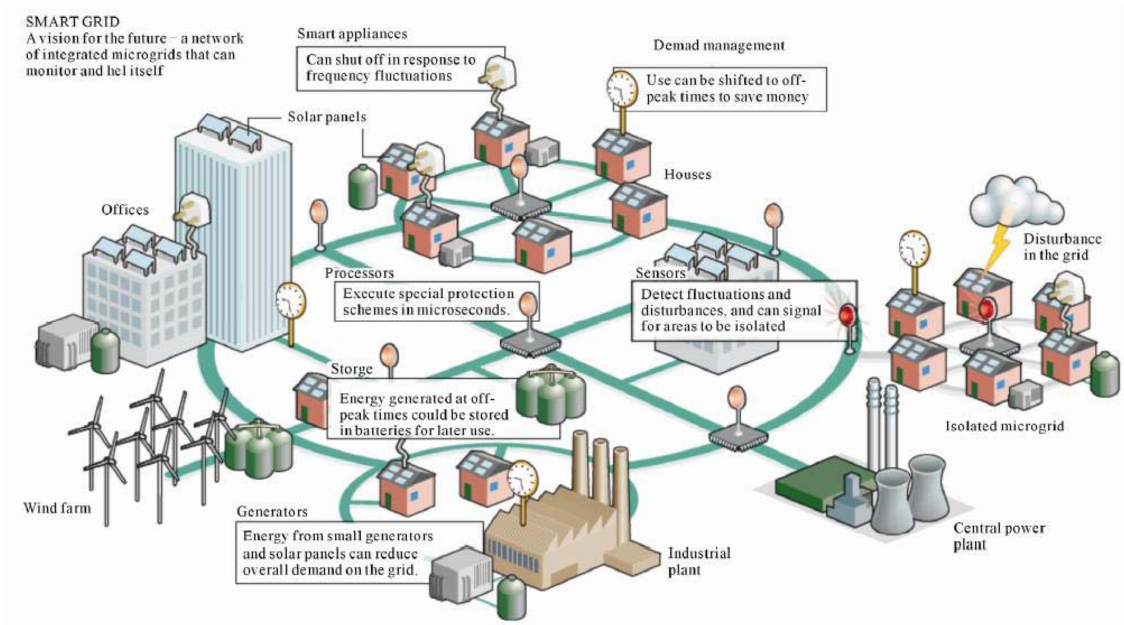


Figure 2.1 Model of Smart Grid Network (Vijayapriya & Kothari, 2011, p. 307)

Under the Energy Independence and Security Act of 2007 established by PUBLIC LAW 110–140 (2007) in its Title XIII Sec. 1301. Statement of Policy on Modernization of Electricity Grid, the main characteristics of Smart Grids are:

1) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid;
2) Dynamic optimization of grid operations and resources, with full cybersecurity;

3) Deployment and integration of distributed resources and generation, including renewable resources;

4) Development and incorporation of demand response, demand-side resources, and energy-efficiency resources;

5) Deployment of "smart" technologies for metering, communications concerning grid operations and status, and distribution automation;

6) Integration of "smart" appliances and consumer devices;

7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning;

8) Provision to consumers of timely information and control options; and

9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid (PUBLIC LAW 110–140, 2007, p. 121 STAT. 1784).

To achieve these characteristics, a smart grid uses a two-way communication network that allows all components of the power grid to communicate through the network (CodeAlias, n.d.). Although a smart grid is not a new concept, it has recently become an international hot topic among engineers, economists, managers, politicians, and scientists because issues such as environmental care and sustainability have never been as important as they are now. Indeed, as stated by Doorsamy, Cronje, & Lakay-Doorsamy (2015), the World Energy Council has recognized three major energy challenges affecting all nations:

1) Energy equity - Task of providing accessible and affordable energy supply for the entire populace.
2) Environmental sustainability - Issues relating to environmental impact, such as supply- and demand-side energy efficiencies, and utilization of renewable and low-carbon sources.
3) Energy security - Challenges with the reliability of the energy infrastructure, the ability to meet current and future demands, and the effective management of energy resources (Doorsamy et al., 2015, p. 1251).

In this research, we review issues concerning the architecture of Smart Grids. A reference architecture was developed to represent the various systems, subsystems, and information flows within a smart grid. In 2008, the GridWise Architecture Council developed an eight-layer architecture for determining interoperability and information requirements in three main categories of processes and objectives: Technical, Informational, and Organizational. In 2010, The National Institute of Standards and Technology (NIST) established a conceptual model of Smart Grid actors and interactions. NIST considered seven domains that interact(2010, p. 33) in *Figure 2.2*. In addition, they describe each domain's actors, communications path, and information network with the objective of defining standards and protocols that allow interoperability between Smart Grid systems and equipment (Moura, López, Moreno, & De Almeida, 2013, p. 627).

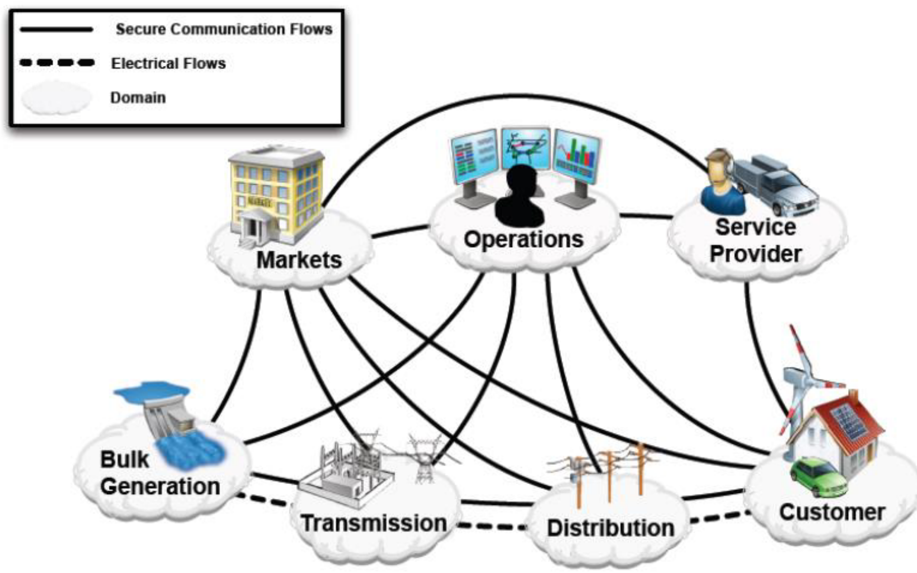


Figure 2.2 NIST Smart Grid Framework 1.0 (NIST, 2010, p. 33)

In 2012, the European Union Mandate M/490, the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI) proposed their Reference Architecture (RA) and Smart Grid Architecture Model (SGAM). The development of RA and SGAM took into account relevant aspects of previous approaches, such as the GWAC and NIST models; also included were specific requirements related to the EU context, such as DERs and flexibility in production, consumption, and storage to support future demand response (CEN/CENELEC/ETSI, 2012, p. 22). *Figure 2.3* shows the EU conceptual model, which includes the same domains as the NIST model. In addition, the model considers the decentralized nature of the DER, which makes room for the existence of the microgrid domain composed by the Distribution, Customer and DER domains. This representation was a first attempt to show interactions between a microgrid and other domains in the power grid and power market, such as generation, transmission, operations, market, and service providers.

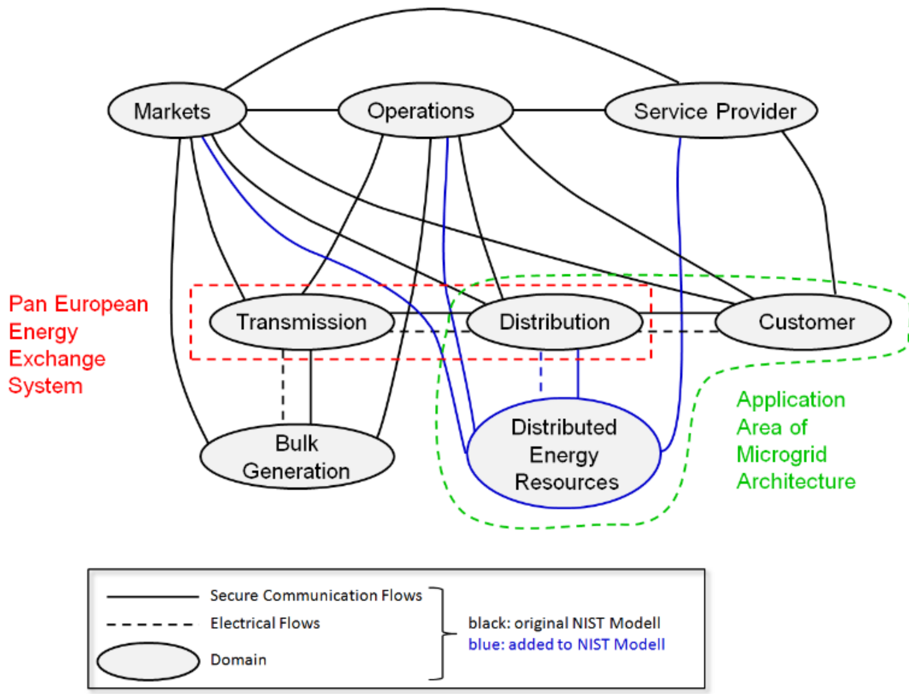


Figure 2.3 EU Smart Grid Conceptual Model (CEN/CENELEC/ETSI, 2012, p. 21)

The SGAM is a three dimensional model with five interoperability layers, six zones or hierarchical levels of power system management, and five domains, or phases in the electrical energy conversion chain (CEN/CENELEC/ETSI, 2012, p. 22). *Figure 2.4* shows the SGAM, which aims to represent a use case with its actors, relationships, and functional requirements by mapping the component, business, function, information, and communication layers onto one another.

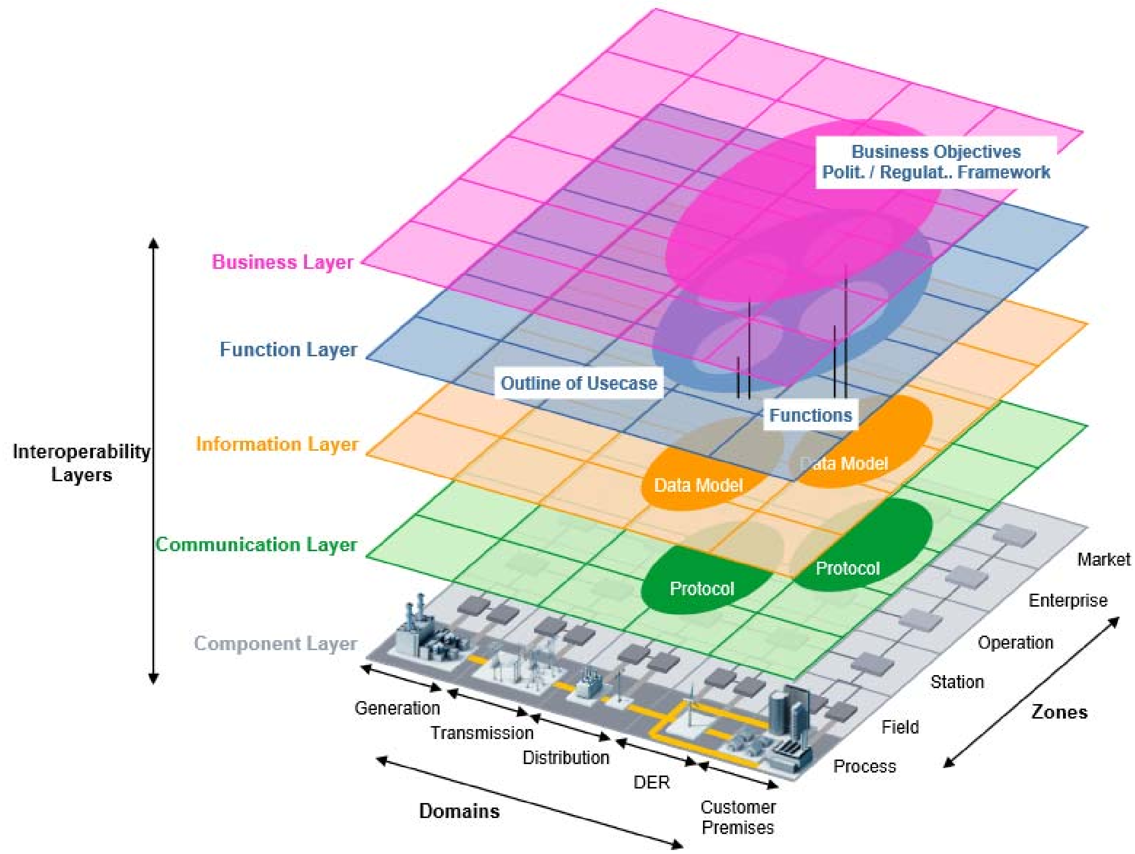


Figure 2.4 SGAM framework (CEN/CENELEC/ETSI, 2012, p. 30)

The NIST conceptual model was updated in 2014 to decentralize the generation and include DERs. Hence, a new architectural framework was developed using the SGAM and The Open Group Architecture Framework – Architecture Development Methodology (TOGAF/ADM), a collaboration of the Smart Grid Architecture Committee (SGAC), the European SG-CG, the International Electrotechnical Commission (IEC) TC57 WG19 (IEC 62357), and IEC TC8 WG5. As shown in *Figure 2.5*, according to the NIST (2014), this architecture includes four layers (Technical, Automation, Information, and Business) and four levels (Conceptual, Logical, Physical, and Implementation), but each level is represented by a 3-dimensional plane where the four layers constitute one axis; another axis is constituted by the domains of the NIST conceptual model, and the third axis is the zones or physical management aspect of the grid. (NIST, 2014, p. 131).

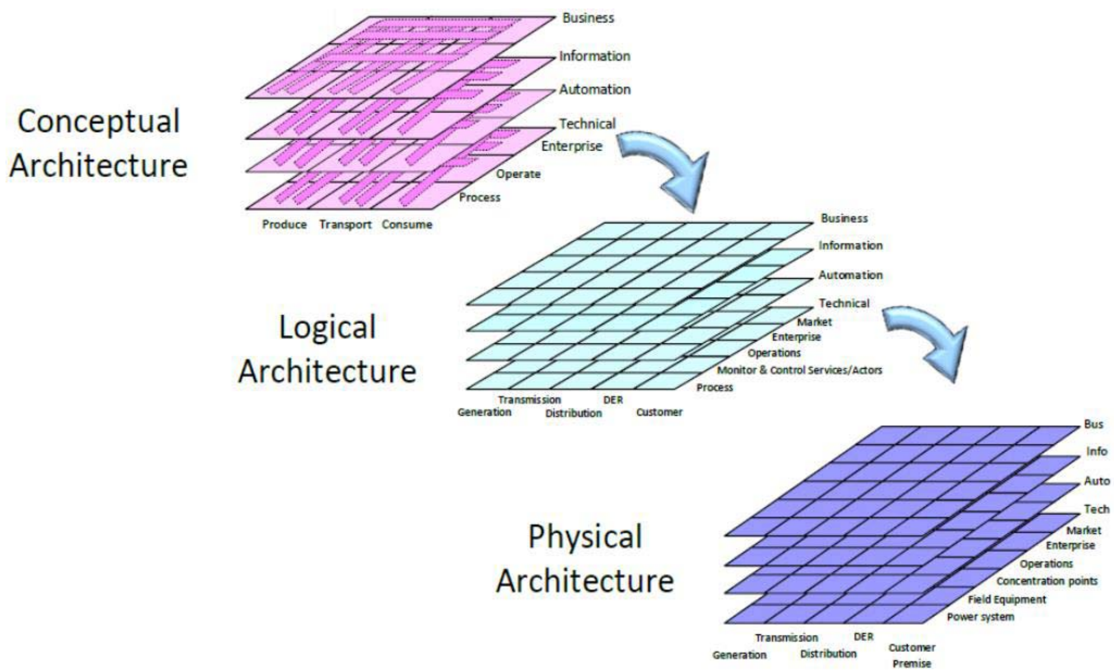


Figure 2.5 NIST SGAM Interactions, layer and planes (NIST, 2014, p. 135)

The definition of a Smart Grid reference architecture has been an iterative process. in which various organizations and parties have collaborated and new developments become more complex as they consider new aspects of the real complexity of smart grids. In fact, the NIST document states that a smart grid is a system of systems with several stakeholders and elements structured in a complex evolving network.

Moreover, a microgrid architecture could be involved as part of the SGAM analysis. However, the particularities of microgrids, and the fact that it is possible to implement a microgrid without a smart grid, make it necessary to work in an exclusively microgrid reference architecture.

2.3 What is a microgrid?

The concept of smart grids implicates the use of distributed energy resources handled by microgrid technologies. Therefore, microgrids are localized electrical grids with the ability to disengage from the utility distribution grid and continue operating independently to "help mitigate grid disturbances to strengthen grid resilience … [because they] can function as a grid resource for faster system response and recovery" (Office of Electricity Delivery & Energy Reliability, n.d.). When there is a power quality incident in the main grid, a microgrid islands and reconnects itself once the event has been removed. For an electric utility, a microgrid is seen as a single, combined load which consists of "two critical components: a static switch and micro source, which consists of generator, storage and an inverter" (Banerji et al., 2013, p.27).

According to Marnay et al. (2015), the main advantages of a microgrid are: "improved energy efficiency, minimization of overall energy consumption, reduced environmental impact, improvement of reliability of supply, network operational benefits, congestion relief, voltage control, security of supply, and more cost-efficient electricity infrastructure replacement" (p. 1).

Microgrid implementation does not just add renewable energy sources: "rather than add distributed generators to the power grid in an ad hoc manner, in a microgrid approach the global power grid is, in essence, apportioned into smaller power grids" (Bush, 2014, p. 172). The goal of a microgrid is to control and reduce peak demand, and determine the best energy storage technologies, building energy management, advanced metering infrastructure (AMI), and communication required with the inherent cyber security issues.

“Microgrids integrate distributed generation, load management and storage in smart networks providing ancillary, mitigation of disturbances and strengthening the grid, emergency back-up services, improve energy efficiency, reliability and resilience” (Corum, 2015, p. 36). Microgrids can be understood as building blocks of a future, smarter electric grid. They integrate various subsystems and goals in a complex systems or system of systems (SoS) depending on the magnitude of the microgrid and its elements. In this context, some authors have analyzed recent developments in microgrid modeling and control methods for both grid-connected and autonomous mode as well as SoS control strategies such as networked control system and obtaining a better control of microgrids. (Mahmoud, Azher Hussain, & Abido, 2014).

According to Banerji et al. (2013), microgrids can be classified into two types, AC and DC, based on the output voltage to the loads. In addition, a microgrid can work in two operational modes: grid-connected and islanded. In the grid-connected mode, the microgrid exchanges power with the electric utility grid. The utility sees the microgrid as a controlled load; therefore, the microgrid must regulate the harmonics and power quality introduced to the grid. In the islanded mode, the microgrid operates independently of the main grid. The microgrid islands automatically when there is a power issue in the main grid (p. 28).

> A microgrid’s control and operation functions are described in the Smart Grid Interoperability Panel (SGIP) and synthesized by Bower, Guttromson, Glover, Stamp, & Bhatnagar (2014) as follows:
>
> Function 1. Frequency control
>
> F1.1 Islanding mode

F1.2 ACE control and connected mode (similar to AGC)

F1.3 Frequency smoothing

F1.4 Frequency ride-through

F1.5 Emergency load-shedding

F1.6 Steady state control

F1.7 Transient control

Function 2. Volt/VAR control

F2.1. Grid-connected Volt/VAR control

F2.2. Islanding Volt/VAR control

Function 3. Grid-connected-to-islanding transition

F3.1 Intentional islanding transition

F3.2 Unintentional islanding transition

Function 4. Islanding-to-grid-connected transition

Function 5. Energy management

F5.1. Grid-connected energy management

F5.2. Islanding energy management

Function 6. Protection

Function 7. Ancillary services (grid-connected)

F6.1. Real-power-related ancillary services

F6.2. Reactive-power-related ancillary services

Function 8. Black start

Function 9. User interface and data management (p. 25).

According to Schwaegerl & Tao (2013), these functions can be offered to consumers via ancillary services, by into the two operational modes analyzed previously. For a grid-connected mode via frequency control support, voltage control support, congestion management, reduction of grid losses, and improvement of power quality such as voltage dips, flicker, and compensation of harmonics. In islanded operation mode via black start and grid-forming operation and frequency/voltage control (p. 15).

2.4 Recent microgrid projects

Although the concept of microgrids has been around for several years, the implementation of this technology has taken time, mainly due to a lack of regulatory policies and standards to encourage the participation of industrial customers and utilities. Recently, the importance of using alternative, sustainable energy sources, and the necessity for energy efficiency have prompted attention to the microgrid as an effective solution. Some recent projects "have integrated a more diverse set of distributed energy resources, with roughly one-third of projects deploying battery storage" (Klemun, 2014, p. 2). In addition, the costs per installed capacity of a fossil fuel-based microgrid are more expensive than renewable-based microgrids; the comparison is around $3,500 to $4,500 per kilowatt versus $1,000 per kilowatt respectively (Klemun, 2014). "Several East Coast states, including New York, New Jersey, and Connecticut are investing millions of dollars in Microgrids, installing the power systems Microgrids need, independent of or in cooperation with utilities" (Corum, 2015, p. 37). Furthermore, in the regulatory arena there are some initiatives "where Microgrids could play a role in providing demand response services and regulation support while stabilizing the utility customer rate base" (Corum, 2015, p. 37).

Although the technology is not new, the market itself is new and there are some important legal barriers, especially in the case of multi-building and multi-owner microgrids. Consumer priorities, regulation, and prices vary by region and state. For instance, the Midwest has low electricity prices, which makes it difficult to demonstrate the necessity of microgrids. On the east coast, the government acknowledges microgrids as an alternative electricity to remedy main grid incidents caused by natural disasters (Klemun, 2014).

Within smaller east coast communities and cities, a fast increase in microgrid initiatives for critical infrastructure, such as universities, schools and hospitals, due to state government incentives is expected (Grid Edge, 2014). The microgrid market is facing a transformation “from a niche application intended for military bases and remote communities to a grid modernization tool for utilities, cities, communities and public institutions” (Saadeh, 2015, p. 1). From 2015 and 2020, microgrids are expected to increase market incomes by over 3.5 times and reach $829 million annually. (Saadeh, 2015, p. 1). This expected market growth is based on rate structures, utility franchise rights, and the adoption of photovoltaics in states with high radiation. These changes are already occurring in New York, Maryland, California, and Hawaii (Saadeh, 2015, p. 2).

Current microgrid-related project collaborations in the U.S. include:

- The U.S. military is working on cyber secure microgrid reference architectures through its Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) program, which was developed and tested in 2015 at Hawaii's Camp Smith.

- State-led initiatives, such as Connecticut's microgrid pilot program, were implemented in close cooperation with local electric utilities United Illuminating and Connecticut Light and Power.
- The collaboration of Power Analytics, OSIsoft, and Viridity Energy worked on a project at the University of California, San Diego and now cooperates to link three San Diego naval bases to one microgrid.

Some organizations actively working on microgrid implementation projects are:

- Vendors that have experience across several microgrid types, such as S&C and ZBB Energy Corporation
- The Microgrid Resources Coalition (including NRG Energy, Inc. and the International District Energy Association)
- The Microgrid Alliance (Alstom, Enbala, HOMER Energy, General Microgrids, and Landis+Gyr)
- The Galvin Electricity Initiative (Klemun, 2014)

Recently, some states have been encouraging energy efficiency and microgrid projects. For instance, the New York State Energy Research and Development Authority (NYSERDA) has financed projects aimed to improve the overall performance of its energy delivery system. *Table 2.1* shows the main projects funded and the cost, according to the Governor of New York State (2014).

Table 2.1 Energy efficiency projects founded by NYSERDA.

Beneficiary	Location	Cost investment	Description
Brookhaven National Laboratory	Long Island	$250,000	Using radars for real-time response to the restoration of electric utility systems
Clarkson University	Potsdam	$381,000	Design of a resilient underground microgrid
ClearGrid Innovations Inc.	New York City	$100,000	Using computer vision to analyze electric distribution problems
Con Edison	New York City	$2 million	Demonstrating grid link: a non-synchronous microgrid solution
Cornell University	Ithaca	$227,000	Advanced microgrid integration with distributed energy resources
Lockheed Martin Mission Systems Training	Owego	$300,000	Integrated aerial weather damage assessment system
Rochester Institute of Technology	Rochester	$78,000	Micro-grid cooperation for improving economic and environmental cost and grid resilience

In addition, the US Department of Energy awarded $8 million in September 2014 to seven companies and institutions in order to help communities become more adaptive with microgrids and build grid resiliency (Corum, 2015). This action suggests that the U.S. government is invested in microgrid initiatives. However, based on previous projects, it is evident that the customer, the final microgrid user, is trying to take advantage of these governmental incentives but there is a lack in the participation of electric utilities.

Companies that have received awards regarding to the implementation of microgrids include: GE in Potsdam NT, ALSTOM Grid, Inc. in Philadelphia, and EPRI. Schneider Electric has the necessary experience in European inverters to meet the California Energy Commission's Smart Inverter Working Group requirement that inverters are “more flexible and utility transmission and distribution friendly.” “Homer Energy designs microgrid systems and modeling software for users across the globe, mainly for islands and small villages in developing countries with unreliable power systems that rely on diesel generators (Corum, 2015).

Peter Lilienthal, CEO of HOMER Energy, says there is a lack of standardized regulation of microgrids in the U.S., and therefore disincentives for utilities to permit them. Some states have created performance-based ratemaking in order to eliminate disincentives toward distributed generation. In some states, companies with microgrids cannot sell or distribute power across right-of-ways because they will be considered as utilities. For electric utilities, they should change their business models; however, without directions from regulators, the utilities have little incentive to change (Corum, 2015).

Despite regulatory restrictions, private companies are developing tools and products to encourage microgrid adoption. Power Analytics has created power network, “cloud-based software platform to operate microgrids, distributed generators, battery storage, and electric vehicles, allowing owners to sell power to another entity or the grid” (Corum, 2015, p. 38).Moreover, Oliver Pacific from Spirae “builds real time controls and has developed WAVE platform for electric distribution operators which allow them to reliably integrate and operate renewable energy, storage systems, and electric vehicles.” Spirae uses Power Analytics software to manage power quality with real time controls. Microgrids must provide frequency regulation, voltage support, and reactive power when exporting power so that grids remain stable. For distributed energy resources, “currently, rules and regulations don’t allow inverters to control output and the incentives for controlling output are not there.” (Corum, 2015, p. 39). However, Pacific believes that the de costs of DER will come down and that will encourage the development of combined heat and power (CHP).”.

JLM Energy in Rocklin CA develops microgrid projects for islanding conditions. They offer solar, wind, storage, and controller systems. WIPOMO, in Hayward CA and Denver CO, offers mobile microgrid off-grid systems called a “Mobile Energy Ecosystem” for applications such as traffic lights, lifeguard stations, and outdoor events with sound stations and food trucks (Corum, 2015).

2.5 Microgrid and Utility Interactions

An important concern is whether the microgrids will complement electric utilities or compete with them. It is necessary to define interconnection standards, standby rates, and sub-metering rules. (Wood, 2014). The traditional business model of utilities is to react to the demand by building additional centralized power plants and applying the same rate bases; this is now changing because 12% of new power plant capacity comes from distributed solar resources. Electricity suppliers argue they “cannot reduce output when supplies or reserves are low, […] so they spread the fees to all retail generators” (Corum, 2015, p. 40).

The new role of utilities is to become a distributed system operator (DSO) “responsible for ensuring there is available capacity for distribution of electricity generated either behind the customer’s meter, or connected on the utility side or flowing from the transmission grid” (Corum, 2015, p. 40). The DSO “is able to schedule and dispatch the two-way flow of electricity and manage the stability of the distribution system.” The DSO is in charge of distribution system maintenance and operation. Valentin de Miguel from Accenture Smart Grid Services asserts that “transforming business models would include adopting new tariff structures; opening up markets; aligning subsides; investing in grid optimization such as automation, sensing devices, and real-time analytics; and developing new customer products and services" (Corum, 2015, p. 40).

According to Wood (2014), there are several concerns that limit utility companies' participation in microgrid projects. These concerns are as follows:

- How will microgrids influence their business model and the functioning of the central grid? Microgrids may harm the reliability of the larger grid through faulty interconnection, tripping or failing to island and re-connect correctly.
- A microgrid provider may find it difficult to deal with the utility's legacy system and navigate interconnection procedures.
- The cost to provide back-up power for microgrids, especially if they proliferate, is considerable.
- If customers flee the system for distributed generation and microgrids in great numbers, that leaves the utility with a rate base too limited to fund needed infrastructure without dramatic rate increases.
- In many locations, a microgrid cannot string wires across a public street to serve customers; doing so infringes on the local utility's franchise rights.
- Microgrid developers "depend on the goodwill of the regulators and local utility, or the utility's willingness to form a financial partnership or agreement with the microgrid"
- Utilities typically cannot own or develop power plants in restructured states

- Should utilities be allowed to charge a premium rate, given the high quality of the power?
- Should utilities or grid operators create some form of locational pricing to attract microgrids to areas of the grid where they are needed, such as points of congestion?
- How to calculate and recognize the environmental value of a microgrid? Must the benefit/cost analysis for any grid modernization consider the value of greenhouse gas emissions reductions?
- The importance of a regulation that can help utilities and microgrids navigate many of these risks (Wood, 2014).

The Future of Utilities seems to have undergone a considerable change in their business models; however, nowadays there are some companies already following these market trends. For example, Central Hudson Gas and Electric Company, a New York-based utility, has designed a new service based in microgrids for customers who need improved reliability. The utility would build, operate, and maintain a microgrid with a single or group of customers whose demand is at least 500 kilowatts with a necessity for uninterrupted and high quality power supply. These customers are mainly hospitals, government and military facilities, police, universities, schools, and large commercial and industrial facilities (Jenkings, 2014).

Another example is Duke Energy, which partnered with developers and vendors of equipment to implement a Microgrid Testbed Project denominated Coalition of the Willing. Jason Handley, Duke's Director of mart grid Emerging Technology and Operations, said that financing the microgrid equipment is necessary for customers, as well as the installation and operation. Handley added that “Other companies are trying to install them for customers, but Duke believes there could be a business case to do this on our own. We have good access to capital and know how to operate a grid better than anyone else. It’s potentially a win-win and fully takes advantage of distributed energy resources coming on line” (Lisa Cohn, 2016).

According to Navigant Consulting, Inc. (2015), the lack of established microgrid business models, uncertainty about technologies used, and legal issues are the biggest challenges for market growth. These lead to uncertainty, complexity, and considerable risks; collaboration and partnership will play a key role in the success of microgrid projects. Navigant highlighted the importance of “careful segmentation and targeting of markets and customers” (Burger, 2015). In this context, Navigant developed a tool shown in *Figure 2.6* to represent the microgrid commercial ecosystems and analysis components. This diagram clearly depicts the main microgrid participants and their interactions. Accordingly, the distribution service provider interacts with the community , the microgrid user, the microgrid assets owner, the DER owner, etc., However, this diagram shows that the distribution service provider does not interact with the regulator or suppliers directly; in reality, there are microgrid projects carried out by direct partnership between electric utility companies and suppliers , regulatory changes, and new business models initiatives proposed by joint work between electric utilities and regulators.

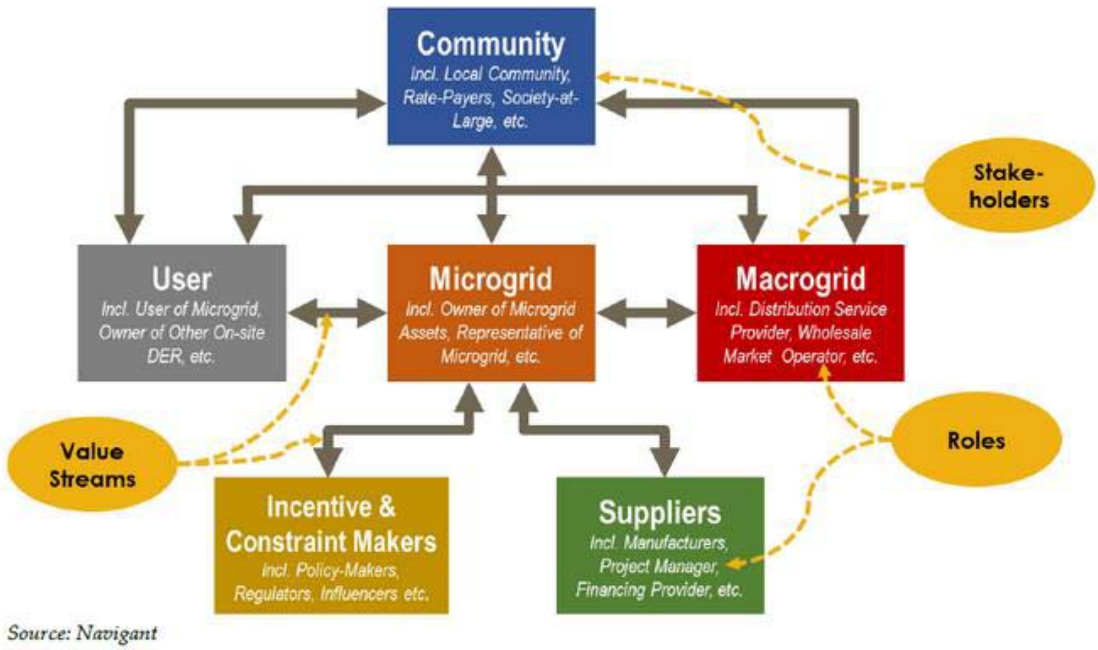


Figure 2.6 Microgrid Commercial Ecosystem (Navigant Consulting, Inc., 2015, p. 3)

Furthermore, microgrids function within the energy markets; the relevant actors, according to Schwaegerl & Tao (2013), are:

- Consumers: Users of the distribution network; they pay a retail company for their energy supply (p. 12).
- DG owner/operator: those who inject DG production to the network and enjoy feed-in tariffs; sometimes they pay distribution network charges (p. 12).
- Prosumer: consumers who are also DG owners and can inject the surplus of energy produced back to the grid (p. 12).
- Customer: a broad category that include consumers, DG owner/operator, and prosumers (p. 12).

- Market regulator: independent organization that defines the rules of operate in the market, guaranteeing open access to the grid and efficient allocation of grid costs (p. 12).
- Retail supplier, energy service company (ESCO): provide electricity and supplementary services to its customers. They acquire energy from different sources, including DER, and define products and energy prices when those are not regulated (p. 13).
- Distribution system operator (DSO): Responsible for the operation, maintenance, and development of the distribution network in a certain area. The DSO manages the HV, MV, and LV distribution systems, delivers electricity to consumers, and absorbs energy from DG/RES. However, the DSO is not involved in retail activities like the ESCO. In a future microgrid market, DSOs “will contract both with suppliers managing microgrid customers and with individual distributed generators to utilize their flexibility for local network balancing” (p. 13). In the future, “a new set of agreements between suppliers and DSOs will ensure that customers benefit from proper functioning of the market, smooth processes and a secure and reliable electricity supply; suppliers will market new products and optimize their supply and balancing portfolio, while DSOs can guarantee local grid stability and security of supply through system services” (p. 13).
- Microgrid operator: In charge of the operation, maintenance, and development of the local distribution grid of the microgrid elements. This

> function can be performed by the local DSO or by an independent DSO acting on behalf of microgrid customers (p. 14).

2.6 Microgrids Decision Making and Optimization

There are several articles that focus on microgrid optimization and decision-making; most are focused on the technical aspect of the microgrid. For example, Amin (2013) addresses the microgrid self-healing issue by which a “grid isolates problems immediately as they occur, before they cascade into major blackouts, and reorganizes the grid and reroutes energy transmissions so services continue for all customers while the problem is physically repaired by line crews” (Amin, 2013, para. 6). He suggests that “a self-healing smarter grid can provide a number of benefits that lead to a more stable and efficient system” (Amin, 2013, para. 7).

A simple scenario to understand and simulate the self-healing characteristic assumes that there are no distinct energy demands for which alternative supply sources must be allocated in the short term to respond to disruptions. For each of these n demands, there is a finite set of available supply sources that can be allocated to meet the demand (Nygard et al., 2011).

The solution can be found with different optimization methods. One approach is the Karush–Kuhn–Tucker condition that allows inequality constraints and generalizes the method of Lagrange multipliers used only with equality constraints. Another approach is the simplex method that uses matrices to calculate reduced cost coefficients and update the canonical augmented matrix (Chong & Żak, 2013). The problem with the previous methods is that they require a great deal of mathematical calculations and they are more useful for smaller numerical value; otherwise, a smart grid simulator is preferred, which runs as a Multi-Agent System (MAS) using the Java Agent Development Framework (JADE).

Another important issue in microgrid decision-making is to determine the economic and environmental value microgrids can provide. Some research has studied the impact of solar thermal and heat storage of CO2 emissions and annual energy costs by formulating a microgrid's (DER) adoption problem as a mixed-integer linear program. In this case, the optimization problem is minimizing the annual energy costs. A case study was applied to the California service territory of San Diego Gas and Electric (SDG&E). The results show "A CO2 pricing scheme would be needed to incent installation of combined solar thermal absorption chiller systems, and no heat storage systems are adopted [as well as] photovoltaic (PV) arrays are favored by CO2 pricing more than solar thermal adoption" (Marnay et al., 2009, p. 1).

Islanding issues are another significant microgrid concern. Although distributed generations (DG) such as photovoltaic and wind energy sources present great benefits to society, their interconnection with electric power systems (EPS) introduces some important issues like islanding, which is dangerous to utility workers who may not realize a circuit is still powered by DG; for this reason, the detection of islanding is necessary to stop the generation of energy from the DG to the EPS. Current islanding detection methods require expensive communications infrastructure, cause degradation of power quality, or have large non-detection zones (NDZ). Studies have proposed a new islanding detection technique for microgrids based on critical system features, a pattern of different types of system events, and decision tree based classifiers to determine islanding conditions(Azim et al., 2015). The contribution to the field is an alternative to detect islanding without incurring the costs of expensive communication and control equipment that accompany the existing methods.

2.7 Systems Thinking

While the decision-making and optimization approach is important to address different issues in microgrids, a better approach is to analyze the interaction between different actors holistically using systems theory. First it is important to understand the definition of a system. According to Blanchard & Fabrycky (1990), "A system is an assemblage or combination of functionally related elements or parts forming a unitary whole, such as a river system or a transportation system." Gibson, Scherer, & Gibson (2007) state, "A system is a set of elements so interconnected so as to aid in driving toward a defined goal." A third definition of a system is "a set of different elements connected or related so as to perform a unique function not performable by the elements alone" (Rechtin & Maier, 1997).

These definitions concur on the system's three important aspects: a collection of smaller elements or subsystems, an interconnection and interdependence between those elements, and all are working to fulfill a goal. Accordingly, systems are everywhere and exist in different magnitudes. For instance, a biological system like the human body consists of the nervous system, which is a subsystem of the human body but constitutes a system by itself; other examples include technological systems, like a smartphone, or social systems, like an ant colony.

"Systems thinking is a discipline for seeing wholes ... for seeing interrelationships rather than things, for seeing patterns rather than static snapshots. It is a set of general principles spanning fields as diverse as physical and social sciences, engineering and management" (Senge, 1990). In other words, systems thinking considers the whole rather than the parts in an interdisciplinary approach to solve complex real world problems which do not have one simple answer. According to Blockley & Godfrey (2000), the three main ideas in systems thinking are: the group of parts, wholes, and layers; the connections, and the processes.

In order to obtain successful solutions to these complex problems, it is necessary to use the Twin-focused approach to Systems integration, which envisions the opportunities, innovation, and risks of the future by considering the experiences, literature review, and case studies of the past. We cannot obtain good solutions based on just one of these dimensions or, even worse, based simply on our own thoughts and knowledge.

According to s guide published by The Royal Academy of Engineering and edited by Elliott & Deasley (2007), there are six principles for creating systems that work: "debate, define, revise and pursue the purpose; think holistic; follow a systematic procedure; be creative; take account of the people; and manage the project and the relationships" (p. 11).

The literature on systems thinking is widely applied in different fields of knowledge to analyze complex problems for which a mathematical equation will not necessarily obtain the best solution. Furthermore, methodology of this research is the framework of engineering design of systems.

2.8 Systems Engineering

Similar to the various concepts of a system, there are multiple concepts of Systems Engineering. We can review two concepts from different authors. According to

Blanchard & Fabrycky (1990), "Systems engineering is a process employed in the evolution of systems from the point of when a need is identified through production and/or construction and ultimate deployment of that system for consumer use" (p. 21). The International Council on Systems Engineering (INCOSE n.d.) defines systems engineering as "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem" (para. 1).

Two additional important definitions to understand the idea of engineering a system is presented by Buede (2009): Engineering is the "discipline for transforming scientific concepts into cost-effective products through the use of analysis and judgment" (p. 10). Consequently, Engineering of a System is the "engineering discipline that develops, matches, and trades off requirements, functions, and alternate system resources to achieve a cost-effective, life-cycle-balanced product based upon the needs of the stakeholders" (p. 10).

From those concepts, one important difference between design engineering and systems engineering is that systems engineering does not create the design of the operational system; rather. it defines what is to be done by creating requirements, concepts, and architectures that will be used by functional engineering. Systems engineering focuses on the architecture and the starting point is determining the user requirements (Forsberg, Mooz, & Cotterman, 2005, p. 103) .

The systematic approach to system design follows a life-cycle. There are different approaches, but most of them are based on the project life-cycle from the project management area of study. The most relevant systems life cycles are: linear, evolutionary, Waterfall, Spiral, and Vee models. One very well extended and commonly used model is the Vee model presented by Buede (2009, p. 10) in *Figure 2.7*. This model includes the stages of user requirements, specifications of the system, implementation, integration & testing, operation & deployment. However, this process is not completely sequential because there is a dependency and feedback relationship between the phases of specification and integration & testing, and the requirements and operation & deployment phases. These relationships are best represented in a V-shape.

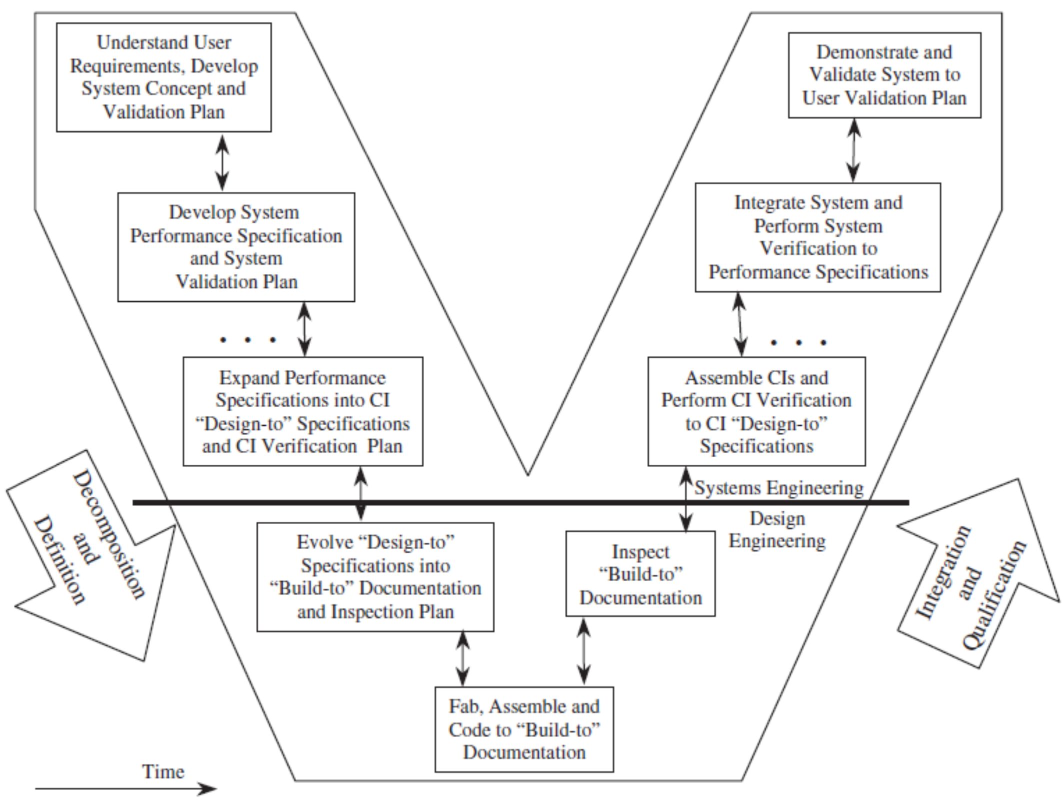


Figure 2.7 Systems Engineering Vee Model (Buede, 2009, p. 10)

The use of the appropriate model depends on the system's complexity. When the system presents a great complexity and uncertainty, it is better to start small with a very basic model and then improve the model using an incremental model approach.

An example of systems engineering applied to microgrids was developed by Doorsamy et al. (2015) by using a traditional iterative model like the one shown in Figure 2.8. The authors described the stakeholder analysis and requirement analysis for the development of rural microgrids. Although they identified different stakeholders, subsystems, boundaries and external interfaces, as shown in Figure 2.9, the interactions between these different actors are not completely clear because this approach includes just one level of analysis where the interactions seems to have the microgrid as a central node.

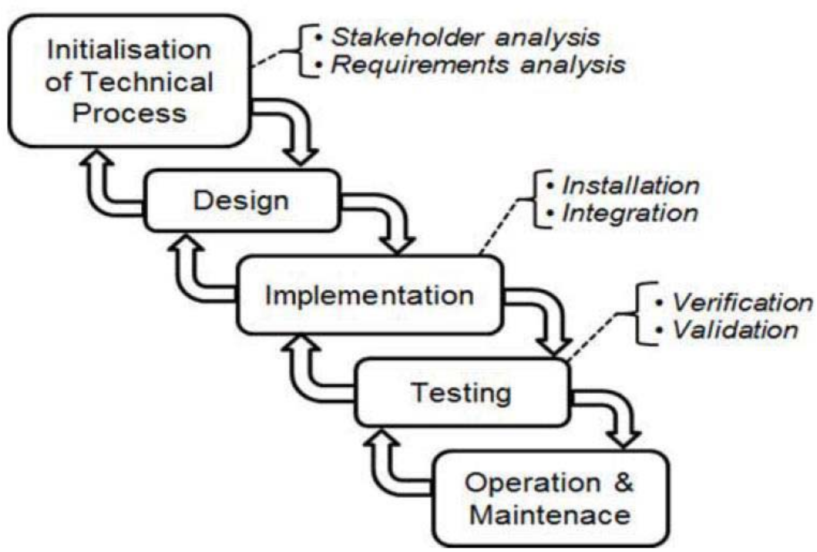


Figure 2.8 Iterative Systems Engineering Life-Cycle (Doorsamy et al., 2015, p. 1252)

However, in a microgrid system there are interactions between utilities, regulators, and customers that do not depend exclusively on the technical infrastructure.

Hence, some of the element interactions would be better represented in a multilevel architecture using a System of Systems perspective.

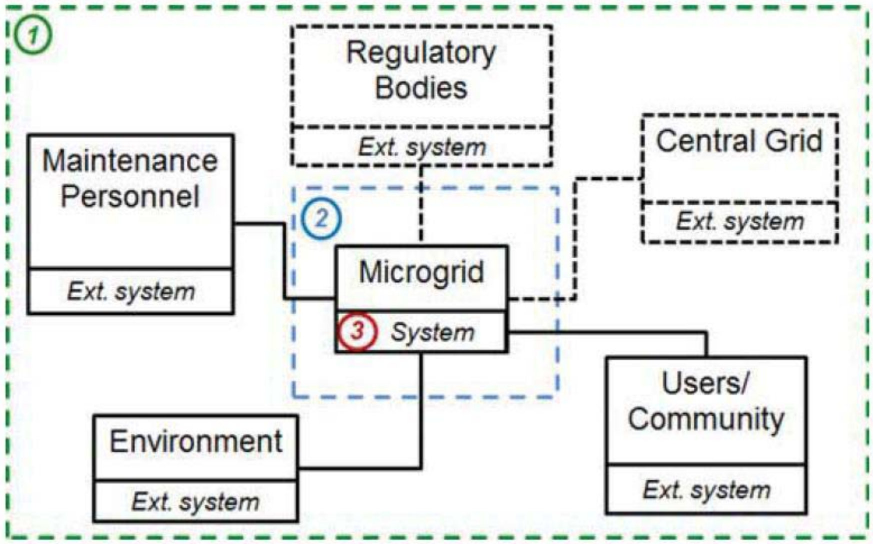


Figure 2.9 Context Diagram for a Microgrid System (Doorsamy et al., 2015, p. 1254)

2.9 System of Systems

Systems of Systems (SoS) is a relatively new special class of systems. The term first appeared in 1989, but the concept has not been completely clear until recently (Gorod, Sauser, & Boardman, 2008, p. 486). After an iterative process and the collaboration of different researchers, some agreement exists on an SoS:

- It is constituted by components which individually may be considered as systems
- The behavior of the SoS is not obtained from any individual component
- The components are operationally and managerially independent. There is no directed or governing structure. Instead, it is a collaborative environment (Maier, 1998, p. 271).

- There is a significant complexity and heterogeneity.
- There is an emergent behavior that cannot be analyzed by dividing the analysis in parts.
- The interactions and relations between systems are crucial for analysis.

In Table 2.2, Gorod et al. (2008) synthesize a comparison between the approaches of Systems Engineering (SE) and System of Systems Engineering (SoSE). Even more, DeLaurentis (2016b) states that the six common major phases used in the Systems Engineering processes cannot be applied in System of Systems because of their unique characteristics, In addition, DeLaurentis presents a comparison of these phases in both SE and SoSE, shown in *Table 2.3*.

Table 2.2 SE vs. SoSE (Gorod et al., 2008, p. 488)

	SE	**SoSE**
Focus	Single Complex System	Multiple Integrated Complex Systems
Objective	Optimization	Satisficing, Sustainment
Boundaries	Static	Dynamic
Problem	Defined	Emergent
Structure	Hierarchical	Network
Goals	Unitary	Pluralistic
Approach	Process	Methodology
Timeframe	System Life Cycle	Continuous
Centricity	Platform	Network
Tools	Many	Few
Management framework	Established	?

From both Table 2.2 and *Table 2.3*, we can see that the focus of SoSE relies on multiple integrated complex systems, while SE is focused on a single, complex system. This implies that in SE, the problem, goals, and measure of performance can be defined clearly, and it is possible to obtain an optimized solution through a process approach. On the contrary, in SoSE the problem is not easily identifiable because there exist multiple objectives and an emergent behavior as a result of the interactions of the different systems. Because this emergent behavior cannot be obtained by analyzing each system component separately, optimization is usually not possible in SoSE. Furthermore, the management framework and tools for SoS analysis are limited due to the fact that a Microgrid can be considered as a SoS. This reinforces the justification of this research in which we identify the lack of tools to determine the interaction between electric utilities and customers, and the necessity for a methodology that can address this situation.

Table 2.3 Systems Engineering Process in SE and SoSE (Dan DeLaurentis, 2016b)

Phase	**SE**	**SoSE**
Define goal	Fixed objectives	SoS evolves with time, so goals may change
Set measure of performance	Easier to define	Multiple objectives, sitting at different levels (& dependent)
Generate solution alternatives	Brainstorming , etc. are approaches to develop alternatives	Problem mainly of selection rather than solution generation
Iterate and Optimize	Optimization is possible	Optimization usually not possible, satisficing
Evaluate and rank alternatives	Have to select one main system	Evolutionary nature means ranking is difficult
Select and implement solution	Design and manufacture the system	Emergent behavior has to be accounted

In order to delineate principles and concepts to analyze SoS, DeLaurentis, Crossley, & Mane (2011) defined a taxonomy to guide SoS decision making in air transportation problems. Even though this taxonomy is applied in air transportation, it can be applied to other SoS. The taxonomy considers three dimensions: types of systems, control of systems, and connectivity of systems. There are three types of systems, too: technological, humans, and human-enterprise systems (p. 762). Control of systems refers to the degree of control by the authorities and the autonomy of the entities. Hence, there are four main types of systems regarding control: directed, acknowledged, collaborative, and virtual (p. 763). Finally, connectivity of Systems refers to the interrelationships and communication links between SoS systems. The main implications of connectivity are "the ability to capture emergent behavior, the potential presence of positive emergent behavior, and the evolution of connectivity" (D. A. DeLaurentis et al., 2011, p. 763).

In addition to the previously mentioned taxonomy, DeLaurentis (2005) defined a three-phase SoS Modeling Process to guide and order the steps of modeling and analysis. DeLaurentis' SoS modelling process is shown in *Figure 2.10.* The three phases of this process are: Definition, Abstraction, and Implementation. Definition is an understanding of the system, its operational context, status quo, barriers, scope categories, and levels. Abstraction frames key descriptors and their evolution, stakeholders, drivers, resources, disruptors, and networks. Modeling is a consideration at this point. Finally, implementation is related to analyzing, exploring, and interpreting the model. It is important to define objects, classes, methods, data, and measures (Daniel DeLaurentis, 2005, pp. 9–11).

One important step in the initial approach is to establish an effective language to facilitate the communication between the different parties. A lexicon of categories and levels developed by DeLaurentis (2005, p. 5) is shown in *Table 2.4*. This lexicon categorizes a SoS in different levels where the α-level is the base level, and no further decomposition is analyzed in the context of an SoS; however, each element in this level is a system itself and has subsystems that can be analyzed with a SE approach. A higher level is a collection of the slower level and represents a system composed of other systems interacting between themselves. The four categories describe each level and help to organize and structure a SoS to identify the problem to address.

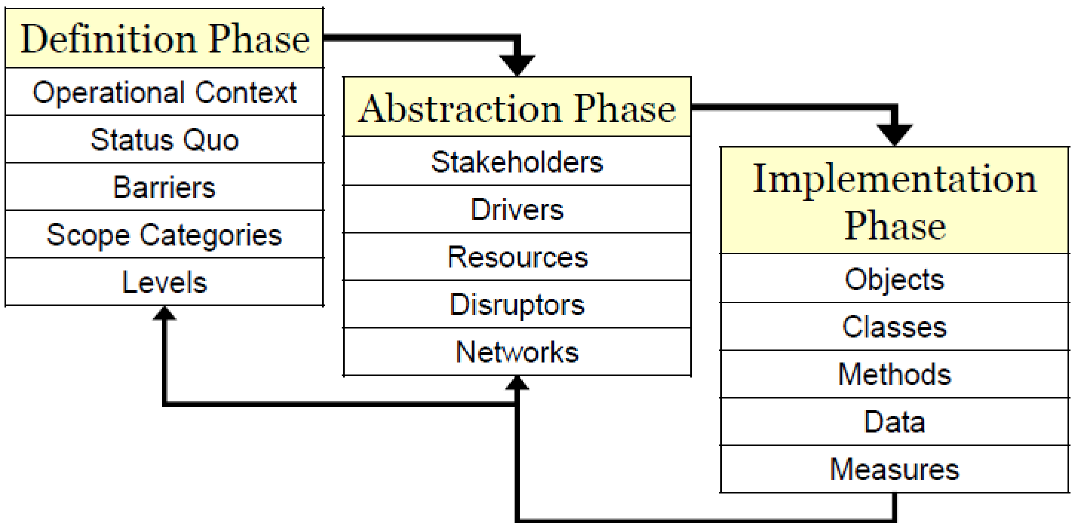


Figure 2.10 SoS Modeling Process. (Dan DeLaurentis, 2016b, p. 5)

Table 2.4 Lexicon for SoS. (Daniel DeLaurentis, 2005, p. 5)

Categories	**Descriptions**
Resources	The entities (systems) that give physical manifestation to the system-of-systems
Economics	The non-physical entities (stakeholders) that give intent to the SoS operation
Operations	The application of intent to direct the activity of physical & non-physical entities.
Policies	The external forcing functions that impact the operation of physical & non-physical entities.
Levels	**Descriptions**
Alpha (α)	The base level of entities, for which further decomposition will not take place, α-level components can be thought of as building blocks.
Beta (β)	Collection of α-level systems, organized in an network.
Gamma (γ)	Collection of β -level systems, organized in an network.
Delta (δ)	Collection of γ -level systems, organized in an network.

In this research, the SoS analysis helps to understand the nature of a microgrid as not just a specific technology, but a collection of different elements from non-centralized electric power sources such as photovoltaic modules, biogas digesters, small wind turbines; storage devices, flexible loads, power conditioners, and the management, operation and control equipment, interconnected and operated by electric and communication interfaces to satisfy the power necessities of a specific local community (Phillips, 2008, p. 252) (Banerji et al., 2013, p. 27). It is clear that the microgrid is a system. In fact, it is a system of systems because each element constitutes a complete system. For example, a wind generator can operate independently of the microgrid, and it is made of several different elements, such as blades, a rotor, a generator, gear transmission systems, and a tower. However, the wind generator is part of the power generation system, which in turn is part of the microgrid infrastructure, and this is part of the microgrid market. The interactions become more complex and dependent of the other elements and systems. Hence, the complete behavior in this case is difficult to model without specialized tools.

2.10 ICT and Enterprise architecture

The approach of architecting, rather than engineering, a system comes from the Information and Communication Technologies (ICT) domain and has been expanded to the enterprise level. IT-architecture is the art and science of structuring and organizing information and systems. It is impossible to engineer the situation because it is too complex; therefore, it is necessary to architect. “There are many players having limited authority, different requirements, a variety of systems and so on […] Architecting focuses on ill-structured problems and on the need to create a shared view on what the future landscape should look like" (Janssen, 2009).

When dealing with open systems with high complexity--too many interconnected and interwoven parts--traditional project planning and control tools are not useful; hence, new instruments and tools are required for managing the evolving IT landscape. It is not possible to obtain an optimum, but it is possible to use heuristics to improve the landscape. In other words, the use of past experiences to arrive at suitable solutions (Janssen, 2009).

Enterprise architecture (EA) extends the ICT architecture to the business process to guide design decisions by defining the system from its composition, dependencies among its elements, and the complexity involved. This EA is considered a master plan and a SoS. According to Janssen (2009), a good architecture contains both descriptive and prescriptive elements, as is shown in *Figure 2.11*. A descriptive architecture is an abstract representation of the existing infrastructure. A prescriptive architecture represents a desired situation obtained through a design process. The implementation of the prescriptive architecture is made through design projects; which results influence the prescriptive architecture for redefining standards or architectural principles. In addition, these design projects can change the current infrastructure; therefore, the descriptive architecture must be updated. Finally, after an iterative process, a new infrastructure is obtained. This is referred as New Generation Infrastructure (NGI) (Janssen, 2015).

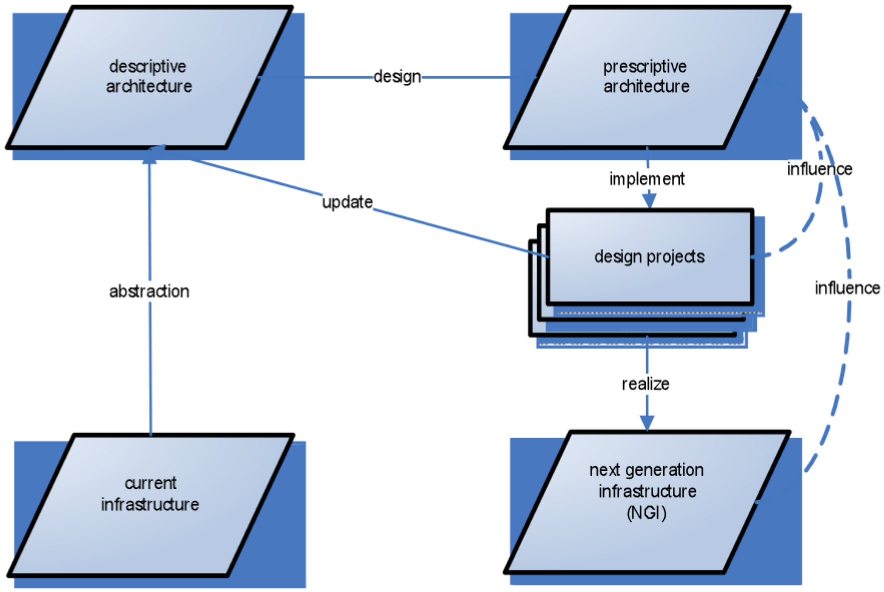


Figure 2.11 Enterprise Architecture cycle (Janssen, 2009, p. 111)

The architecture and its components can be characterized in a 3-D architecture model similar to the one used in the SGAM reviewed in Section 2.2. In this case, the domains and zones will vary for each enterprise, but the interoperability layers can be generalized and classified as follows: business, business process, information, application, and technical architectures.

Business architecture describes the relationships between value-creating activities. It is focused on the organizational level, interfaces, and service-level agreements between the business domains. The Business Process Architecture is focused in the processes and relationships. The Information Architecture describes the assets and resources involved in processing, storing, and distributing information among actors. The Application Architecture focuses on software applications, components, objects, and the IT portfolio. Finally, the technical architecture describes the generic infrastructures, operating systems and facilities used for other systems (Janssen, 2009, pp. 116–119). This Enterprise architecture meta-framework, as defined by Janssen (2009, p. 113), is shown in *Figure 2.12*.

In addition, Architectural Governance deals with directing, controlling and decision making of the enterprise. This governance is present in all the stages of the enterprise architecture cycle: programing requirement, descriptive architecture, prescriptive architecture, and implementation of the architecture.

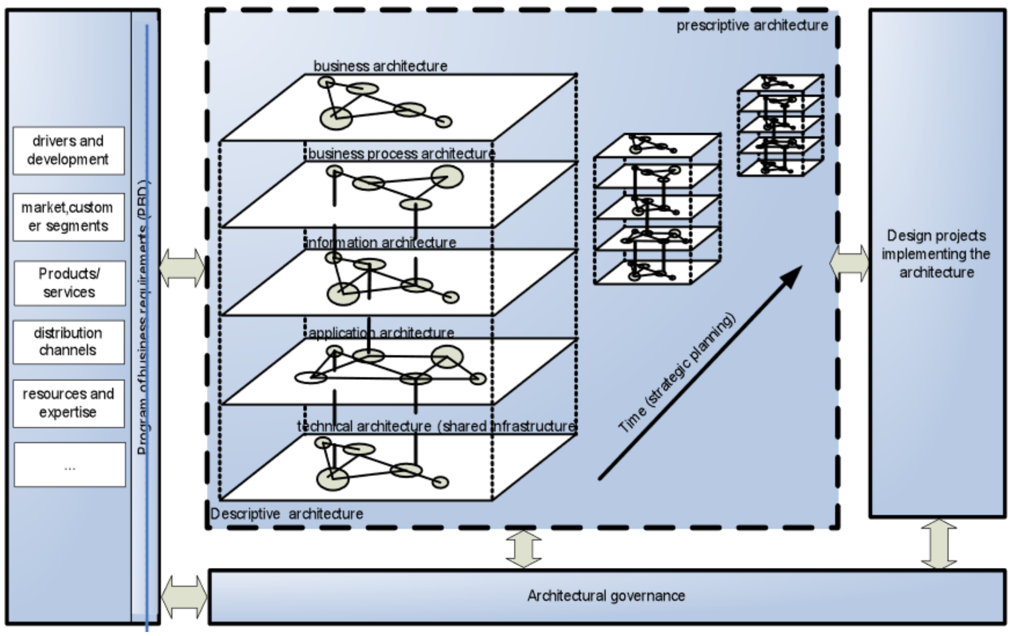


Figure 2.12 Enterprise Architecture Meta-Framework (Janssen, 2009, p. 113)

The analysis of ICT and enterprise architecture can be useful in the context of microgrids because they are also complex systems that have multiple, interconnected elements and different interoperability layers; thus, engineering all dimensions of the complete system would not be suitable. The application of these insights is reflected in Chapter 4 with the specific design of the methodology proposed in this research.

2.11 Modeling tools

"A model is a simplified representation of a system at some particular point in time or space intended to promote understanding of the real system" (Bellinger, 2004). Hence, modeling allows the exploration of different ways a system works and develops without the necessity of working with the real system in real time. A good model can help the design or redesign of a system, and help stakeholder during their decision-making processes. A good model reproduces the key behaviors of a system within a minimal set of parameters, therefore reducing the complexity. In addition, a necessary first step in modeling is defining the problem correctly; otherwise someone may model something that is not useful to themselves or the problem's solution. A good model has been verified and validated. Verification is about checking the computer model implemented versus the paper model. Validation is checking that it meets the objective and correctly solves the problem stated (Dan DeLaurentis, 2016a).

According to Daellenbach, McNickle, & Dye (2012), there are four different modeling methodologies that can be used depending on the type of system:

- Discrete system: changes its states at discrete points in time, but it remains unchanged between these points in time.
- Continuous system: changes its states continuously, but sometimes if the changes are not representative it is possible to approximate a continuous state variable to a discrete state variable.
- Deterministic system: its behavior is predictable and it always exhibits the same behavior as a response to the same starting conditions.

- Stochastic system: its behavior is affected by uncertain or random inputs (Daellenbach et al., 2012, pp. 44–45).

For microgrids, there are basically three main approaches that can be used to model and simulate different systems and processes: System Dynamics (SD), Process-centric or Discrete Event (DE) modeling, or Agent Based modeling (ABM). The first two use a top-down approach, while ABM is a bottom-up approach, which means that the focus is on the behavior of the individual elements (AnyLogic, n.d.).

Discrete event modeling is a medium-low abstraction level modeling approach that is useful when there is a sequence of operations that describes the system. It simulates process workflows and the behavior of entities and resources in the system. On the other hand, System Dynamic Simulation is used to model complex systems and strategic models to design new policies. This is a high level modeling in which individual properties of discrete items are not important. What is important is the stock and flow diagrams and decision rules.

Agent Based Modeling (ABM) can model systems with participants that are not passive entities and can be represented with an average value or behavior. Rather, these agents "have different expectations, interests, intentions, and complex interactions and relationships" (AnyLogic, n.d.). Furthermore, there are different types of agents. According to DeLaurentis (2016a), there are mobile, adaptive, reactive, utility, goal-based, info-gathering, interface and autonomous agents. A way to classify them is shown in *Figure 2.13*. It is important to mention that ABM is not a technology; it is a way of thinking which does not seek an optimized answer, but an adaptive and intelligent behavior.

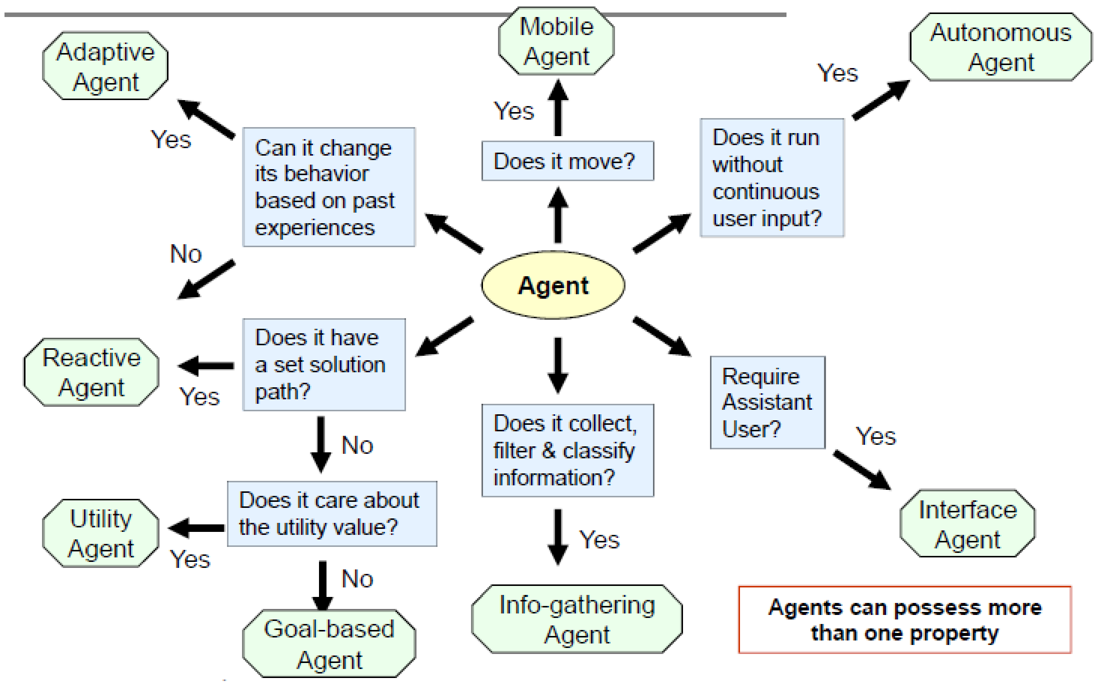


Figure 2.13 Types of Agents (Dan DeLaurentis, 2016a)

Recently, a different modelling approach has been used to model some microgrid systems. This approach is called Dynamic Data-Driven application system (DDDAS). The advantage of this paradigm is that it incorporates new real-time data to update the inputs of a simulation model. This dynamic approach adjusts its fidelity while the system is running and automates the simulation adaptation, thereby reducing the participation of the human being in the learning and improvement process of the modeling (Thanos, Moore, Shi, & Celik, 2015, p. 341).

In addition to the previous approaches for modeling and simulating generic systems, there exist different modeling and simulation tools to analyze the behavior of different variables in power systems. However, none of those tools simulate and model the complete microgrid system with consideration of the higher levels and layers in its architecture. For example, the business level in the SGAM model is not considered by power systems simulators. *Table 2.5* shows some commercial tools and their main characteristics and suitability for power systems simulation.

Table 2.5 Commercial tools for power system simulation

Software	Characteristics
ETAP (ETAP automation)	Suitable for load flow studies, harmonic analysis, short circuit, and grounding, etc. Can work with big number of busses (state utility network). Easy to create buses and execute huge amount of data.
DIgSILENT PowerFactory	Suitable for load flow analysis, short circuit, etc. Can work big number of busses (state utility network). Easy to create buses and execute huge amount of data.
PSCAD	Suitable for a small number of busses and depth analysis. Useful for transient/over voltage/charging studies/mathematical analysis/other domain analysis
MATLAB	Suitable for less number of busses and depth analysis. Useful for transient/over voltage/charging studies/mathematical analysis/other domain analysis
MIPOWER(PRDC	For load flow analysis, short circuit. Big number of busses (state utility network). Easy to create buses and execute huge amount of data.
PSS/E(Siemens)	For load flow analysis, short circuit. Big number of busses (state utility network). Easy to create buses and execute huge amount of data.
NEPLAN(ABB)	For load flow analysis, short circuit. Big number of busses (state utility network). Easy to create buses and execute huge amount of data.
HOMER ™	Specialized for simulation, cost investment optimization and sensitivity analysis of microgrids. Calculates Net Present Values of capital requirement and operational costs.

2.12 Chapter summary

Chapter Two summarizes important basic concepts in microgrid technology, and the current scenario for energy markets regarding utilities cooperation. In addition, the approach of systems thinking, system of systems and ICT architectures were referenced as important concepts and tools to analyze microgrids. Finally, modeling and simulation tools currently available to analyze systems in general and power systems were explained, showing the lack of an integral simulator to model the complete microgrid system.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Abstract

This chapter explains the process carried out to perform this research. It covers the research framework, sample set, data collection, analysis procedures, testing procedures, and threats to validity used in this thesis.

3.2 Qualitative framework or perspective

This research is an exploratory study to propose a methodology to ensure mutual benefit to the main actors in a microgrid project while mitigating risk and conflict. This methodology will be useful in order to effectively implement microgrids with proper planning.

3.3 Sample (type, number, and access)

This research was carried out using a nonprobability sample design, specifically a convenience and judgment sampling. The population of analysis in this research includes utility companies and industrial customers in the state of Indiana, specifically those with expertise on the topic investigated, which is microgrid implementation. In addition, costs and time constraints led to interviews with representatives from companies available through the Center of Technology Development of Purdue University. The objective was to interview at least one electric utility and one industrial customer in the state of Indiana; however, the expectations were achieved by interviewing and applying questionnaires to two electric utilities and three industrial customers.

3.4 Data Sources

The research includes a phase of obtaining data from secondary and primary sources. The secondary sources were journals, magazines and reports on past and current microgrid implementations in different U.S. states, focusing mainly on the perspectives of the utilities and customers. The primary information sources were surveys and interviews with representatives of the aforementioned sampling population with the aim to determine their interests.

3.5 Data collection procedures

Semi-structured questionnaires were applied to representatives of the sampling population to determine specific information obtained by secondary data sources. These questionnaires were sent electronically because the interviewee might need to ask other areas of the company to answer specific information, regarding technical, financial, regulatory and business information.

In addition, interviews were applied to the same representatives to expand the understanding of the questionnaire responses. These interviews were performed via teleconference and recorded. Some important answers were written down to complement the answers provided by the previous questionnaires.

3.6 Data analysis strategy/procedure

The data collected by interviews and questionnaires was processed to determine patterns, causes, and objectives of the participants. This information was contrasted with the information obtained by secondary sources to obtain a base line of the perspectives of the actors in a microgrid project.

In addition, different system models and approaches were analyzed to determine the best strategies according to the data collection process.

3.7 Testing conditions and procedures

The methodology was validated with a generic case study in a simulation environment using the insights obtained by utilities and industrial customers via the questionnaires, interviews and literature review. It was performed face validity comparing the outcomes of a microgrid project with the application of the microgrid reference methodology proposed, therefore determining its usefulness to address factors that traditional approaches do not. Furthermore, different infrastructure alternatives were simulated using commercial tools to compare the evaluation of the alternatives obtained through the developed methodology.

In addition, the microgrid methodology was validated in terms of the own validity of the concepts, framework, models, and body of knowledge used as a basis to develop in this methodology.

3.8 Threats to validity

The use of insights that do not reflect the current reality utilities face and the real situation of customers who want to incorporate electric microgrids to their current infrastructure can generate errors in the determination of the mutual benefits for both technical and non-technical variables.

Because there were a reduced number of interviews with representatives of electric utilities and customers, the opinions may be biased. This situation could create a misperception of the real objectives that utilities and customers seek and therefore lead to the development of misguided policies.

Because the researcher is an important participant in the research process, there is the possibility of bias created by the influence of previous knowledge, experience, or ideas.

In order to increase the validity and overcome intrinsic biases, triangulation was applied during different stages of the research by using different reliable secondary data sources, principles and framework to establish a valid methodology. In addition, the experiences of professionals and researchers with knowledge and expertise in microgrids and related topics were considered and incorporated.

3.9 Chapter summary

Chapter Three covered important aspects about how the scientific investigation was be conducted. The sources of information required, measurement variables and testing conditions to evaluate the hypothesis were explained. Finally, some threats of validity were pointed.

CHAPTER 4. MICROGRID REFERENCE METHODOLOGY

4.1 Abstract

The purpose of this chapter is to consider important concepts of Systems Engineering, System of Systems, Management Science and Infrastructure Architecting approaches in the context of microgrid systems, especially in the interactions between electric utilities and customers. This chapter shows an initial integration of these areas of knowledge, and seeks to develop a Microgrid Reference Methodology (MRM) that can be used as a tool to solve problems and assist the decision-making process consideration of socio-economic concerns about microgrid technologies by different actors in the energy market.

4.2 Introduction

Microgrid systems clearly have a complex nature and their analysis has been performed from different perspectives, mostly addressing the technical complexity of their operation and control functions. Due to the fact that the implementation of a microgrid involves not only technical factors but socio-economic concerns as well, a Microgrid Reference Methodology (MRM) is proposed in this chapter to obtain a complete representation of the microgrid system and the applicability of decision-making concepts to address specific problems concerning the cooperation between utilities and customers. This reference methodology combines different approaches and insights from the literature reviewed in Chapter 2.

We initially defined the main phases in the microgrid system life cycle. As referenced in Chapter Two, a microgrid can be considered as a System of Systems (SoS); therefore, a microgrid can be analyzed using the methods and approaches defined for modeling a SoS. However, the focus of this research relies on the factors that allow to successful microgrid implementation for the mutual benefits of its actors. The purpose is not just modeling the system as it is, but also considering all its phases, from planning to operation. A microgrid system will change its behavior according to different social, technological, economical and regulatory factors constantly in flux with the market. For this reason, the life cycle shown in *Figure 4.1* includes aspects of the SE and SoS adapted to the microgrid context.

This life cycle is sequential but not unidirectional. The iterative nature of the system makes updating necessary, and this can be done through feedback loops after obtaining preliminary results and consulting with the stakeholders. In addition, it is important to have in mind that verification and validation processes are important in each stage of the cycle to improve the correctness and usefulness of the model.

Next we will explain the phases and design for our current research question. The implementation, integration and testing, operation and maintenance phases are beyond the scope of this work because they are executed in real implementations once the design phase has been completely verified and validated by the stakeholders and the problem owner. In addition, no further observations are necessary to be made about these stages because the methods and guidelines are generic and very well documented by systems engineering and project management bodies of knowledge.

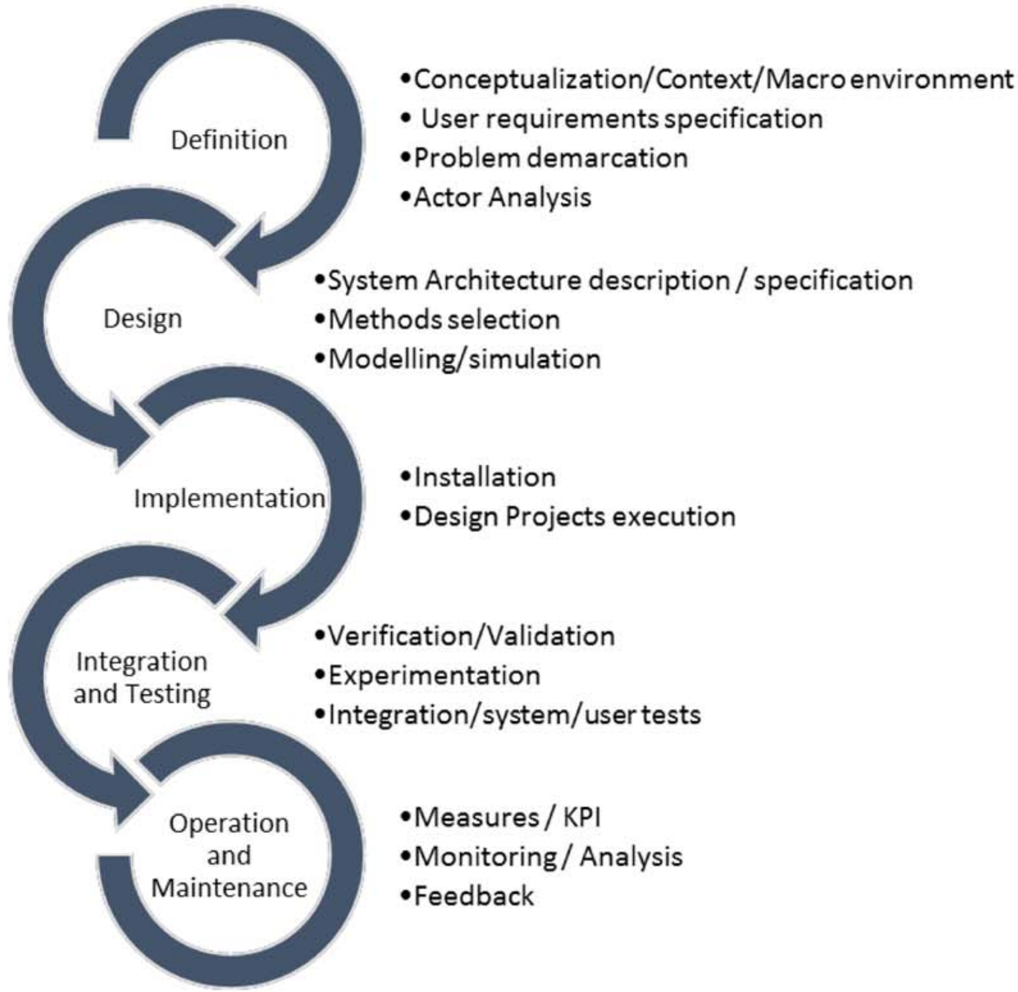


Figure 4.1 Microgrid Reference Methodology Life Cycle Phases

4.3 Definition

The definition phase aims to understand the problem situation and the microgrid context for analysis. It is necessary to understand all the dimensions, the environment, stakeholders, interrelationships, interests, goals, etc. Hence, the collection of relevant information is crucial to accurately define this context.

Figure 4.2 is a flow chart of the definition phase process. The first step is to use a system lexicon to maintain a common language within the microgrid project actors. We will use a modification of the lexicon proposed by DeLaurentis (2004, p. 832) indicated in *Table 2.4*. It is important to consider some additional factors at each level. The lexicon used to represent microgrid systems in this research is shown in *Table 4.1*.

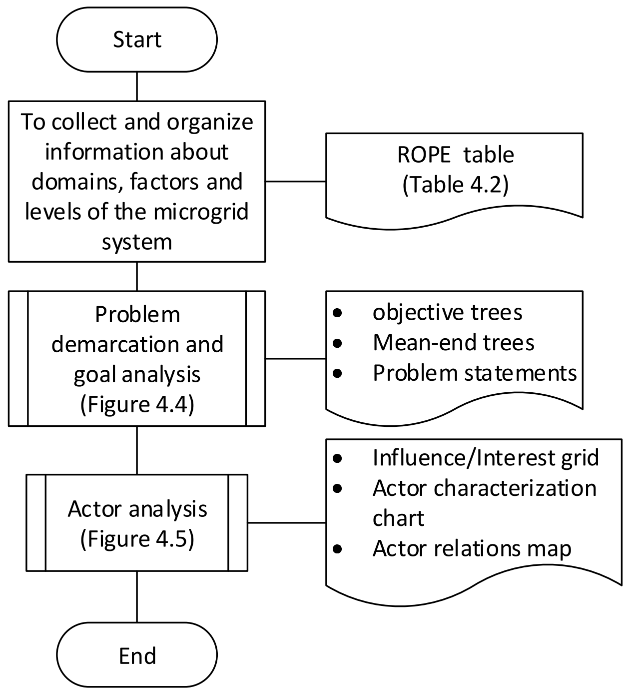


Figure 4.2 Definition phase flow chart

The second step is to collect information related to the dimensions and levels of the microgrid system and organize it in a table similar to the ROPE table proposed by DeLaurentis et al. (2004, p. 835), with dimensions that are modified to include some PEST analysis factors, a tool used in strategic planning to identify the microenvironment and external forces of an organization. PEST analysis focuses on Political, Economic, Social, and Technological environments. The ROPE table modified and applied for a generic microgrid system is shown in *Table 4.2*.

Table 4.1 Lexicon used to represent Microgrid Systems

	Category	Description
Domains	Resources	Physical entities in the microgrid system that are used and affected by operations.
	Stakeholders	Social entities that can affect or be affected by the microgrid system. They have interests and goals and can influence the system.
	Operations/ Processes	Processes that direct the activity of the resources
	Policies	The external forcing functions that impact the operations. Norms and laws that must be observed because they stablish constraints in the system behavior
Factors	Financial	Financial concerns and objectives of the different stakeholders in a microgrid project
	Technical	Technological interests and concerns of the different stakeholders in a microgrid project
	Market and Business	Business interests and concerns of the different stakeholders in a microgrid project
	Social	Social interests and concerns of the different stakeholders in a microgrid project
Levels	Alpha (α) - Technical	The base level of the system. It is made of subsystems but no further decomposition is analyzed. It represents the technical layer in a 3-D infrastructure architecture.
	Beta (β) - Application	Contains or manages α-level systems. It represents the application layer in a 3-D infrastructure architecture.
	Gamma (γ) – Information	Collections or manages of β-level systems. It represents the information layer in a 3-D infrastructure architecture
	Delta (δ) - Business	Collections or manages of γ-level systems. It represents the business layer in a 3-D infrastructure architecture

Once we have represented different levels and dimensions of the system, it is possible to identify specific problems and the interdependencies between different elements. For example, an improvement in the efficiency of PV panels would fit into the α level, while a reduction in peak demand consumption would fit into the β and γ levels because it involves different resources in the microgrid user's facilities.

Currently, most research has been conducted on the first three levels, resulting in mostly technical improvements of the system. However, the δ level has not been formally analyzed as an additional level in the design of most microgrid projects. Recently, most of the research on the δ level focuses on business models and regulatory aspects carried out by policy makers, market analysts, and regulatory entities.

Table 4.2 ROPE table for microgrid systems

	Resources	Stakeholders	Operations	Policies	Factors
α Technical	Microgrid elements and devices (e.g. batteries, solar panels, AC/DC converters, loads, etc.)	Technical personnel (e.g. installers, engineers, etc.)	Operating a single technical resource (e.g. PV energy conversion, relay tripping, etc.)	Policies relating to technical resources (e.g. standards, certifications, electric specifications, etc.)	Financial/ Technical/ Market / Social Concerns relating to single resources (e.g. efficiency in PV energy conversion, costs of fuel for a micro generator, etc.)
β Application	Collection of α-level resources with a common application (e.g. generation systems, storage system, distribution, management, operation and control, communication, cybersecurity subsystems, etc.)	Responsible for areas associated to a collection of α-level resources (e.g. generation manager, operations manager, etc.)	Operating a collection of α-level resources for a common application (e.g. Volt/Var control, frequency control, power quality monitoring, security monitoring, economic dispatch, state estimation, LOAD/DER forecast, etc.)	Policies relating to a collection of α-level resources for a common application (e.g. service level agreements, design specifications, etc.)	Financial/ Technical/ Market / Social Concerns relating to a collection of α-level resources for a common application (e.g. Power Quality, Cost of systems of equipment, Interoperability, etc.)

Table 4.2 ROPE table of generic microgrid systems (continued)

γ Information	Resources in the microgrid user facilities (e.g. ICT infrastructure, Production machinery, microgrid infrastructure, etc.)	Administration, senior management, leadership of microgrid users.	Operating in the microgrid user local domain (e.g. Grid-connected-to-islanding transition, Energy management, communication and information management, distribution management, microgrid central control, etc.)	Policies in the microgrid user domain (e.g. Electric Utility regulations for customers, internal user policies, etc.)	Financial/ Technical/ Market / Social Concerns relating to the microgrid owner domain (e.g. Power reliability, energy consumption, productivity efficiency, interoperability of infrastructure etc.)
δ Business	Resources in the Microgrid/Energy Market	Organizations in the Microgrid market (e.g. utility companies, industrial customers, microgrid developers, regulators, etc.)	Operations of Energy sector (e.g. implementing of incentives, defining of rate/tariff structures, billing & management, commercialization, etc.)	Policies relating to the Energy Market (e.g. electric service tariffs, rules and regulations, Federal Energy Regulatory Commission acts, etc.)	Financial/ Technical/ Market / Social Concerns relating to the energy sector (e.g. Profits, ROI, environmental impact, social welfare, etc.)

Figure 4.3 shows the four levels of this Microgrid Reference Model. The size of each level represents the number of elements involved in each system. The α level has the largest number of elements, including equipment, devices, feeders, data, software, personnel, etc. These elements represent the initial considerations of the actors interested in developing microgrid projects. Traditionally, these elements have taken most of the time and attention when planning a new microgrid project. In addition, several efforts

have been made in R&D by different developers and universities to obtain better, cheaper, and more efficient technology. For these reasons, the α level is depicted as the base of the pyramid in *Figure 4.3*.

The next two levels have fewer elements, but the resources, operations, and factors involved are in a higher level. The focus of these layers is the efficiency of different systems inside the microgrid and in its operations. These levels are mostly considered when planning projects because they govern the interests of the microgrid user senior management.

Traditionally, the first three levels have been analyzed to improve the technical aspects of the system. On the other hand, the δ level has the smallest number of elements, and it has not been formally analyzed as an additional level in microgrid project design. However, the actors involved in this layer have very powerful interests, influence, and decision-making capabilities. Hence, the lack of a complete understanding of the problem results in decisions that are not fully informed, and sometimes the execution of the microgrid project is not carried out once the technical concerns have been addressed.

For this research, we focus on the δ level because we are specifically interested in the cooperation between utilities and customers; however, the Definition phase specified in this chapter would be very useful for any problem involving any layer of the microgrid system.

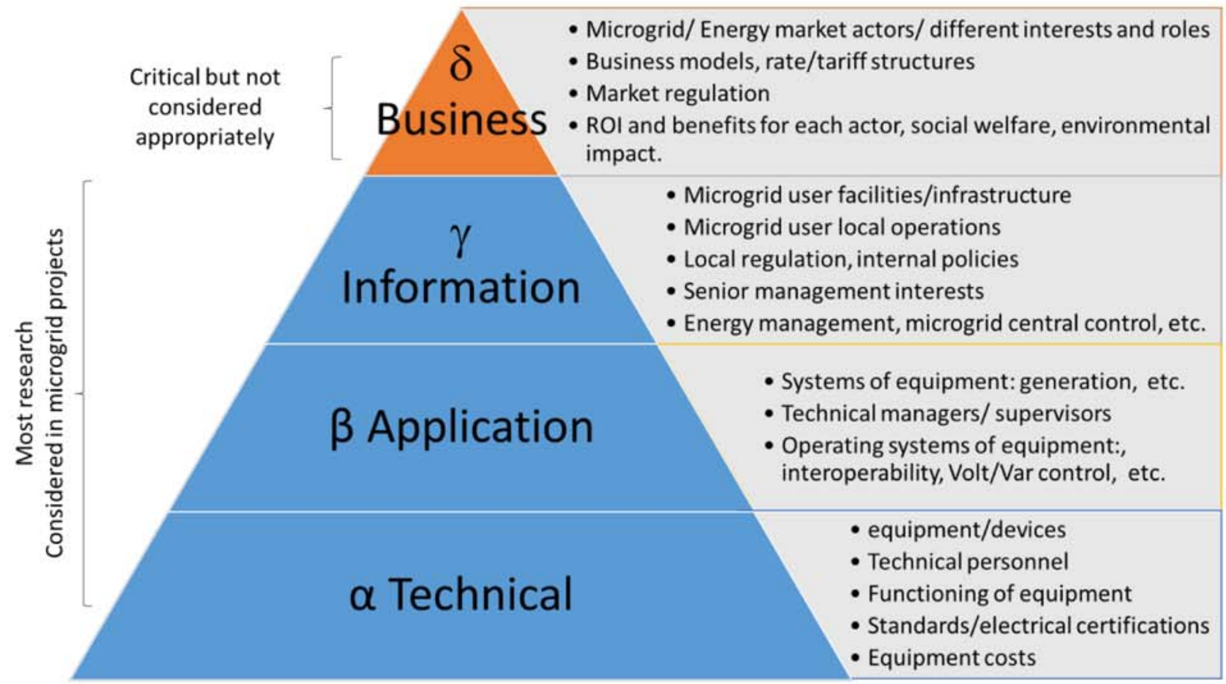


Figure 4.3 levels in the Microgrid Reference Methodology

Prior to beginning the problem analysis, it is crucial to collect relevant information on the specific context of each microgrid project, identify direct stakeholders and actors, and determine their initial interests and concerns related to technical, regulatory, financial and business issues.

After the creation of *Table 4.2*, the next step is the problem demarcation and goal analysis, which will identify higher-class goals, lower class goals, the means to achieve them, and the undesired effects that must be controlled. This process is defined based on the methods and concepts proposed by Bots (2015) and de Haan, Miedema, & de Regt (2015). The preliminary steps of problem demarcation are:

1. Identify direct actors in the microgrid project.
2. Create a table with actors and their interests.

3. Chose an actor that is capable of making changes in the system.
4. Formulate problem statements for all actors involved. The problem statement should not have a specific solution, nor lack a dilemma. There must be a situation in which an actor wishes to achieve something, but also an undesired, associated effect that results in the dilemma.

Figure 4.4 shows the detailed flow and steps to perform problem statements. The process can be represented by a hierarchical tree with relations between goals, means, and undesirable effects. The application of each step and how to create each tool will be presented in the next chapter accompanied by an example of a microgrid generic case study.

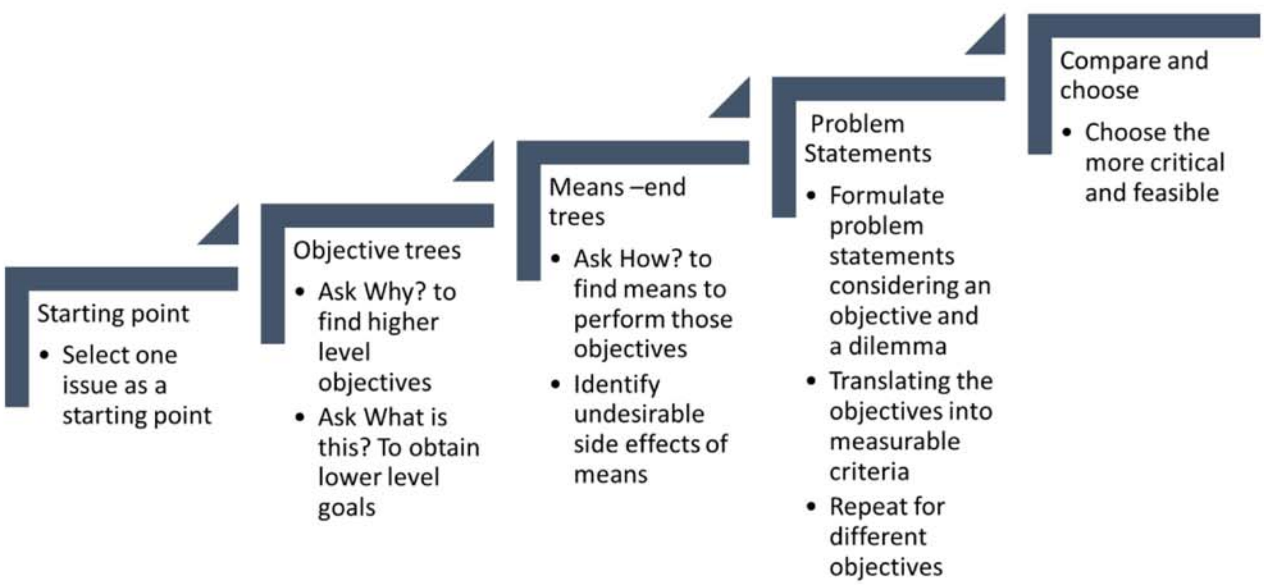


Figure 4.4 Problem demarcation and goal analysis

Some important considerations and advice to perform problem demarcation and goal analysis are:

- The hierarchical goal tree shows main goals, sub goals, and operational goals.
- Remove the overlap.
- Remove words like high, lower, less, faster, etc. to transform the goals into criteria that accurately represent the problem.
- Assign units of measure to the lower class goals. Quantitative goals are better than qualitative because they can be measured in interval and ratio scales
- Avoid main goals that are too broad or too specific, and goal trees with causal relations that contain alternatives.

The next step is to perform a detailed actor analysis. Actors can be individuals or organizations, so an actor analysis helps to understand who is involved in the problem, who can influence the achievement of objectives, and their respective concerns and issues. A systematic process to identify the actors involved in the system is shown in *Figure 4.5*, which was developed using the approach of Enserink (2015) and de Haan et al. (2015). The actor analysis results in a clear specification of the actors, their importance, and relationships in the system. An actor analysis helps to identify who has interests and who can influence the microgrid project. 2I's refers to interest and influence. In addition, the identification of the actors involved is useful to distinguish and understand the allies and the opponents. It is also useful in understanding the levels of power, resources, and interdependencies of different actors. Similar to the problem demarcation and goal analysis, the case study shown in Chapter 5 exemplifies the step-by-step use of the actor analysis.

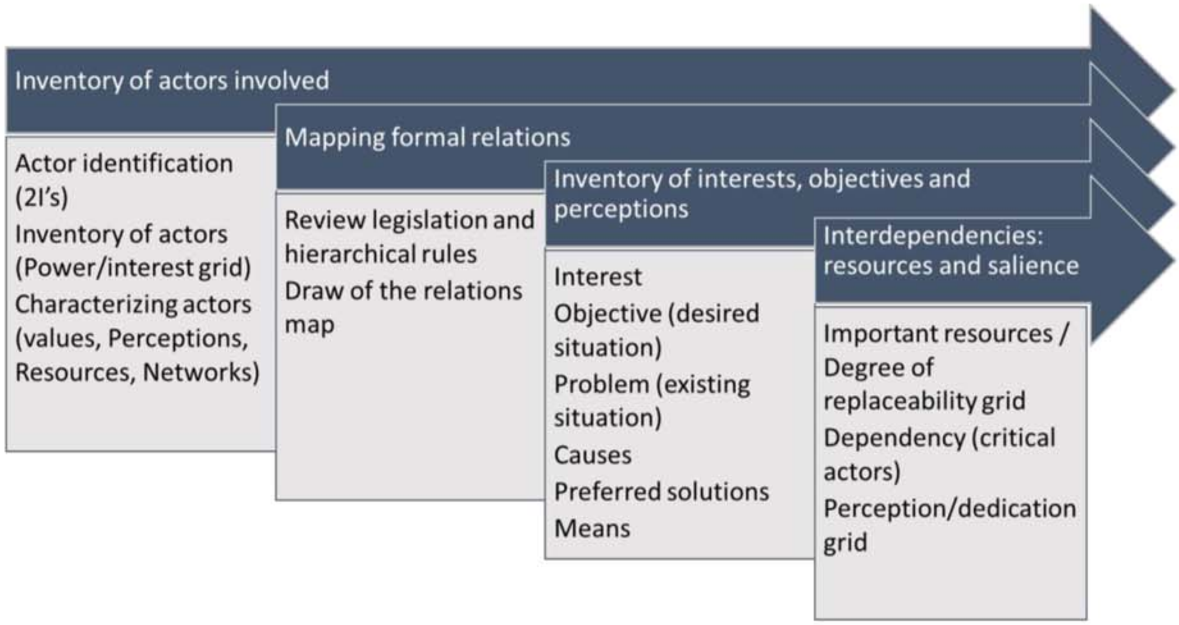


Figure 4.5 Actor Analysis based on (Enserink, 2015)

After defining the context, problem demarcation, and actor identification, the next phase is to develop a visual representation of the system and frame its dynamics using the design process.

4.4 Design

The design phase aims to frame and architect the microgrid system by describing its actors, objectives, criteria, factors, interrelations, and the links between them. In addition, this phase aims to use the abstraction of the system, to define ways to measure its performance in different scenarios, and to provide alternatives for the stakeholders and decision makers. Given that we are focused on the cooperation between utilities and customers in this research, we will use a systems dynamics approach based on the problem solving and decision making processes developed by de Haan et al. (2015). It is worth noting that the methods used in the design stage will vary depending on the problem and levels of interest. For example, if the problem lies at the α level, it might be better to characterize every element and device as an agent and use Agent Based Modelling (ABM). However, if the focus is the operations and processes of the microgrid, such as energy production and consumption over time, a discrete event approach might be more suitable. A flow chart of the general Design phase process is shown in *Figure 4.6*.

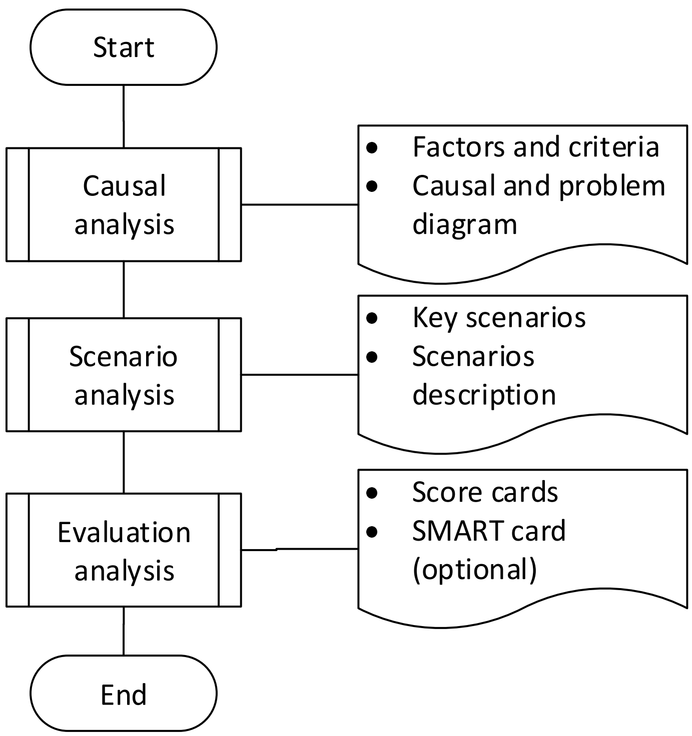


Figure 4.6 Design phase flow chart

After characterizing the problem statement, goals, and actors, the next step is to determine the factors that may influence the criteria and establish a causal relationship. We used the causal analysis specified in *Figure 4.7*, based on de Haan et al. (2015).

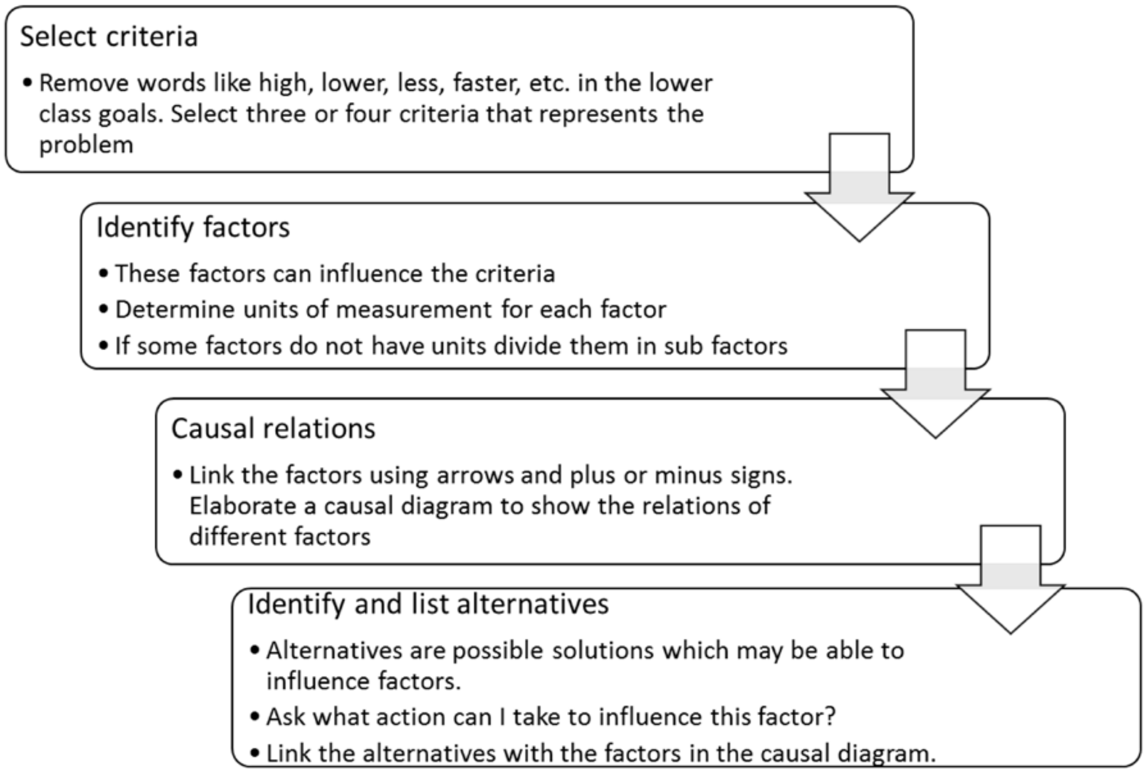


Figure 4.7 Causal Analysis

Some important considerations to perform an accurate causal analysis are:

- The factors should be measurable.
- The causal diagram should begin with the criteria.
- Always define causality (positively or negatively).

Some mistakes to avoid during this process are:

- The criteria in the causal diagram do not originate in the goal trees.
- The alternatives are not linked with the factors in the causal diagram.
- Forgetting to include the zero-option (i.e. doing nothing).

After these steps we will have a problem diagram that represents the dynamics of the system and includes the objectives, criteria, factors, causal relations, and alternatives. The next step is to evaluate these alternatives and consider the uncertainties caused by external factors that cannot be controlled by microgrid actors.

The next step is to perform the scenario analysis and evaluate the alternatives. These steps are based on de Haan et al. (2015) and summarized as follows:

1. Identify the external factors in the causal diagram. The external factors are the scenario variables.
2. Design scenarios that categorize the external factors using two axes: certain-uncertain and high impact- low impact. Theoretically, the minimum number of scenarios is 2^ (number of scenario variables).
3. Select the key scenarios with high impact and high uncertainty.
4. Make scenarios; describe them in words.
5. Create a score card for each scenario. Score cards are tables that show the effects of all alternatives on all criteria. The criteria are placed in the first column and the alternatives in the first raw.
6. Evaluate the impact of each alternative on each criterion and fill each cell with scores.
    - Filling the values in each cell can be done by using the literature review, consulting experts, conducting experiments, or by estimation.
7. Compare the scenarios.
8. An additional step is to use Simple Multi Attribute Rating Technique (SMART).

a. One SMART must be used for each scenario and for each actor because SMART considers the different weights for each criterion and each actor.
b. Normalize the scores between 0 and 1.

Some common mistakes during the scenario analysis are:

a. A misunderstanding of why clients cannot influence external factors
b. Making predictions of the future and using them as scenarios
c. Failure to identify the direction of the criterion as positive or negative, depending on the actor.
d. To use unrealistic weight factors
e. The highest ranked alternative is not always the best solution

After the scenario analysis, we have a quantitative comparison of the alternative options for the utility company and customer. The cooperation between these two actors can be analyzed and alternatives for the decision making process proposed for their mutual benefit.

In the next chapter, we apply this methodology to a generic microgrid project case study in order to demonstrate the usefulness of the approach.

4.5 Chapter summary

In Chapter Four we selected a Microgrid Reference Methodology (MRM) to analyze microgrid systems using a systematic approach. First, we defined the life-cycle process and microgrid system analysis phases. Then, we described the Definition and Design phases in the context of cooperation between electric utility companies and customers. The methodology proposed in this chapter is a sequence of steps to analyze and organize the problem into charts and diagrams that will facilitate decision-making and cooperation between the two key players in microgrid projects. In addition, the process established in this chapter was based on different fields of study that have been validated by previous research.

CHAPTER 5. CASE STUDY APPLICATION

5.1 Abstract

This chapter shows the application of the microgrid reference methodology proposed in Chapter 4 to a generic case study in which the customer desires to implement a microgrid to improve the energy reliability, energy savings, and higher power quality. The utility company is willing to cooperate in this project; however, they have some infrastructure installed on the customer's premises and they would like to obtain mutual benefits from this project. The technical and economic feasibility depends on the cooperation of these two actors, and the alternatives vary drastically depending on the decisions taken.

5.2 Description of the case study

In this case study we are going to skip the three first levels of analysis architecture showed in *Figure 4.3* and focus specifically on the δ level, which is the purpose of this research. We have used HOMER™ software to model a generic microgrid system and obtain some results from its behavior in different scenarios useful in the decision making process. The microgrid system used in this case study and shown in *Figure 5.1.* is a modification of the design of Lambert (n.d.), including PV generation and the Solar profile of the state of Indiana. This system has Distributed Energy Resources (DER) such as PV, wind and diesel generators, a primary load of 2.5 MWh/d and 207 kW peak, batteries, and a converter. The characteristics and costs of the elements and electricity grid tariffs are based on average values in the Midwestern U.S. The details of these values are in Appendix C.

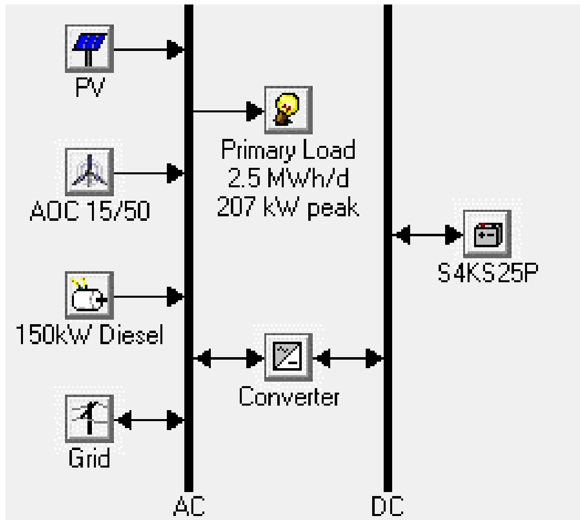


Figure 5.1 Microgrid for the generic case study

HOMER supplies us with different optimal implementation solutions for the customer, who is going to invest in the infrastructure required to implement the microgrid. For example, in *Figure 5.2*, we have the sensitivity results and optimal system combination considering two axes: wind speed and diesel price. Basically, after a wind speed of 6.5 m/s, wind generation might be considered in the system. In addition, in *Figure 5.3*, we have the four optimal infrastructure alternatives. We can see the resources used in each alternative and its respective cost.

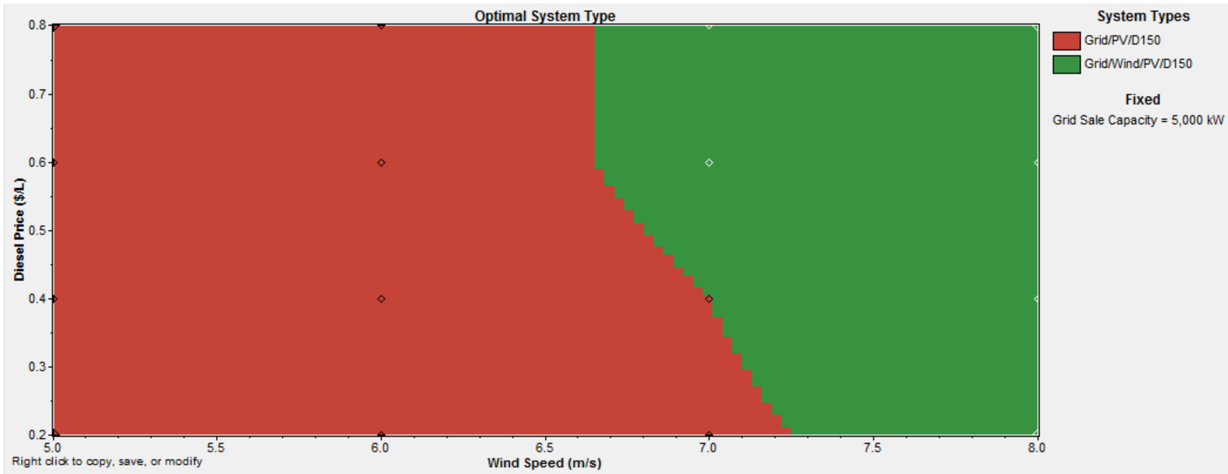


Figure 5.2 Sensitivity results and Optimal system combination

Wind Speed (m/s) 8 Diesel Price ($/L) 0.4 Grid Sale Capacity (kW) 5,000

Double click on a system below for simulation results.

	PV (kW)	15/50	D150 (kW)	S4KS25P	Conv. (kW)	Disp. Strgy	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D150 (hrs)
	10	3	150			CC	1000...	$ 525,000	23,459	$ 824,882	0.071	0.70	6,468	154
	10		150			CC	1000...	$ 45,000	72,143	$ 967,225	0.083	0.01	15,456	368
	10	3	150	24	25	CC	1000...	$ 811,000	25,343	$ 1,134,971	0.097	0.70	6,128	149
	10		150	24	25	CC	1000...	$ 331,000	74,158	$ 1,278,982	0.110	0.01	15,456	368

Figure 5.3 Optimization results and infrastructure combination

We can compare the second and third optimal alternatives shown in *Figure 5.3* to understand some differences in the interests of the customer and the utility company. For example, the second option, shown in *Figure 5.4*, seems attractive to the customer because it represents the lowest initial investment, $45,000; however, the operational costs are very high because this solution mainly uses the external grid and the net present cost of the grid electricity is more than $800,000. In addition, this solution might not meet the energy independent requirements of the customer. However, this scenario seems to be the most beneficial for the utility company because its incomes are the highest.

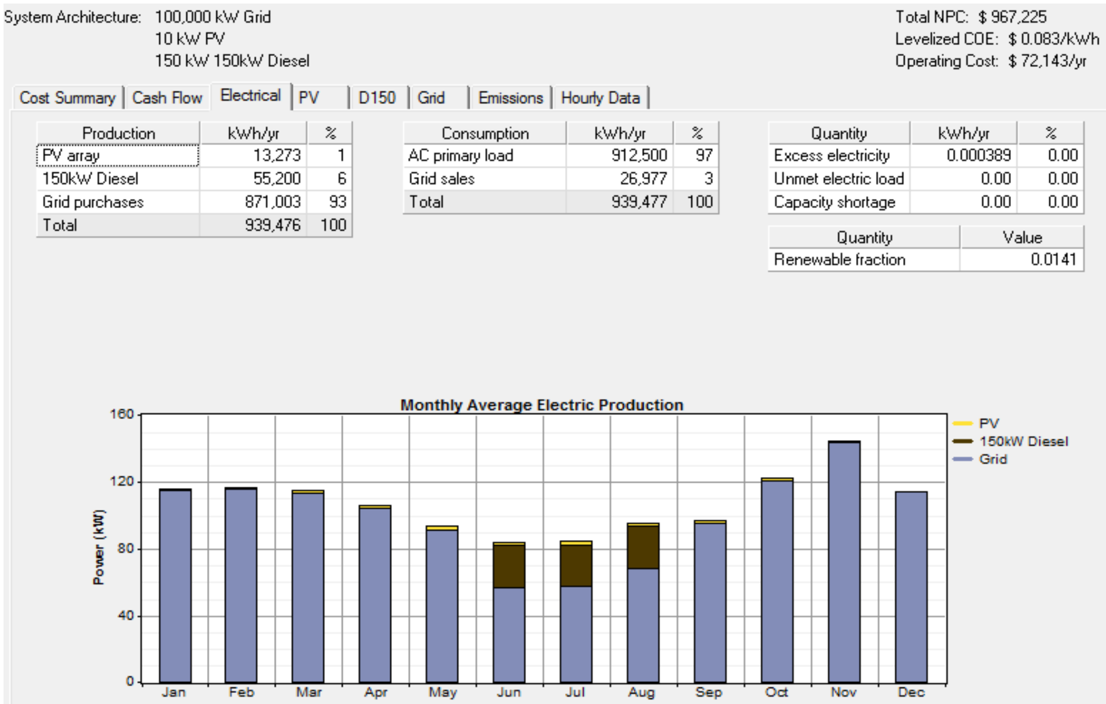
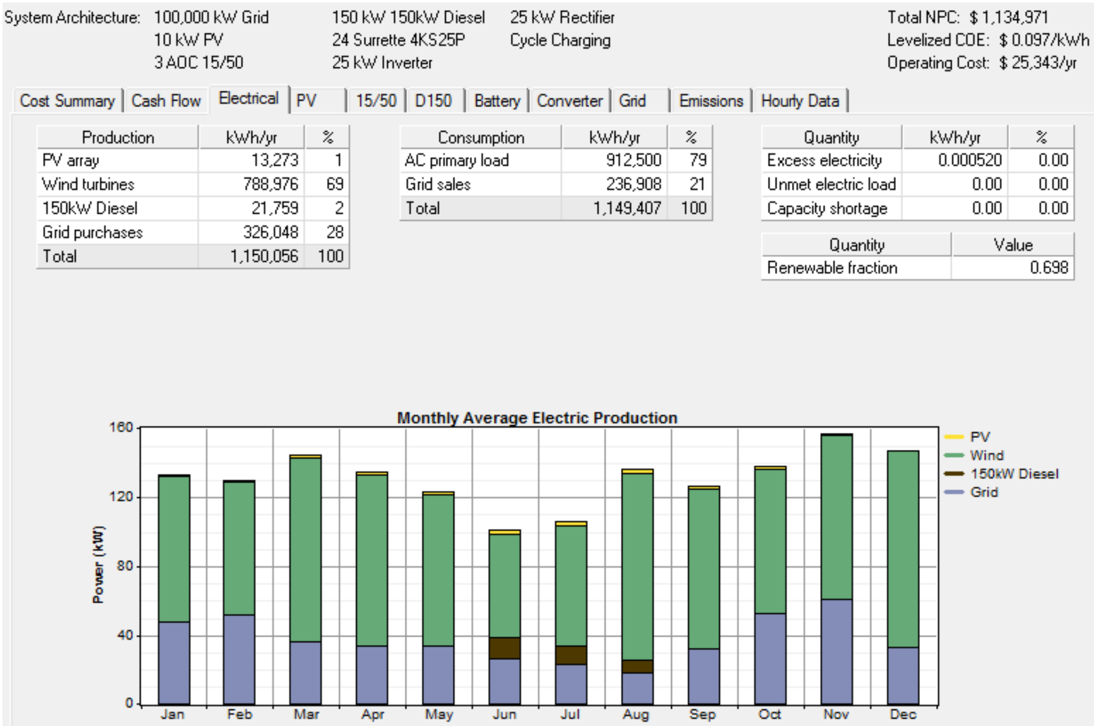


Figure 5.4 Electrical results of the second optimal alternative

The third optimal alternative, shown in *Figure 5.5*, has the highest initial capital required, $811,000; however, this solution uses more DER and some customer requirements--such as energy independence, power reliability, power quality, become greener, etc.-might be met. On the other hand, this scenario might not be very attractive for the electric utility because the purchases of electricity decrease to around $100,000.

HOMER can provide valuable information for the microgrid project, but it does not provide the mutual benefits for the customer and the electric utility company. HOMER's goal is to provide the customer with the optimal combination of generation sources based on costs calculated on their net present value. In contrast, the microgrid reference methodology proposed in this chapter does not focus on the best technical alternative or the cheapest one; instead, the focus is the impact of alternatives on a group of criteria for the achievement of the higher level objectives of both actors.



System Architecture: 100,000 kW Grid, 10 kW PV, 3 AOC 15/50, 150 kW 150kW Diesel, 24 Surrette 4KS25P, 25 kW Inverter, 25 kW Rectifier, Cycle Charging

Total NPC: $ 1,134,971
Levelized COE: $ 0.097/kWh
Operating Cost: $ 25,343/yr

Cost Summary | Cash Flow | Electrical | PV | 15/50 | D150 | Battery | Converter | Grid | Emissions | Hourly Data

Production	kWh/yr	%
PV array	13,273	1
Wind turbines	788,976	69
150kW Diesel	21,759	2
Grid purchases	326,048	28
Total	1,150,056	100

Consumption	kWh/yr	%
AC primary load	912,500	79
Grid sales	236,908	21
Total	1,149,407	100

Quantity	kWh/yr	%
Excess electricity	0.000520	0.00
Unmet electric load	0.00	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.698

Figure 5.5 Electrical results of the third optimal alternative

The generic utility and customer profiles were based on information collected from magazine reports on the current microgrid market issues presented in sections 2.4 and 2.5 of this research, and from questionnaires and interviews with Indiana utility companies and industrial customers. The complete answers from these questionnaires are presented in Appendix A and B.

5.3 <u>Definition</u>

We start the analysis of the current system by describing the δ level. The information was synthesized using the different resources reviewed in Chapter 2, and the questionnaires and interviews with electric utilities and industrial customers detailed in Appendix B and Appendix C respectively.

Resources:

- Microgrid Management, Operation and control systems (MOCS)
- Infrastructure in Customer premises, microgrid user and other customers
- Information systems of service provider and microgrid user

Stakeholders:

- Generic Utility company: e.g. Duke Energy
- Generic customer: e.g. industrial or commercial
- Other neighboring customers and electricity users
- Market regulator: e.g. Indiana Utility Regulatory Commission (IURC)
- Suppliers: manufactures, vendors, providers

Operations

- Information integration
- Business processes
- Billing & management

Policies:

- Regulator policies
- Utility policies
- Customer business policies

Technical factors/concerns

- When exporting power, microgrids must provide frequency regulation, voltage support, and reactive power so that grids remain stable.

- There is a general interest in reducing environmental damage and improving energy efficiency.
- Microgrids could alter the reliability of the main power grid when there are faults in the tripping, islanding, and interconnection processes.
- There is a necessity to deal with the electric utility legacy infrastructure.
- Required investing in additional equipment for automation, control, and monitoring.

Regulatory factors/concerns

- Required regulatory and legislative awareness of new challenges and possible changes
- A regulator is necessary to promote innovation in electricity services and encourage modern grid development.
- There are existing Legal barriers to multi-building and multi-owner microgrids.
- There are different prices and regulations in each state.
- Changes in utility franchise rights and rate structures are necessary.
- There are state government incentives to increase microgrid initiatives on the east coast, but not in the Midwest.
- Lack of U.S. standardized regulation of microgrids and disincentives for utilities to permit them.

Financial Factors/Concerns

- The utility company is concerned about the costs to provide support power to the microgrid during peak hours.
- The necessity for changes in rate tariffs as consequence of reductions in power sales caused by customers using DER and microgrids.
- Currently, the utility does not know how to evaluate the environmental value of implementing microgrids.
- Concern about what to do in low electricity price environments, such as the Midwest.

Market and Business Factors/Concerns

- Positive expectation of market growth in the next five years.
- Considerable government incentives in some states to improve economic and environmental costs and grid resilience.
- It is necessary to define interconnection standards, standby rates, and sub metering rules.
- In current business models, electricity suppliers spread fees to all retail generators independently of the demand because they cannot reduce output when supplies or reserves are low.
- Different visions of electric utility microgrids. Some electric utilities perceive microgrids as new competitors to their traditional business. Others consider them as new business opportunities.
- The traditional business model has been to install new power plants as loads increase and place them in as part of the rate bases.

- Some primary objectives of electric utilities in microgrid projects are economical revenues, grid quality improvement, environmental care, and social welfare.
- Commercial concerns about new rate/tariff structures, opening up markets, developing new products, ancillary services, and aligning subsidies
- Concerns about new role for utilities, such as the Distributed System Operator (DSO) or Microgrid Integral Operator, who builds, owns, operates, and maintains the microgrid in exchange of premium tariffs.

5.3.1 Problem demarcation and goal analysis

The direct actors in this case study are the utility company and the customer. Other actors, such as the regulator, other neighborhood customers, and suppliers are important as well, and they simply respond to the requirements of one or both direct actors. Currently, the regulator does not play an active role in each project; its role is limited to law enforcement. *Table 5.1* shows the actors and their corresponding interests.

Table 5.1 Actors and Interests

Actor	Interests
Utility company	Interoperability of technology Stranded cost recovery Peak shaving Commercialize new products and services
Customer	Lower energy consumption Islanding Higher power quality
Regulator	Compliance with laws
Suppliers	Sales increase
Other neighboring customers	Maintain their quality of service
Community	Environmental care
Municipality	Compliance with regulations and laws

For this case study, we applied the methodology for two actors: the utility company and the customer. The problem demarcation and goal analysis for each actor is as follows:

We started with the goal of peak shaving and then asking: why? what is this? and how? to create a tree with related goals. This tree could be larger and consider more goals, but because this case study is an introductory example of applying the developed methodology, we will work with the tree shown in *Figure 5.6*. We repeated the same exercise for the customer, starting with the goal of islanding. The hierarchical goal tree is shown in *Figure 5.7*.

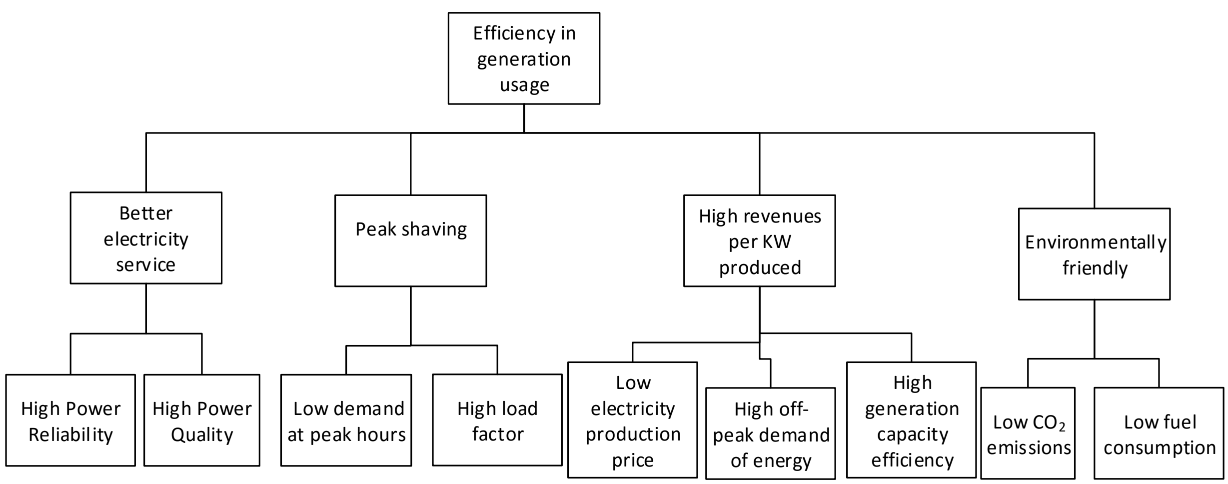


Figure 5.6 Hierarchical goal tree for the utility company

As we see, there are higher-class goals and lower class goals; however, a problem statement requires a dilemma caused by undesirable effects. The means- end trees shown in *Figure 5.8* and *Figure 5.9* show the goals, means, and undesirable effects for the electric utility company and for the customer. The problem statements are defined as follows:

- Utility company: how to obtain efficiency in generation usage without a reduction in profits or an increase in related infrastructure investments.
- Customer: how to reduce the impact of energy issues without incurring high investments or low ROI.

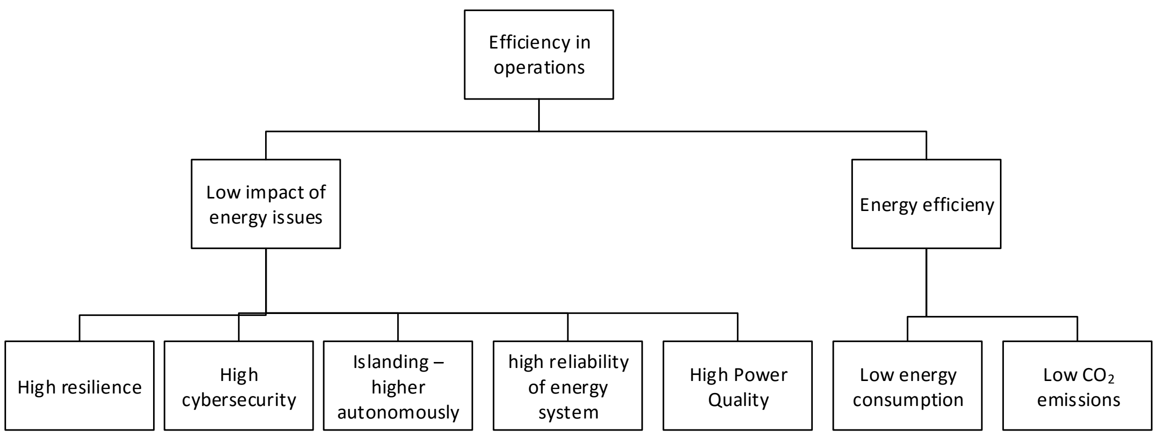


Figure 5.7 Hierarchical goal tree for the customer

We can obtain a list of criteria for our analysis from the hierarchical goal trees. The criteria are the lower class objectives without words such as high, low, etc.

- CO_2 emissions
- Fuel consumption
- Off-peak demand of electricity

- Electricity production price
- Load factor
- Electricity demand at peak hours
- Power quality
- Power reliability
- Power Resilience
- Cybersecurity level
- Energy independence (islanding)
- Customer energy production
- Efficiency of business operations

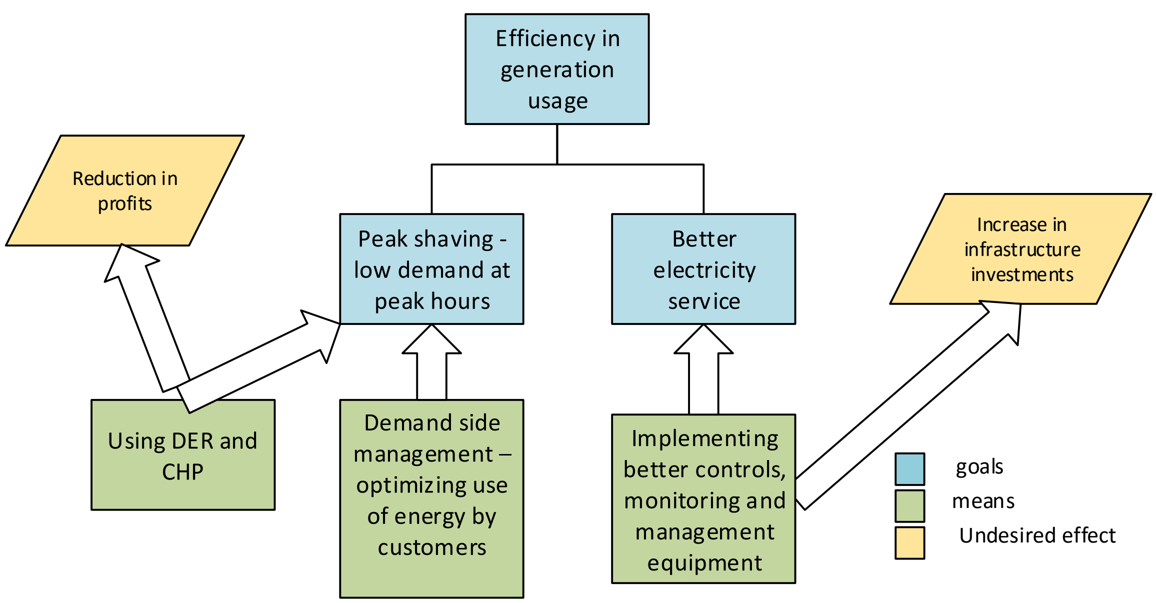


Figure 5.8 Electric Utility means – end tree.

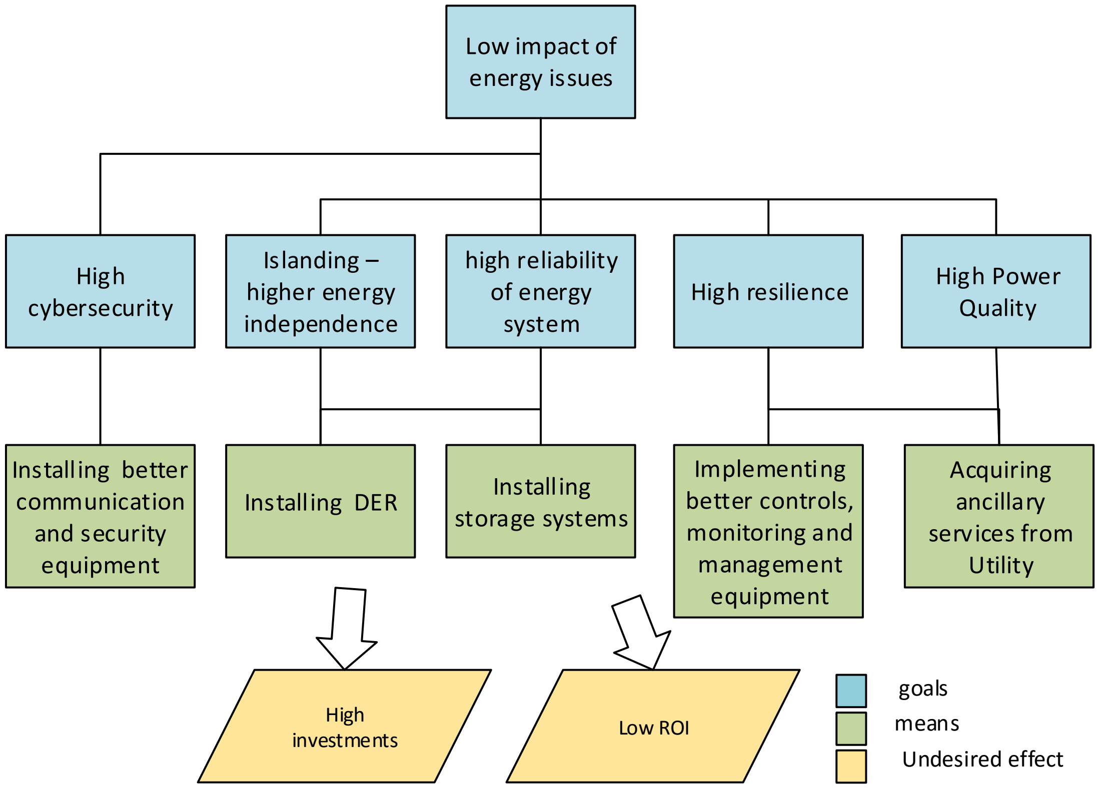


Figure 5.9 Customer means- end tree

5.3.2 Actor Analysis

Until now, the problem demarcation is an initial approximation of the scenario. The next step is to better understand the actors. By following the process detailed in *Figure 4.5*, we performed the actor analysis. The interests of the actors were defined in *Table 5.1*, and their influence is shown in *Table 5.2*.

To visualize the interests and power of influence of each customer in the current system, we created the influence/interest grid in *Figure 5.10*. It shows that the players--those who have high power and high interest--are the utility company and the customer; however, it is important to consider the other actors' positions, because they might alter the decision of the microgrid project at some point during the project's life cycle.

Table 5.2 Actors and influence

Actor	Influence
Utility company	Can change interconnection costs and rates Own important infrastructure and equipment to connect the microgrid to the grid
Customer	The user of the microgrid. Can change abruptly the forecast of energy demanded from the utility
Regulator	Can incentivize or prohibit the implementation of the microgrid.
Suppliers	Can change the prices of equipment and resources needed to implement the microgrid
Other neighboring customers	Can claim against negative effects of the microgrid implementation
Community	Can claim against negative effects in the environment
Municipality	Can incentive or prohibit the implementation of the microgrid.

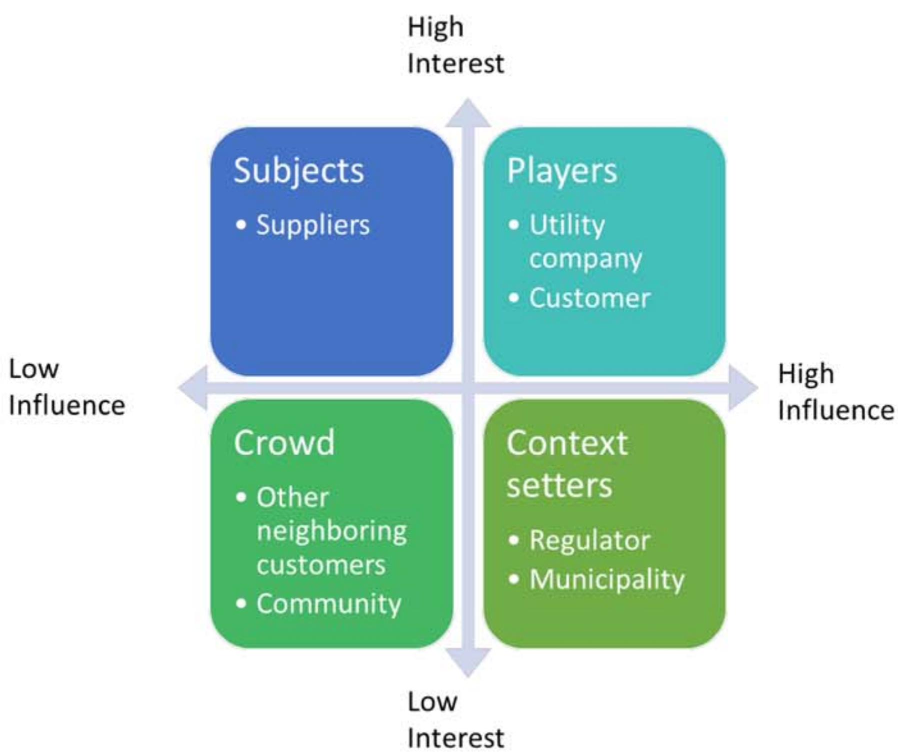


Figure 5.10 Influence/Interest table of actors

The next step is to characterize the actors by identifying their values, perceptions, resources, and network, as shown in *Table 5.3*.

Table 5.3 Actor Characterization Chart

	Values	Perceptions	Resources	Networks
Utility company	Provision of electricity services	The microgrid will reduce the demand in peak hours The incomes might be reduced	Infrastructure Personnel Know how Capital	Power grid companies
Customer	Use of the energy and infrastructure Production of energy through DER	The microgrid will improve energy security The costs required might be high	Capital Personnel Facilities	Industrial and commercial customers
Regulator	Regulation and control in tariffs and participation of each actor	The microgrid project is must meet the regulation	Permits Laws	Government, Parliament authorities
Suppliers	Provision of technology, equipment, labor, etc.	The microgrid project will allow them to provide their solutions	Technology Know how	Developers R&D
Other neighboring customers	Users of energy services	The microgrid will improve the quality of energy in the larger grid	Opinion	Customers Consumer organizations
Community	Look for the socio – economic development of its members	The microgrid will help for a less polluted environment	Population influence	Social organizations Media
Municipality	Regulation and control in its jurisdiction	The microgrid project is must meet the regulation	Permits Laws	Municipalities Government

The next step is to plot the relationship between the system's actors. For example, the regulators relate unidirectionally to the utility company and the customer in a law enforcement relationship. Of course, this is for the current microgrid case study only. The interactions might change in other cases and scenarios. In the case of the suppliers, they have bidirectional interactions with the utilities and customers, but their influence is low because they have a business relationship that is subject to market conditions. The complete map of relations is shown in *Figure 5.11*.

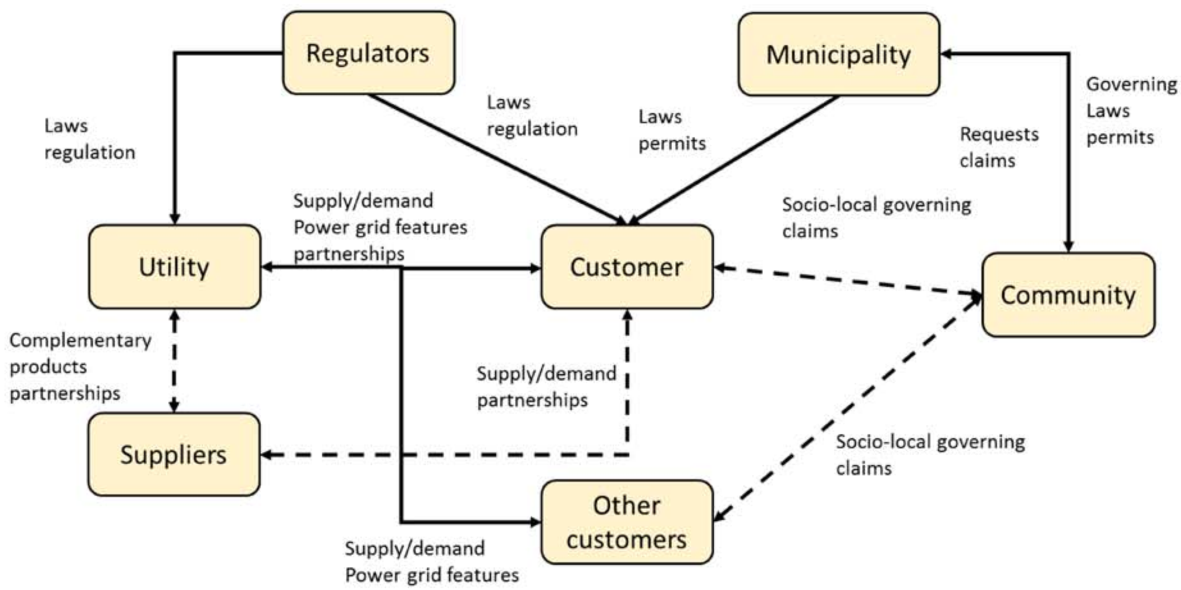


Figure 5.11 Map of relations between actors

Now we have a better understanding of the system, its actors, and their relations. The next step is to design and abstract the system into a model that allows us to visualize alternatives to solve the problem statements.

5.4 Design

In the design phase, we identified the objectives of different stakeholders, problem statements, dilemmas, and criteria. Now we are going to create a problem diagram and identify the factors and alternatives. *Figure 5.12* is the problem diagram for this case study. We can see different factors and the relations between them. For example, an incremental increase in CO2 emissions increases the amount of money the company pays in penalties, which might lead to increase investments in DER. This will increase their generation capacity and investment in Management, Operations, and Control systems (MOCS). The increase in generation capacity may reduce the energy consumption of the grid, the peak hour demand, and the utility revenues. Finally, investment in MOCS may increase the power reliability. Although three criteria are affected positively, the reduction in utility revenues is an effect undesirable to the utility company.

Now we can think of alternatives and analyze how they affect the factors and criteria. A comparison between the effects of each alternative allows for the selection of the most suitable option. Some alternatives for this case study are:

- Built a new infrastructure financed by the customer
- Built a new infrastructure financed by the utility
- Share investments and co-own infrastructure
- Develop new products and services for customers

In addition, we can see there are a considerable number of factors that cannot be influenced or changed by the customer or the utility company. For example, factors concerning regulation and technology development would constitute external factors and consequently lead to different analysis scenarios. However, we can identify other actors who directly influence these factors. For example, technology development depends on additional factors, such as R&D efforts in different fields, interoperability standards, and market conditions. In addition, incentives and restrictions can be controlled and changed. Actors such as equipment producers, universities, standardization organizations, and regulators directly impact those factors and create a scenario more attractive for investment and research in alternative energy generation with rules favorable to implement and commercialize innovative products and solutions.

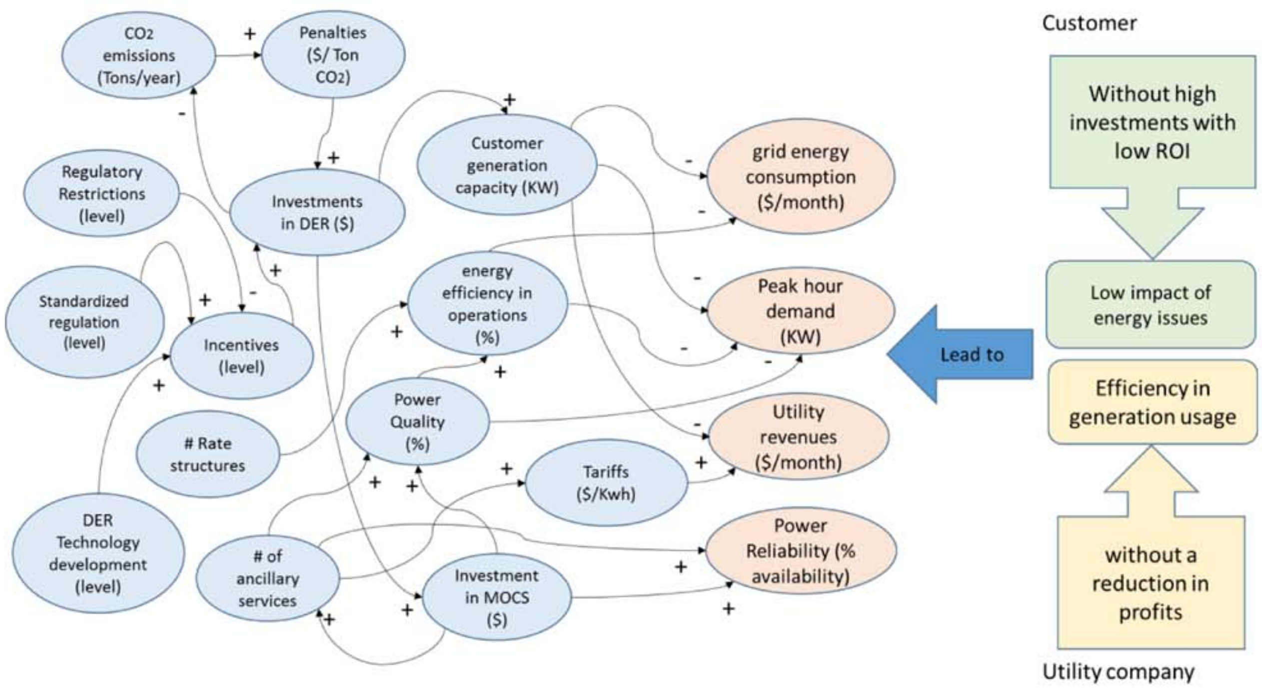


Figure 5.12 Causal and problem diagram of the microgrid

Some alternatives for those actors, especially for regulators, are:

- Legislation in favor of greener energy source adoptions
- New tariff structures with different off-peak and on-peak hours

- To subsidize energy microgrid project implementation
- To allow third parties to participate and franchise

In this case study, we consider the current state of regulatory factors and technology development to identify the alternatives that can lead to mutual benefits for the customer and utility company. The next step is to create a score card with criteria and alternatives to compare the impact of each alternative on each criterion. In this research the generic case study is not proposed to obtain exact numbers, but to exemplify the methodology proposed in Chapter 4; accordingly, we have used an ordinal and scale (very low, low, medium, high, very high) to score each criteria. In addition, we include the dilemma as an additional criterion to be scored for each alternative.

From the score card shown in *Table 5.4*, we can see that the alternative of building the new infrastructure financed by the customer and used for its own purposes is the least favorable to the electric utility and the customer because it does not solve the dilemma. If we use the results from the simulation performed by HOMER in section 5.1, the utility company would reduce its revenues by more than $700,000 during the life time of the project, defined here as 25 years. In addition, this option requires the customer to incur in an initial capital investment of more than $800,000, which is higher than the savings in energy purchased from the grid.

Analyzing the impact of the alternatives for each criterion and the causal effects between the factors shown in *Figure 5.12*, we can see that a mix of alternatives might be more beneficial. For example, we can influence more factors if we combine the alternatives related to the utility company's financing of the infrastructure. This will lead to a situation in which the customer's grid energy consumption would be reduced moderately. However, the customer does not need to worry about investments and initial capitals. In addition, the quality of energy and resilience of the network will be improved considerably, thereby achieving the customer's goal. The utility company in turn can benefit from the provision of ancillary services for this customer and neighboring customers to increase its utility revenues. Finally, a reduction in the peak hour demand will meet the utility company's goal of efficiency in generation usage.

Table 5.4 Case Study Score Card

Criteria\Alternatives	Built the new infrastructure financed by the customer	Built the new infrastructure financed by the utility	Share investments and co-own infrastructure	Develop new products and services for customers
Grid energy consumption ($/month)	Very low	high	medium	low
Peak hour demand (KW)	low	low	low	medium
Utility revenues ($/month)	very low	low	medium	high
Power Reliability (% availability)	High	High	High	medium
Customer ROI	Very low	Very high	Medium	high

While the alternatives of interest in this case study can be performed by the electric utility and the customer themselves, the tools developed with this methodology allow us to identify other factors and alternatives that might be controlled by other actors that are not active players in the current market and regulatory scenarios. When we evaluate the impact of these alternatives on the criteria, the effect may be even more favorable to the mutual benefit of not just electric utility companies and customers, but also suppliers, communities, neighboring customers, and new actors, each with specialized roles such as microgrid operators and distribution supplier operations. The evaluation and validation of these alternatives requires more specific information to score the impact of each criterion. These steps are beyond the scope of this research.

5.5 Summary

Chapter Five shows the application of the methodology proposed in Chapter 4 to a generic case study of microgrid planning. The cooperation between the electric utility company and the customer was analyzed using information from the literature review, questionnaires, and interviews. With this information, a variety of tools, charts, and diagrams were created to characterize the actors in the system, their goals, their undesired effects, and the factors and criteria to evaluate these goals. Finally, the impact of different alternatives on the criteria was evaluated.

CHAPTER 6. SUMMARY, CONCLUSIONS, AND RECOMENDATIONS

6.1 Abstract

This chapter states the main conclusions of this research, drawn from the microgrid reference methodology proposed in Chapter 4 and the results of its application in the case study presented in Chapter 5. These conclusions are in turn used to answer the research question. In addition, this chapter states recommendations about aspects that could be done differently in this research, and suggests future work that could be expanded from this research.

6.2 Conclusions

The microgrid reference methodology proposed in this research provides the framework for a determination and systematic analysis of the interactions between electrical utility companies and customers for their mutual benefit. This methodology guides information collection and processing to understand and describe the microgrid system, its context, and its actors. Unlike an unstructured and empirical negotiation process between these two key actors, as is typically used; this methodology considers the microgrid market as an additional level of the system, as shown in *Figure 4.3*. Hence, a systematic approach is used to identify key actors, and their interests, goals, and relationships at this level. Important here as well is the evaluation of different alternatives in achieving the objectives.

What kind of technical and economic benefits are commonly expected by utilities and customers?

The generic case study analyzed in Chapter 5 showed that the methodology addressed the technical and non-technical factors of both actors. Indeed, different technical, regulatory, and business factors were identified using different tools such as the goal trees, actor analysis, causal analysis, etc. The problem demarcation specifically identified the technical and non-technical goals of the actors, and the evaluation of the alternatives performed on the criteria, which led to achieving the expectations.

How can an existing local distribution grid be turned into a microgrid?

The causal problem diagram is a helpful tool to understand the microgrid system dynamics, and to quantify the impact of changes in different factors. Specific microgrid projects will lead to different interrelations between factors and impacts on the alternatives. Hence, in cases where there exists a desire to turn a local distribution grid into a microgrid, it will be necessary to follow the methodology. The main goals and interests of the actors may be similar to those determined by the case study. However, the alternatives and their impact on the criteria will, of course, be different.

How can the benefits and risks of a microgrid project be quantified to justify its implementation?

The case study showed the interests and undesired effects for electric utility companies and customers, as well as a group of factors and criteria that can be measured and evaluated. The evaluation of alternatives through these factors led to quantify not just cost variables, but the importance of other criteria, such as power reliability or peak demand energy. However, these criteria will change for each specific project and actors, for instance, a customer may be more interested in cybersecurity than the costs or ROI of the equipment necessary to build the microgrid. In this case, the problem demarcation, goal analysis, casual diagrams, and evaluation of alternatives will reflect this interest.

How should the information and control be shared between the utility and customers?

The microgrid reference methodology proposed in this research considers four levels of analysis within the System of Systems Engineering approach. This consideration led to the analysis of different problems in a microgrid system, from the more particular and technical levels to the market and business levels. The information and control the utility company and customer have can be analyzed from the technical level, and also from the higher level (as we saw in the case study). The investments in the Management, Operation, and Control systems are related to the changes in this factors and how they affect different criteria for both parties. The evaluation of these changes might lead to the formulation of new alternatives to sharing and managing information and control between the actors.

How can cyber-security be implemented effectively?

After performing the goal analysis and problem demarcation, different goals were identified concerning the electric utility and customer. One broad category was reducing the impact of energy issues, and a lower level goal concerning cybersecurity was derived. Even though this cybersecurity goal was not the focus of the case study analyzed, this reference methodology is still applicable by changing the specific problem, goals, dilemma, and other factors. The process to address cybersecurity issues as another problem from the business-level perspective and the cooperation arena can be performed using the proposed MRM.

The focus of this research is to address the cooperation and interactions between the electric utility and the customer; even so, the results of the application of the proposed Microgrid Reference Methodology also identified factors that cannot be influenced by these two actors. However, these factors can be influenced by alternatives that might not be feasible at the moment or in the current market conditions. These alternatives might involve important changes in the market and regulatory arena that would incentivize the implementation of microgrid projects and DER. These changes in regulation should not necessarily be solely based on the criteria and impact on the private objectives of electric utilities and customers, but also on social welfare. Energy efficiency, energy security, and environmentally friendly energy sources produce better quality electric service, and reduced environmental damage is beneficial to society in general.

6.3 Recommendations

The case study analyzed in this research exemplified the use of the microgrid reference methodology. Due to cost and time constraints, the application of the MRM in a real case study was beyond the scope of the current research. However, in future evaluation of the methodology, and to obtain more quantitative results, it is recommended to work with a real microgrid project. The participation of different decision makers, and the possibility of collecting specific values of technical and non-technical variables, would facilitate and enrich the process and results.

The application of the methodology in real projects requires the active participation of both electric utility and customer decision-makers. In addition, the process must be performed iteratively to achieve incremental improvement in the model. The first steps and stages of the methodology will produce preliminary results, but the actors' feedback will add depth and breadth to the analysis. Likewise, when the work proceeds to the next stage, it may be necessary to return to the previous steps to improve the description and understanding of the system.

Various branches for future work emerge from this research. This has been just one case study that clearly defines the steps to analyze microgrid systems based on the cooperation of the two main actors. However, this process is perfectible with the time. New research, case study applications, validations, and testbeds will determine better approaches and tools to improve this methodology.

Another research opportunity would be to define an architecture model for microgrid analysis, description, standardization, and information flows through the various dimensions, zones, and levels of the Microgrid System of System. This would be similar to the work performed by NIST, EN/CENENLECT/ETSI for Smart Grids referenced in Chapter 2, with the objective of ICT architecture and enterprise interactions.

Another area of future study is in microgrid modeling and simulation. Nowadays there are different tools for general system simulation and specialized tools for power systems that focus more on the three lower levels featured in *Figure 4.3*. Existing commercial tools for power systems analysis were referenced in Chapter 2; however, none considers the microgrid market as an additional level, as we manually incorporated into this research. A better model based on more complete information about actors, goals, factors and the interrelationships of a microgrid system will produce more optimal solutions. In addition, a better model will identify hidden benefits and costs that are not determined with current tools and sometimes led to incorrect decisions about justifying or rejecting a microgrid project. Therefore, there is a necessity for integral computer tools that simulate the Microgrid as a complete system, and represent its complexity, behavior, and state variables for each level under different conditions. This will reduce the time necessary to design and analyze new microgrid projects, and facilitate the decision making process in order to reach better agreements between the different actors.

6.4 Chapter summary

Chapter Six states the conclusions of this research and answers the research question and sub questions. In addition, this Chapter proposes recommendations for improvement, and suggestions of future work that can be expanded from this research.

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APPENDICES

Appendix A Questionnaire for customers

(industrial, big commercial or government facilities)

Introduction:

This is a research project conducted by Purdue University to contribute with a methodology or framework to help in the cooperation between electric utilities and consumers for microgrid utilization.

Currently, there is not a great participation of utilities in microgrid projects because of different reasons. In addition, in a microgrid implementation there are many actors with their own interests, for example, utilities, industrial customers, vendors and regulators. Hence, the relationships between actors and interactions between them must be analyzed to truly understand the socio-technical complexity in microgrids and to propose solutions that benefits all the actors.

The purpose of this questionnaire is to collect primary information to understand the interests and concerns of those different actors.

Each question could be reviewed and answered by an expert in the area inside your company, and as a second stage we would like to have a teleconference at your convenience to discuss about these same questions so you can explain with more detail your answers and we can collect more valuable information.

Camp Atterbury

Atterbury/Muscatatuck Center for Complex Operations

Edinburgh, Indiana 46124-5000

Questions:

1. What are your main interests in the electricity service used in your facilities? Please rank each criterion in a scale of importance, and specify whether you expect to achieve it by building a microgrid or not. Please feel free to add more criteria you consider important for your company.

Table A. 1 Customer 1 interests

	Importance			Achievable by building a microgrid	
Criterion	Low	Medium	High	Yes	No
Higher power quality		X		X	
lower energy consumption			X	X	
higher reliability			X	X	
Reduction in environmental damage		X		X	
reach efficiency incentives	X				X
To commercialize overcapacity	X				X

Additional insights from the interview:

- Requirements from government to reduce energy consumption
- As military base, Atterbury needs to have energy independence and to operate in face of a natural or emergency situation
- Environmental issues, going green is mandatory but not critical from Atterbury perspective
- Tax incentives are not an issue
- A lot of laws and issues with the federal government if a customer sells energy excess back to the grid.
- Atterbury prefers to have a microgrid that cover 70 – 75% of their power needs to not overproduce energy.

2. Do you use performance indexes or have a way to measure the impact of problems caused by your current electricity system in the operations of your company? (For example, the cost of poor power quality, costs of blackouts, return of investment expected to invest in new technology, etc.)

   Atterbury-Muscatatuck does not currently track problems caused by our current electrical system. We do have issues with brownouts, power outages and poor quality power causing spikes and other issues. Tracking these issues is something we need to consider putting into place.

   Additional insights from the interview:
   Atterbury would be interested if the microgrid can provide those performance indexes. Atterbury is open to receive some measurements from the utility or with own equipment

3. What are your main concerns, or barriers, to collaborate with other actors (utilities, regulator, vendors, other companies, etc.) to implement a microgrid? (for example, share of consumption information, cyber security issues, regulatory and commercial aspects, etc.)

   The first and largest issue is cost and how to fund such a project. Unless the project can show a reasonable ROI, it is difficult to get funds in the current austere environment. Additional issues we have include the fact that Duke Energy owns most of our electrical grid on post. That limits what we can do based on their company policy and IURC regulations. Cyber security is always a concern, and depends greatly on how the energy is controlled in the grid.

   Additional insights from the interview:
   Atterbury expects an improvement in cybersecurity with microgrids

   Options for implementing a microgrid:

   1. Built a parallel grid to the Duke's grid. However, this solution was discarded because of the high costs.
   2. Purchase the lines, equipment, etc. from Duke. However, Camp Atterbury does not want to incur in the utility business
   3. Use another facility which is 40 miles away from Camp Atterbury

   Three main goals of a microgrid

   1. Energy security in the event of a power outage
   2. Energy savings, using solar and batteries
   3. Higher power quality to reduce spikes

Faurecia Emissions Control Technologies
950 West 450 South, Columbus, IN, 47201

Questions:

1. What are your main interests in the electricity service used in your facilities, please rank each criterion in a scale of importance, and specify whether you expect to achieve it by building a microgrid or not?

   Please feel free to add more criteria you consider important for your company.

Table A. 2 Customer 2 interests

	Importance			Achievable by building a microgrid	
Criterion	Low	Medium	High	Yes	No
Higher power quality	FECT-Power quality acceptable				
lower energy consumption			FECT – Cost Reduction		
higher reliability	FECT-Current system is highly reliable				
Reduction in environmental damage			FECT – If this relates to Carbon Footprint, this is high.		
reach efficiency incentives		FECT- unsure of potential			
Commercialize overcapacity	FECT-not a concern				

2. Do you use performance indexes or have a way to measure the impact of problems caused by your current electricity system in the operations of your company? (Ex. The cost of poor power quality, costs of blackouts, return of investment expected to invest in new technology, etc.)
   Poor quality has minimal impact on operations.
3. What are your main concerns, or barriers, to collaborate with other actors (utilities, regulator, vendors, other companies, etc.) to implement a microgrid? (Ex. Share of consumption information, cyber security issues, regulatory and commercial aspects, etc.)
   No concern with data sharing. If it is business to utility interface, barrier is cost. Other than that, I would need to understand what collaboration opportunities we are referencing.

Deere & Company
Moline, IL 61265-8098

1. What are your main interests in the electricity service used in your facilities? please rank each criterion in a scale of importance, and specify whether you expect to achieve it by building a microgrid or not Please feel free to add more criteria you consider important for your company.

Table A. 3 Customer 3 interests

	Importance			Achievable by building a microgrid	
Criterion	Low	Medium	High	Yes	No
Higher power quality		XXXX			XX
lower energy consumption			XXXX	XX	
higher reliability			XXXX		XX
Reduction in environmental damage			XXXX	XX	
reach efficiency incentives			XXXX		XX
Commercialize overcapacity	XXXX				XX

Additional insights from the interview:
John Deere does not see how a microgrid can help to improve power quality or harmonics because of the variable nature of PV sources and wind turbines. In addition, John Deere believes the utility offers a higher reliability than the one a microgrid can offer.

2. Do you use performance indexes or have a way to measure the impact of problems caused by your current electricity system in the operations of your company? (Ex. The cost of poor power quality, costs of blackouts, return of investment expected to invest in new technology, etc.)

   Varies unit by unit but overall yes we have some means to calculate this.

   Additional insights from the interview:
   John Deere uses tons/kwh.

3. What are your main concerns, or barriers, to collaborate with other actors (utilities, regulator, vendors, other companies, etc.) to implement a microgrid? (Ex. Share of consumption information, cyber security issues, regulatory and commercial aspects, etc.)

   We are working with utilities, regulators and third parties on PV installations-we have the cart before the horse though, we need standards first which I have the task of creating but have not been created to date. Deere will be leasing systems designed at approximately 20% of total load demand of the facility at which it is installed. Some cyber security concerns on these PV installs. More concerns on the payback of the units and not inducing problems onto the electrical systems, roofing/structural systems and fire protection systems. We need these units to be safe but cost justifiable.

   Additional insights from the interview:
   Overall, John Deere would like to know how to answer questions related to the best combination of resources, whether to use batteries or not, ways to calculate pay back and break-even point, etc.

Summary of customer responses

1. What are your main interests in the electricity service used in your facilities? Please rank each criterion in a scale of importance, and specify whether you expect to achieve it by building a microgrid or not
   Please feel free to add more criteria you consider important for your company.

Table A. 4 Customer interests summary

	Importance			Achievable by building a microgrid	
Criterion	Low	Medium	High	Yes	No
Higher power quality	Faurecia	Camp Atterbury John Deere		Camp Atterbury	John Deere
lower energy consumption			Camp Atterbury Faurecia John Deere	Camp Atterbury John Deere	
higher reliability	Faurecia		Camp Atterbury John Deere	Camp Atterbury	John Deere
Reduction in environmental damage		Camp Atterbury	Faurecia John Deere	Camp Atterbury John Deere	
reach efficiency incentives	Camp Atterbury	Faurecia	John Deere		Camp Atterbury John Deere
To commercialize overcapacity	Camp Atterbury Faurecia John Deere				Camp Atterbury John Deere

2. Do you use performance indexes or have a way to measure the impact of problems caused by your current electricity system in the operations of your company? (For example, the cost of poor power quality, costs of blackouts, return of investment expected to invest in new technology, etc.)
   - Camp Atterbury: Atterbury-Muscatatuck does not currently track problems caused by our current electrical system. We do have issues with brownouts, power outages and poor quality power causing spikes and other issues. Tracking these issues is something we need to consider putting into place.
   - Faurecia: poor quality has minimal impact on operations.
   - John Deere: Varies unit by unit but overall yes we have some means to calculate this.

3. What are your main concerns, or barriers, to collaborate with other actors (utilities, regulator, vendors, other companies, etc.) to implement a microgrid? (for example, share of consumption information, cyber security issues, regulatory and commercial aspects, etc.)
    - Camp Atterbury: The first and largest issue is cost and how to fund such a project. Unless the project can show a reasonable ROI, it is difficult to get funds in the current austere environment. Additional issues we have include the fact that Duke Energy owns most of our electrical grid on post. That limits what we can do based on their company policy and IURC regulations. Cyber security is always a concern, and depends greatly on how the energy is controlled in the grid.
    - Faurecia: No concern with data sharing. If it is business to utility interface, barrier is cost. Other than that, I would need to understand what collaboration opportunities we are referencing.
    - John Deere: We are working with utilities, regulators and third parties on PV installations-we have the cart before the horse though, we need standards first which I have the task of creating but have not been created to date. Deere will be leasing systems designed at approximately 20% of total load demand of the facility at which it is installed. Some cyber security concerns on these PV installs. More concerns on the payback of the units and not inducing problems onto the electrical systems, roofing/structural systems and fire protection systems. We need these units to be safe but cost justifiable.

Appendix B Questionnaire for Utilities

Introduction:

This is a research project conducted by Purdue University to contribute with a methodology or framework to help in the cooperation between electric utilities and consumers for microgrid utilization.

Currently, there is not a great participation of utilities in microgrid projects because of different reasons. In addition, in a microgrid implementation there are many actors with their own interests, for example, utilities, industrial customers, vendors and regulators. Hence, the relationships between actors and interactions between them must be analyzed to truly understand the socio-technical complexity in microgrids and to propose solutions that benefits all the actors.

The purpose of this questionnaire is to collect primary information to understand the interests and concerns of those different actors.

Each question could be reviewed and answered by you or an expert in the area inside your company, and as a second stage we would like to have a teleconference at your convenience to discuss about these same questions so you can explain with more detail your answers and we can collect more valuable information.

Questions:

Duke Energy

400 South Tryon Street, #1331 | Charlotte, NC 28202

1. What are the incentives to collaborate with potential customers in microgrid projects versus simply building your own microgrid, or not building a microgrid?

   Questionnaire:
   It's essential to demonstrate a customer-centric mindset and deliver solutions based on customers' wants and needs. Customers win through enhanced service and the utility wins through improved customer satisfaction and the creation of new revenue streams.

   Additional insights from the interview:

   - Both parties must see value in the project.
   - Most of the customers built their own microgrids.
   - There are not incentives to provide any sort of ability to the customers to island themselves.
   - Duke is interested in ways for the utility to invest and the customers so they do not have to provide the upfront capital to the project.
   - Depending of the states and jurisdictions, some are very friendly to Utilities, some are very strict and do not allow for third party ownership nor third party leasing.
   - Duke have account managers to work with the customers to see how they can work together.

2. What are your interests and concerns in the technical aspects when implementing microgrids? The next table contains examples of factors that may be relevant for you, but feel free to discard and/or add criteria you consider important for your company. Please indicate the level of importance of your criteria in low, medium or high.

Table B. 1 Electric Utility 1 Technical interests

	Importance			Not apply
Criterion	Low	Medium	High	
Peak shaving		X		
Interoperability			X	
Cyber security		X		
Ownership of the infrastructure (microgrid)			X	
Standardization		X		
Islandability			X	
Ancillary Services		X		

Additional insights from the interview:
Interoperability and plug and play technology because Duke does not want to be locked with a specific technology or provider.
If the customer owns completely the infrastructure, then the utility cannot help too much.

3. What are your interests and concerns in the regulatory aspects when implementing microgrids? (For example, laws, incentives, restrictions, environmental issues, etc.)
Questionnaire:

A regulatory climate opens to exploring new products and services with the utility and its customers beyond standard service.

Additional insights from the interview:
It is necessary regulatory support. Duke is interest in working with regulation to understand pros and cons of doing these kind of projects (microgrids).
Duke has willingness to explore new alternatives because regulators didn't open dialogue in the past, it was just imposed.
Duke has to explore how to do with the current law.

4. What are your interests and concerns in the business and financial aspects when implementing microgrids?
The next table contains examples of factors that may be relevant for you, but feel free to discard and/or add criteria you consider important for your company. Please indicate the level of importance of your criteria in low, medium or high.

Table B. 2 Electric Utility 1 Business interests

	Importance			Not apply
Criterion	Low	Medium	High	
Implementation and maintenance costs			X	
Change in incomes				X
Rate structures			X	
New business models			X	
Opening up markets				X
New products and services			X	
Competitive risks				X
Energy trading				X
Load and Price forecasting				X

Additional insights from the interview:

- Duke thinks there is a market now that they have to serve, they are not looking for opening new markets.
- Low and price forecasting is not necessary arbitraging and looking at cycling these types of systems based on signaling or something like that.
- In other jurisdictions, microgrid owners can recover their investments, but the savings and payback in Indiana are not the same.
- Duke is looking microgrids not as a treat, but more as an opportunity.
- About charging especial rates to the customer to provide a higher quality electricity, it will depend on each case. Some areas have microgrids as a service model, while other utilities.
- DER need to have additional control and protection, and the markets that are commercializing them are those with high rates and perhaps lower liability.
- R&D now is focused in the business models; the technology is more mature, but there is a need to answer questions related to how to commercialize, scale and deploy these microgrids.

Consumers energy
1945 W Parnall Road | Jackson, MI 49201

1. What are the incentives to collaborate with potential customers in microgrid projects versus simply building your own microgrid, or not building a microgrid?

   In collaboration, the customer would raise capital (debt) at their risk (construction, ownership, sufficient return), reducing the risk profile for the utility.

2. What are your interests and concerns in the technical aspects when implementing microgrids? The next table contains examples of factors that may be relevant for you, but feel free to discard and/or add criteria you consider important for your company. Please indicate the level of importance of your criteria in low, medium or high.

Table B. 3 Electric Utility 2 Technical interests

	Importance			Not apply
Criterion	Low	Medium	High	
Peak shaving			X	
Interoperability			X	
Cyber security			X	
Ownership of the infrastructure (microgrid)		X		
Standardization			X	
Market Impact (demand forecast, resource adequacy)			X	
Regulator Impact (stranded cost, ratemaking equity, reliability standards		X		

3. What are your interests and concerns in the regulatory aspects when implementing microgrids? (For example, laws, incentives, restrictions, environmental issues, etc.)

   Stranded cost recovery, ratemaking equity, interoperability, and establishing expectations for reliability standards.

4. What are your interests and concerns in the business and financial aspects when implementing microgrids?

   The next table contains examples of factors that may be relevant for you, but feel free to discard and/or add criteria you consider important for your company. Please indicate the level of importance of your criteria in low, medium or high.

Table B. 4 Electric Utility 2 Business interests

	Importance			Not apply
Criterion	Low	Medium	High	
Implementation and maintenance costs			X	
Change in incomes		X		
Rate structures		X		
New business models		X		
Opening up markets			X	
New products and services			X	
Competitive risks			X	
Energy trading		X		
Load and Price forecasting			X	

Summary of Electric Utilities responses

1. What are the incentives to collaborate with potential customers in microgrid projects versus simply building your own microgrid, or not building a microgrid?

    - Duke: It's essential to demonstrate a customer-centric mindset and deliver solutions based on customers' wants and needs. Customers win through enhanced service and the utility wins through improved customer satisfaction and the creation of new revenue streams.
    - Consumers Energy: In collaboration, the customer would raise capital (debt) at their risk (construction, ownership, sufficient return), reducing the risk profile for the utility.

2. What are your interests and concerns in the technical aspects when implementing microgrids? The next table contains examples of factors that may be relevant for you, but feel free to discard and/or add criteria you consider important for your company. Please indicate the level of importance of your criteria in low, medium or high.

Table B. 5 Electric Utilities Technical interests summary

	Importance			Not apply
Criterion	Low	Medium	High	
Peak shaving		Duke Energy	Consumers Energy	
Interoperability			Duke Energy Consumers Energy	
Cyber security		Duke Energy	Consumers Energy	
Ownership of the infrastructure (microgrid)		Consumers Energy	Duke Energy	
Standardization		Duke Energy	Consumers Energy	
Islandability			Duke Energy	
Ancillary Services		Duke Energy		

3. What are your interests and concerns in the regulatory aspects when implementing microgrids? (For example, laws, incentives, restrictions, environmental issues, etc.)
    - Duke Energy:
      A regulatory climate opens to exploring new products and services with the utility and its customers beyond standard service.
    - Consumers Energy:
      Stranded cost recovery, ratemaking equity, interoperability, and establishing expectations for reliability standards.

4. What are your interests and concerns in the business and financial aspects when implementing microgrids?
   The next table contains examples of factors that may be relevant for you, but feel free to discard and/or add criteria you consider important for your company. Please indicate the level of importance of your criteria in low, medium or high.

Table B. 6 Electric Utilities Business interests summary

	Importance			Not apply
Criterion	Low	Medium	High	
Implementation and maintenance costs			Duke Energy Consumers Energy	
Change in incomes		Consumers Energy		Duke Energy
Rate structures		Consumers Energy	Duke Energy	
New business models		Consumers Energy	Duke Energy	
Opening up markets			Consumers Energy	Duke Energy
New products and services			Duke Energy Consumers Energy	
Competitive risks			Consumers Energy	Duke Energy
Energy trading		Consumers Energy		Duke Energy
Load and Price forecasting			Consumers Energy	Duke Energy

Appendix C Microgrid simulation characteristics of the case study

This appendix details the values and characteristics of the elements used in the microgrid simulation showed in *Figure 5.1*. as part of the generic case study.

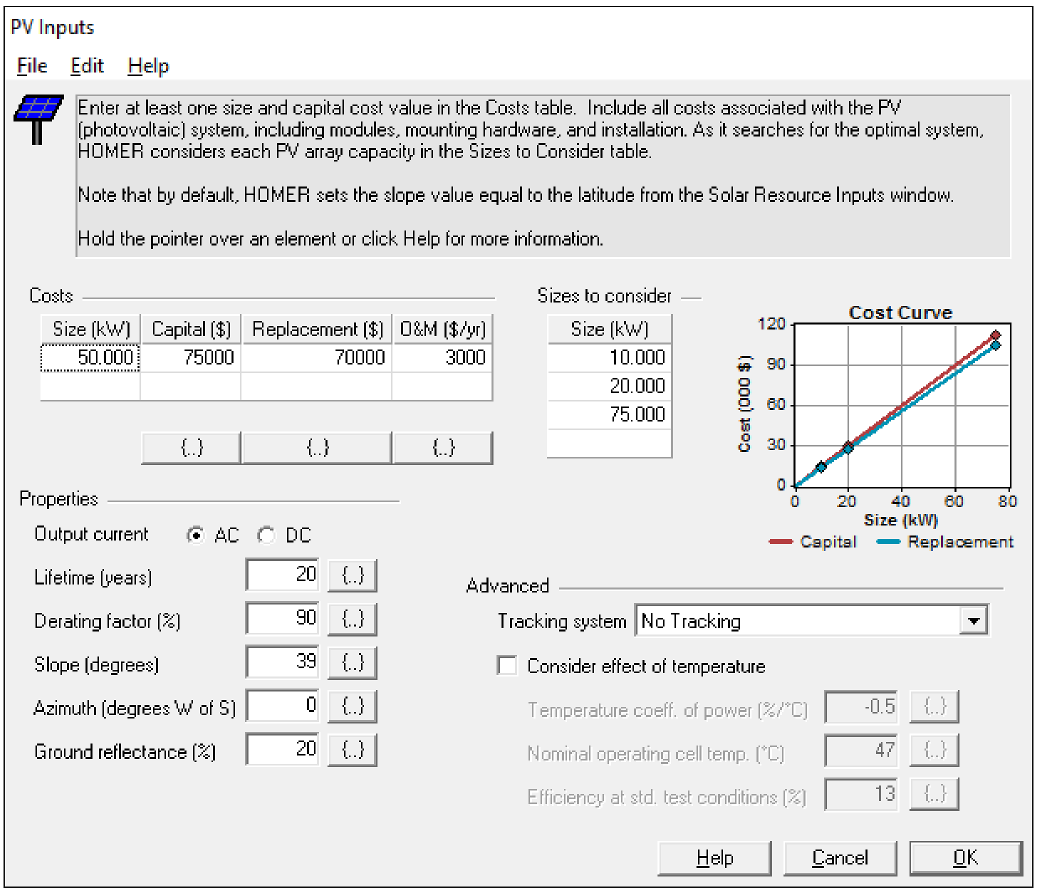

Figure C. 1 PV inputs

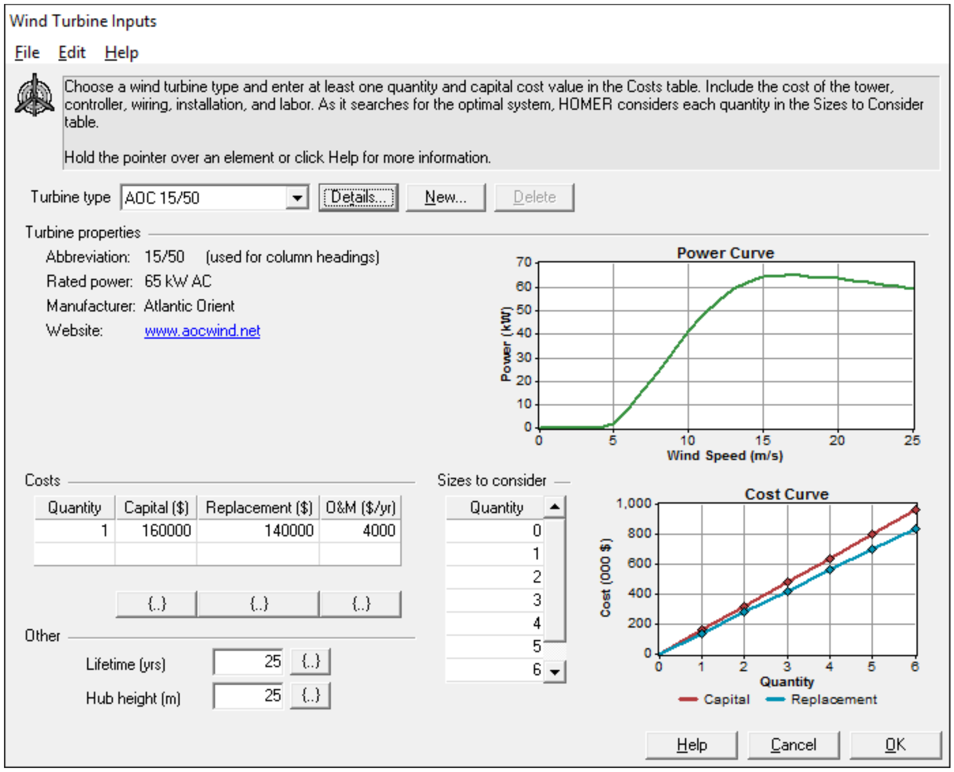

Figure C. 2 AOC 15/50 Wind turbine inputs

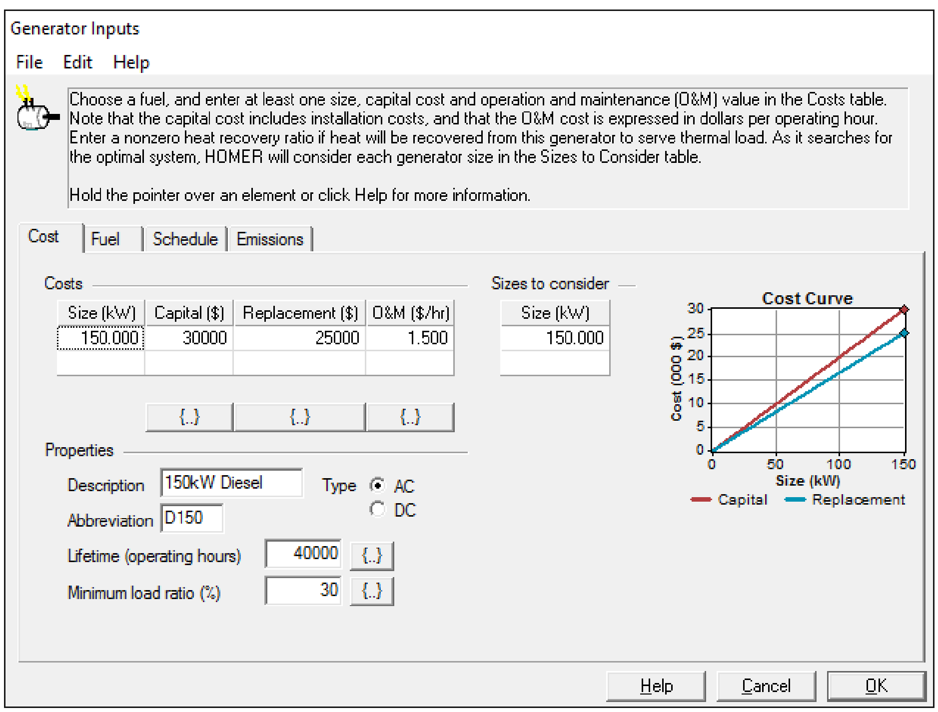

Figure C. 3 150 KW Diesel generator inputs

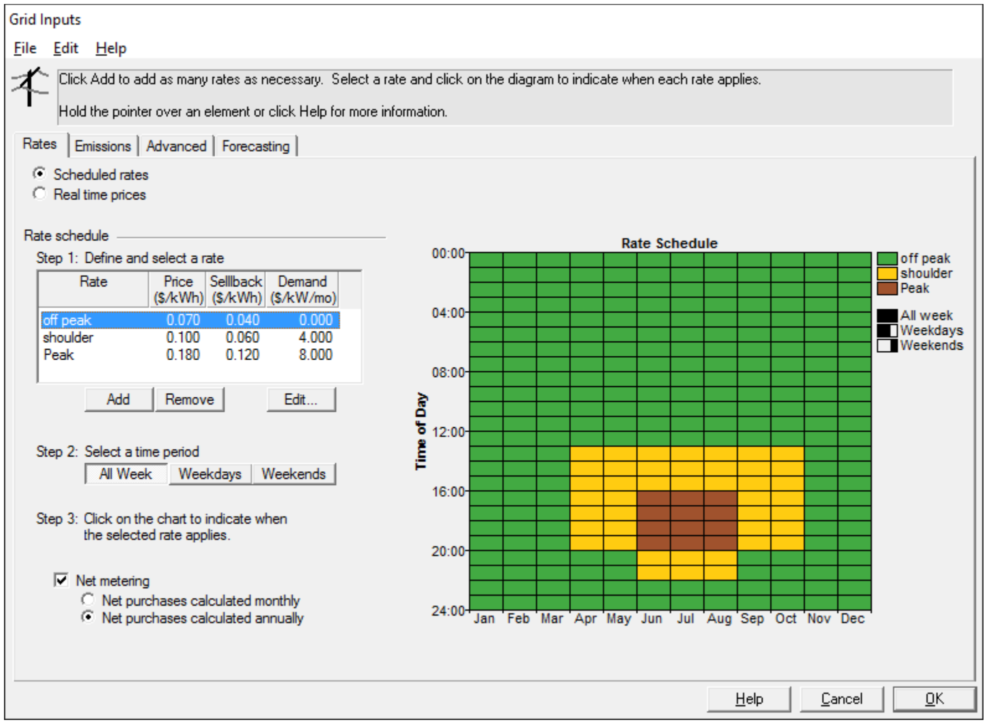

Figure C. 4 Grid inputs

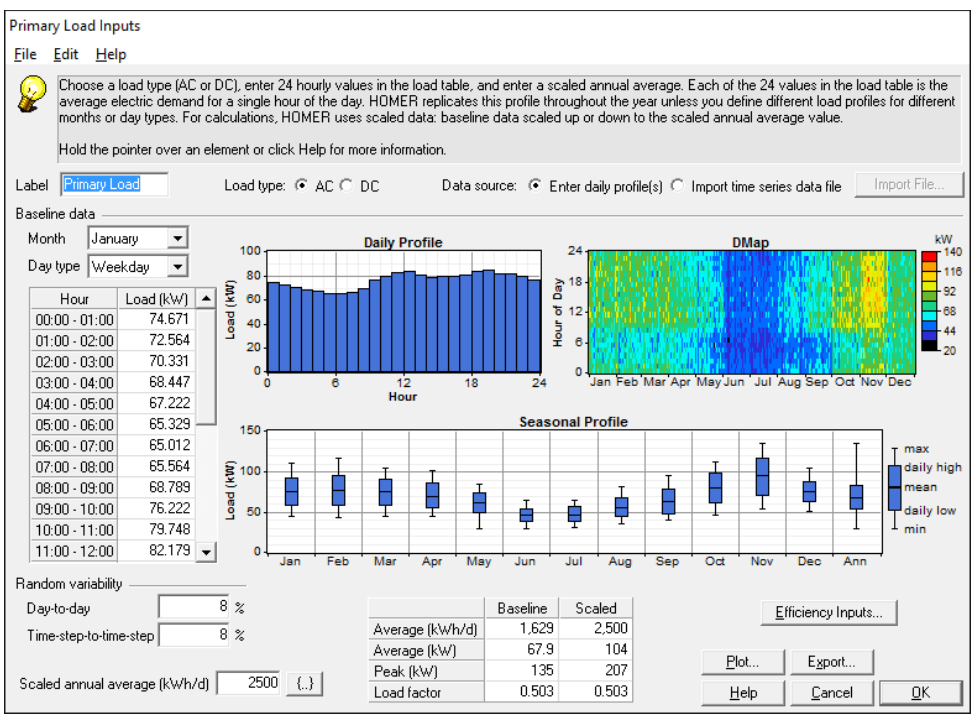

Figure C. 5 Primary Load inputs (2.5 MWh/d 207 kW peak)

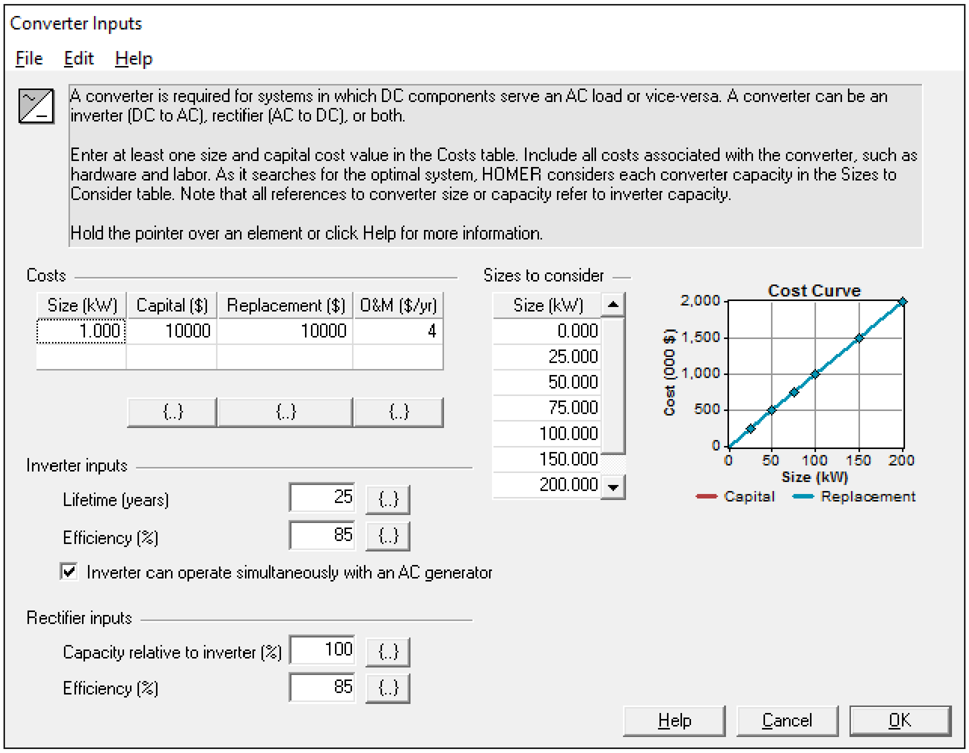

Figure C. 6 Converter inputs

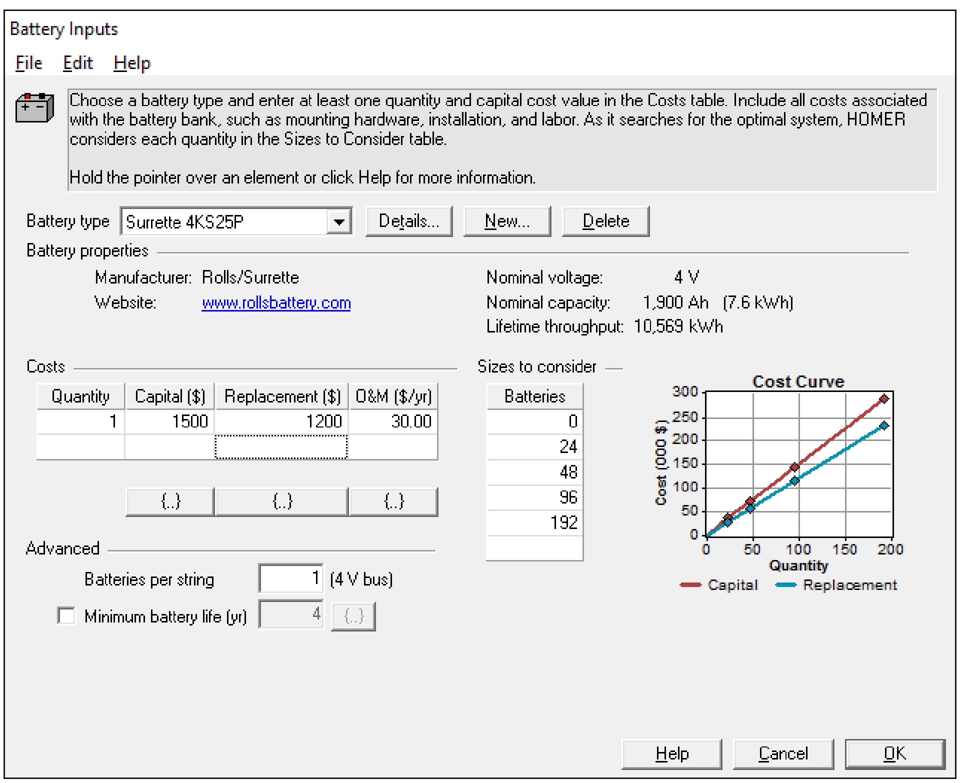

Figure C. 7 S4KS25P Battery inputs

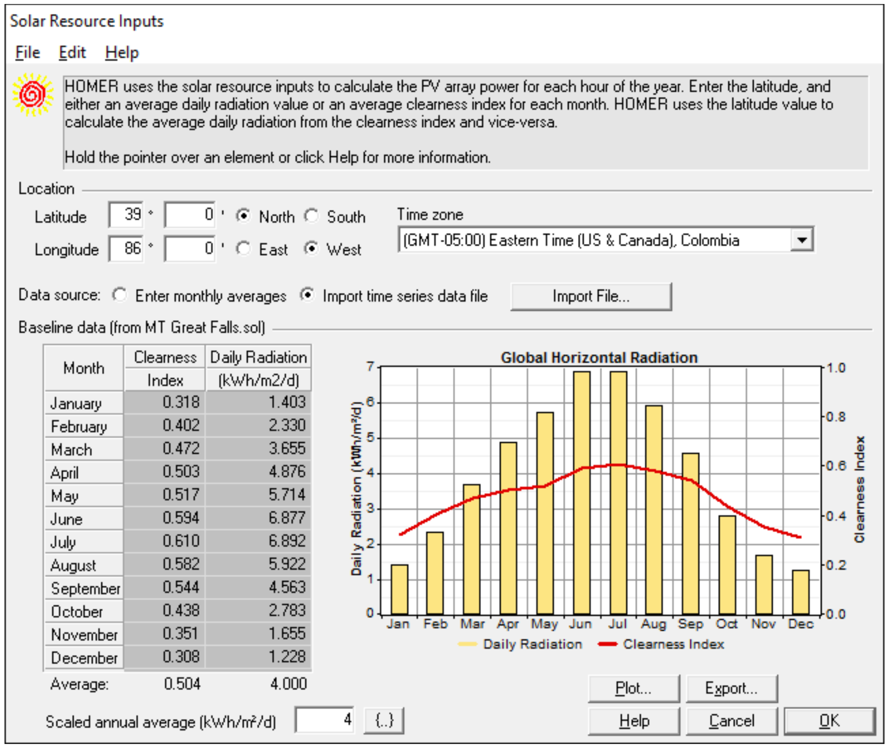

Figure C. 8 Solar resource inputs

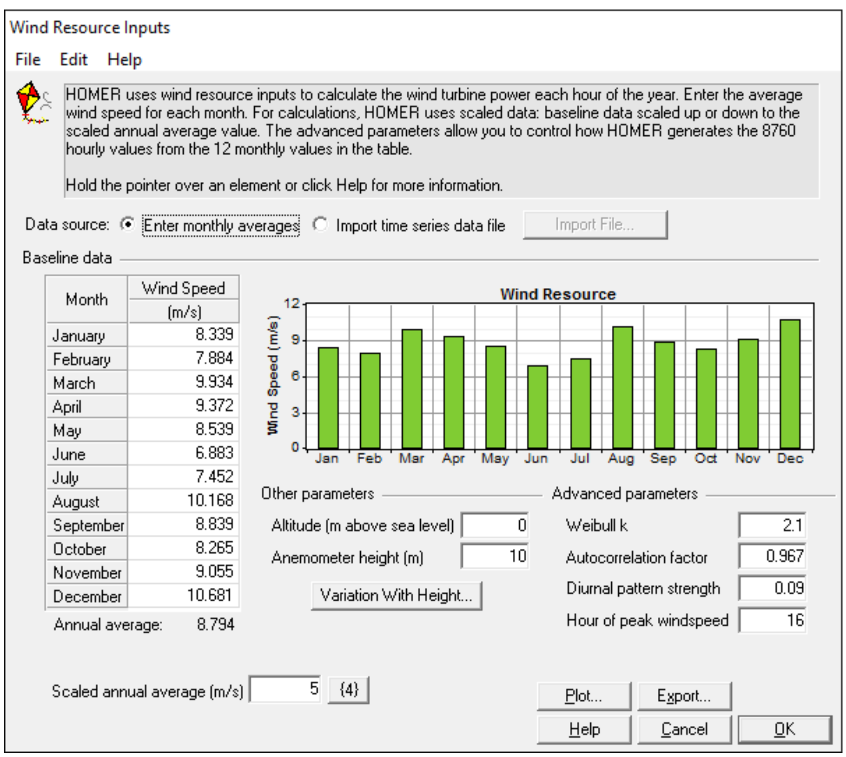

Figure C. 9 Wind resource inputs