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Published in:
Renewable & Sustainable Energy Reviews

DOI (link to publication from Publisher):
10.1016/j.rser.2014.07.198

Publication date:
2014

Document Version
Early version, also known as pre-print

This document is a preprint version of the final paper: M. Soshinskaya, W. H. J. Graus, J. M. Guerrero, and J. C. Vasquez, "Microgrids: experiences, barriers and success factors," *Renewable and Sustainable Energy Reviews*, 2014 – Elsevier.

Microgrids: experiences, barriers and success factors

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Keywords
Microgrids; Renewable Energy; Islanding; Distributed Generation; Energy Storage; Barriers

Acronyms
greenhouse gas (GHG); distributed generation (DG); distributed energy resources (DER); distributed storage (DS); Distribution System Operator (DSO); Independent Power Producer (IPP); Microgrid Central Controller (MGCC); photovoltaics (PV); Electric vehicles (EV); low voltage (LV); point of common coupling (PCC); intelligent electronic devices (IED); medium voltage (MV); high voltage (HV); Consortium for Electric Reliability Technology Solutions (CERTS); Integrated Power Supply (IPS); molten carbonate fuel cell (MCFC); phosphoric acid fuel cell (PAFC); Alternating Current (AC); Direct Current (DC); use of system (UoS); research and development (R&D); Power Flow and Quality Management System (PoMS)

Abstract
Although microgrids have been researched for over a decade and recognized for their multitude of benefits to improve power reliability, security, sustainability, and decrease power costs for the consumer, they have still not reached rapid commercial growth. The main aim of this research is to identify the common barriers and ultimate success factors to implementing a microgrid in the real world. We found that microgrids vary significantly depending on location, components, and optimization goals, which cause them to experience different types of challenges and barriers. However, the most common barriers were identified and grouped into four categories: technical, regulatory, financial, and stakeholder, based on the literature and overlying patterns recognized amongst the thirteen case studies. The most common technical barriers include problems with technology components, dual-mode switching from grid-connected to island mode, power quality and control, and protection issues. There is extensive research on how to overcome these issues, so technical

solutions are becoming available yet case specific. Regulatory barriers exist due to interconnection rules with the main grid and the prohibition of bi-directional power flow and local power trading between microgrid and the main network. The latter issue is the barrier experienced most often and has only recently been addressed, so solutions need further research. The main financial barrier is still the burden of high investment and replacement costs of the microgrid. This can be resolved with proper market support in the short term and might naturally resolve itself through learning over the long run. Lastly, stakeholder barriers include issues with conflicting self-interest and trust, and having the expertise to manage operations. These stakeholder barriers are not yet addressed in the literature and need to be further researched.

1. Introduction

In light of rising energy demand and greenhouse gas (GHG) emissions, countries all over the world are implementing targets for GHG emission reduction, improved energy efficiency, and increased clean energy production. This has led to increased implementation of distributed generation (DG) technologies, which supply efficient and/or renewable power, and are dispersed throughout the macro power system. Up until recently, DG units have not been interconnected and have only been seen as a backup rather than primary energy source [1]. Moreover, the intermittency of renewable energy generation makes it difficult to balance power in the main electricity grid. However, with a multitude of country targets on the horizon to increase renewable energy penetration, the role of DG is changing from backup to primary energy supply. The integration of these distributed energy resources (DER) into “microgrids” can thereby play a major role in achieving these targets and balancing power in the electricity grid.

A microgrid is a small scale, discrete electricity system consisting of interconnected renewable and traditional energy sources and storage with energy management systems in smart buildings. This means local consumers have the potential to meet some or all of their electricity needs through the generation and use of their own power sources, yet still be connected to the main electricity grid. At the same time, a microgrid can operate independently without connecting to the main distribution grid during islanding mode [2]. This type of onsite energy generation and management can help address concerns over how to meet rising energy demands by both reducing demand and locally implementing and further integrating energy sources and storage near the end-user.

The opportunities and benefits of integrating DERs into a microgrid exist for both end-users and electricity utilities, transmitters, and distributors to service a variety of loads including residential, office, industrial parks, commercial, and institutional campus. For these end users, onsite microgrid implementation can provide improved electric service reliability, better power quality, lower electricity costs by 20-25% [3]. It also improves overall sustainability since expanding and integrating onsite clean energy generation allows end users to directly meet their electricity requirements via a locally controlled grid that reduces the risk of power loss since they don’t have to rely on the main grid [4,1]. Microgrid implementation can also benefit local utilities by allowing system repairs without affecting customer loads, providing dispatchable load for use during peak power conditions, and lowering stress on the transmission and distribution system. This can be seen via improved efficiency by lowering distribution system loss since increasing the amount of on-site generation minimizes transmission and distribution line losses by up to 7% of electricity generated [1,4]. Thus, microgrid implementation may benefit the current infrastructure, provide demand side energy management, significantly decrease costs, and improve reliability for the consumer through a new way of generating and managing electricity.

While the concept and first trials of the microgrid date back to the 1980s [5], they have only recently started crossing over from the experimentation to commercialization phases, with pilot projects popping up all over the world [6]. However, scaling up of microgrids is proving difficult because renewable energy and storage technologies are still very expensive, and pilots are demonstrating that challenges exist in microgrid operation and control [1]. Although microgrid technology is finally reaching its commercialization phase, there often needs to be an energy crisis before decision makers will decide to add and integrate the technologies [6]. Due to the novelty and evolution of the microgrid concept, there seems to be a need to clarify what a microgrid entails and understand the barriers to implementation and which factors are crucial for successful microgrid realization and operation. This study focuses on what barriers to microgrid implementation have been experienced so far and what lessons can be learned from microgrids around the world. By answering these questions, this project aims to identify the success factors for microgrid implementation as a guide to help institutions, organizations, and energy consumers identify how local areas can effectively implement microgrids in the near future. This can in turn facilitate the growth of the microgrid market around the world.

The research method is a literature review and case analysis of different microgrids around the world. This provides insight into the underpinnings of a microgrid, which technologies must be included in a microgrid to optimally function, and which barriers are still preventing more rapid implementation. Literature was used first to identify the most common barriers and solutions that are researched, and then an analysis of patterns amongst the challenges presented by the case studies was used to support the literature or add new barriers not discussed in the literature. Thirteen cases were chosen based on publicly available information to illustrate the various types of elements, configurations, and levels of ownership. Demonstration cases were included to emphasize challenges that microgrids are still experiencing and lessons learned from those pilots. Real world cases, defined as those currently functioning successfully, as well as cases that transitioned from demonstration to real-world status were included to identify their challenges and particularly solutions during implementation. In order to gain more detail and information about certain microgrids, questionnaires were sent out to the professionals in the field. Note that while a microgrid may be integrated with distribution networks for other types of energy carriers than electricity, such as heat, the focus of this paper is only on the electricity part of the system.

This paper will begin by defining what a microgrid is, based on ownership and its essentials (Section 2). Then, the technical, regulatory, financial, and stakeholder barriers along with solutions identified by the literature and case studies will be explored (Section 3). After that, conclusions and ultimate success factors for microgrid implementation will be offered (Section 4). Lastly, the paper will end with a discussion of the results (Section 5).

2. What is a Microgrid

The term microgrid does not have a concrete definition that is ubiquitously used everywhere. For example, Lasseter (2002) took a very broad view to see a “microgrid” as “a system approach which views generation and associated loads as a subsystem” [7]. Schwaegerl et al. (2009), has gone on to define a microgrid as "an integration platform for supply-side (micro-generators) and demand-side resources (storage units and controllable loads) located in a local distribution grid" [8]. Laaksonen (2011) has added that it is a part of a distribution network which has islanding capability and reduces outages so that the microgrid works as a part of future self-healing smart grids [9].

In the definition of microgrid there is no universally accepted minimum or maximum size. Microgrids are defined by their function, not by their size. Although the architecture and size of a microgrid can vary widely, it is usually considered to be a small part of a medium voltage or low voltage distribution network where power is supplied by local sources. It can be operated either in grid connected mode or in islanded mode depending on factors like planned disconnection, grid outages or economical convenience [53]. The size of a microgrid depends basically on the peak power required by the loads, which will fix the minimum peak power to be supplied by the generation and storage systems, and the amount of available generated and/or stored energy that will provide the required autonomy to the microgrid.

Microgrids combine various distributed energy resources (DER) to form a whole system that is greater than its parts. However, regardless their size, fully grid-tied system with distributed generation (DG) that cannot operate in island mode are not microgrids, but instead can be defined as active distribution networks. An active distribution network can be defined as an electrical distribution network with systems in place to control a combination of DERs, comprising of generators and storage [3]. However, active distribution networks do not have islanding capability and can thereby be much larger in size than an equivalent power rated microgrid.

The variety in definitions proves that microgrids have different functions and in turn a multitude of characteristics. However, the basic concept is to aggregate and integrate distributed energy resources (DER), also known as distributed generation (DG)), distributed storage (DS) and loads, ideally near the end-user in order to optimize the end user’s power consumption and provide them with the following functionality and operational conditions:

- **power production** to meet the consumer’s electricity consumption demand,
- **energy management** from the supply and demand-side so that the basic requirements of electricity system operation such as power balance, voltage quality, flexibility and electrical safety are taken into account,
- **“plug & play” functionality** on two levels: 1) flexible system where new things [devices] can be implemented smoothly and 2) to be able to enter islanding mode by disconnecting from the main grid at one central point, where enough power is produced to reduce outages, and then re-synchronize connection with the main grid [10].

To achieve these functional and operational conditions, microgrids can have diverse structures, which can be predominantly explained by the internal stakeholder structure and the ownership of the microgrid. The internal makeup of a microgrid can consist of a few independent market players or a uniform coalition, encompassing both demand- and supply-side entities that are involved from a physical and financial perspective. Moreover, operational ownership is mainly decided based on ownership of the Micro-sources, or DER, which are presented in Figure 1 as four cases: Distribution System Operator (DSO) owns DER, end consumer owns DER, DER operate independently as Independent Power Producer (IPP), or energy supplier owns DER (Schwaegerl, 2009).

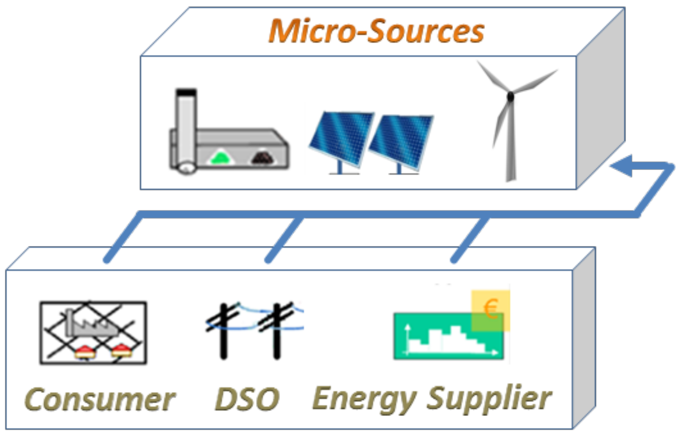

Figure 1. Sample Micro-Source (or DER) Ownership Possibilities in a Microgrid

Although Microgrids can take numerous forms, Schwaegerl (2009) groups them into three typical microgrid models—DSO Monopoly, Prosumer Consortium, and Free Market, which are summarized in table 1, based on operator, beneficiary, and DER size.

Table 1. Type of microgrid models based on ownership, indicator operational responsibility, beneficiary, and DER size

Microgrid Model	Operator	Who Benefits	DER Size
DSO Monopoly Microgrid	DSO	DSO	larger and storage units located near substations
Prosumer Consortium Microgrid	single or multiple consumer(s)	consumer reduces electricity bill or maximize sales revenue from power export	small and dispersed (esp. plug-in electric vehicle).
Free Market Microgrid	Microgrid Central Controller (MGCC)	Split accordingly between stakeholders	DER and storage vary in forms, sizes, and locations.

The *DSO Monopoly microgrid* is owned and operated by the DSO, which normally occurs in non-liberalized markets where the DSO owns the distribution and retail of the energy, and in turn are solely responsible for the costs and benefits of microgrid operation. Due to the large scale of operation and distribution, DER size is also normally larger for DSO Monopoly microgrids. In the *Prosumer Consortium Microgrid*, on the other hand, single or multiple consumer(s) purchase and operate the DER, thereby benefiting from lower electricity bills and potential sales revenue from DER power export if export tariff is high. Due to the more local scale of distribution, DER tend to be smaller. Lastly, the *Free Market Microgrid* is driven by various stakeholders (DSO, consumer, regulator etc), which means that a Microgrid Central Controller (MGCC) is necessary to operate as the energy retailer and distributor, and potential benefits are split accordingly between stakeholders. Since this type of microgrid can take various forms depending on the stakeholders involved, DER and storage varies in forms, sizes, and locations [8].

2.1 Components of a microgrid

In order to meet the aforementioned functionality and operational conditions, a variety of components are integral to the functioning of a microgrid. These technologies are first of all a combination of Distributed Energy Resources (DER), which can be a distributed generation unit (DG), distributed storage (DS), or an active load. Second a physical network to connect them all, and third advanced control and demand response technology, to operate and control the distribution of energy flows and provide energy usage information.

The load(s) of a microgrid are the components that consume electricity, like water heaters, air conditioners, refrigerators, etc. These loads require electricity at different points in the day depending on usage. Ideally these loads should be controllable with some discretionary ability in when these are used, in order to provide more flexibility in matching demand to supply. Moreover, since the microgrid can serve a variety of customers, including residential, commercial, and industrial, the classification of loads is important to achieve expected operating strategy to:

1. Meet net import/export power in grid-connected mode and stabilize voltage and frequency in island mode by facilitating load/generation shedding.
2. Improve power quality and reliability of critical and sensitive loads (commercial and industrial users).
3. Reduce the peak load to optimize the DER ratings [11].

Distributed generation units are the base of microgrids, which provide the power to meet the consumer's need. Moreover, since the goal is to deploy more efficient and cleaner power generation compared to the main grid, renewable (non-controllable) on-site generation options include solar photovoltaics (PV), micro-wind turbines (<MW), fuel cells, and micro hydropower—although the latter is a location-limited technology. Conventional yet controllable and high efficiency DG options include internal combustion engines, diesel generators, and modern Combined Heat and Power (CHP) units under 50 MW, which can even be fueled by locally produced biomass or methane instead of natural gas as a cleaner option [4,11,12]. In terms of DG scale, they seem to be in the range of kW rather than MW [8]. According to [4] a microgrid should have one or more

controllable DG units to increase flexibility and reliability of power. Moreover, it has been found that multiple smaller DGs are better at automatic load following, thereby improving energy security [12].

Distributed storage options are essential to a microgrid because power generation from DG units cannot be perfectly matched to load demands. Therefore, DS enhances the overall performance of the microgrid by acting as a bridge to meet its power and energy requirements. These storage options include high-tech options like batteries, flywheels, energy capacitors, compressed air and pumped hydroelectric storage, or relatively low-tech solutions like chilled water or ice storage. Electric vehicles (EV) are also seen as an alternative DS option in order to store power at night when the demand and cost of electricity is low. These storage options stabilize and permit DG units to run constantly, despite load fluctuations. This mitigates the intermittency of renewable primary energy sources, like the sun and wind, and it allows DG to seamlessly operate as dispatchable units to provide additional power on request [4,1].

The physical network that distributes the power between DG units, DS units, loads, and the main grid is the first layer of the power system, which connects all the essential parts. Loads are supplied via *service wires or cables* which connect customers to their DERs and the main grid from a low voltage (LV) distribution feeder. This is either an overhead construction (open wires on ceramic or synthetic insulators) or underground (cables that are buried or in conduit) [13]. Lastly, then the LV feeders are connected to a central distribution substation via an interconnection switch, which is the central point of common coupling (PCC) where synchronization with the medium voltage main grid takes place. This network comes alive and functions as a distribution network with the use of intelligent electronic devices (IED). These are e.g. circuit breakers and digital protective relays to protect personnel and equipment during faults, remotely operated switches, current and voltage sensors, and condition monitoring units for switch gear and transformers [13,10].

In order to actively operate and control DG units together with DS units and controllable loads, advanced power electronic conversion and control capabilities are necessary to integrate communication between all components into a coordinated microgrid management system. This can be similar to the current distribution management system upgraded with LV automation [14]. This requires specialized hardware and software control systems, like digital protection relays to detect, isolate, and repair faults quickly. If direct current (DC) DER like solar generation or batteries are employed, an inverter interface is crucial to convert DC generation into alternating current (AC) at the appropriate voltage level [15]. Table 2 below summarizes the interfacing and power flow control options of common DER.

Table 2. Typical interfaces used with DER [11]

Primary Energy Source Type		Typical Interface	Power Flow Control
DG	CHP	Synchronous generator	AVR and Governor (+P,+/-Q)
	Internal combustion engine	Synchronous or induction generator	
	Small hydro	Synchronous or induction generator	
	Fixed speed wind turbine	Induction generator	Stall or pitch control of turbine (+P, -Q)
	Variable speed wind turbine	Power electronic converter (AC-DC-AC)	Turbine speed and DC link voltage controls (+P, +/-Q)
	Micro-turbine	Power electronic converter (AC-DC-AC)	
	Photovoltaic (PV)	Power electronic converter (DC-DC-AC)	Maximum power point tracking and DC link voltage controls (+P, +/-Q)
	Fuel Cell	Power electronic converter (DC-DC-AC)	
DS	Battery	Power electronic converter (DC-DC-AC)	State of charge & output voltage/frequency control (+/-P, +/-Q)
	Fly wheel	Power electronic converter (AC-DC-AC)	Speed control (+/-P, +/-Q)
	Super capacitor	Power electronic converter (DC-DC-AC)	State of charge(+/-P, +/-Q)

Distribution supervisory control and data acquisition (SCADA) software is also an essential control component, along with advanced microprocessor meters (smart meter) and meter reading equipment to create transparency into all devices and optimize and balance supply and demand in real time. These advanced control systems enable proactive management of the system. Advanced demand response software furthermore detects the need for load shedding, communicates the demand to participating users, automates load shedding, and verifies compliance with demand-response programs [4].

2.2 Network configuration

Based on the microgrids components described, it is clear that they can have different configurations depending on the type of network configuration, the voltage level, and the types of generation units implemented.

The network grid can be configured in three different ways: radial, ring, or mesh, as seen below in Figure 2.

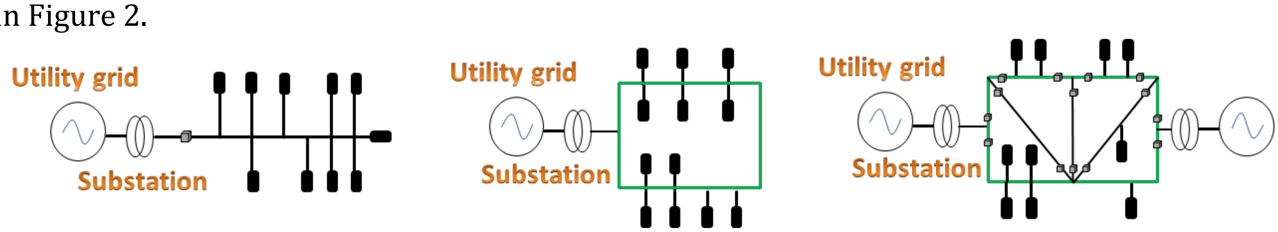

Figure 2. Examples of radial, ring, and mesh grid configurations (left to right)

A radial grid configuration is based on one main line (or multiple parallel lines in real life) to which power consumers and generation are connected so the current goes in one direction, and microgrid control and protection is optimally located at the substation. This configuration is the simplest and has the advantage of being the easiest to technically implement, particularly in rural areas [16]. In residential areas, the ring configuration is more common where electrical current flows in more than one direction. This offers better voltage stability and lower power losses, but makes protection against faults more difficult. The mesh grid configuration is the most complicated since it includes many alternative connections between nodes, which makes operation and protection challenging [10].

2.3. Low voltage versus medium voltage microgrids

In order to help differentiate between the different microgrids, they can be grouped into four categories as seen in Table 3 below [9].

Table 3. Different types of microgrids

Type of Microgrid	Example
Separated island microgrid	One village, city or island outside utility grid
Low voltage customer microgrid	One household that includes DER
Low voltage microgrid	Low voltage network that can include many DER units and customers
Medium voltage feeder microgrid	Output of one high voltage/medium voltage substation

In the first case of an island microgrid, a combination of DG units and DS units provides enough electricity for one customer or small community separate from the utility grid, because its remoteness often makes it difficult to connect to the grid. In the second case, a low voltage (LV) customer microgrid services the power demands of one customer, like a farm or detached house by connecting and operates parallel to the grid. Then when there is a fault in the utility grid, the customer's power needs are met by one or two of their own DG and DS units in islanding mode. The third case, an LV microgrid, is characterized by a group of LV customers, where power production is based on many small scale DGs, like solar panels on the roof of a house and a microturbine, for example. The LV microgrid can range from just a few consumption points to an entire low voltage network fed by an MV/LV transformer. Lastly, LV microgrids can be grouped into a MV microgrid where bigger production units, like wind power parks, can be applied. These are then centrally connected at one HV/MV substation, and can consist of partial or the entire output of the HV/MV substation (Laaksonen, 2011). These four cases are visually represented below in Figure 3.

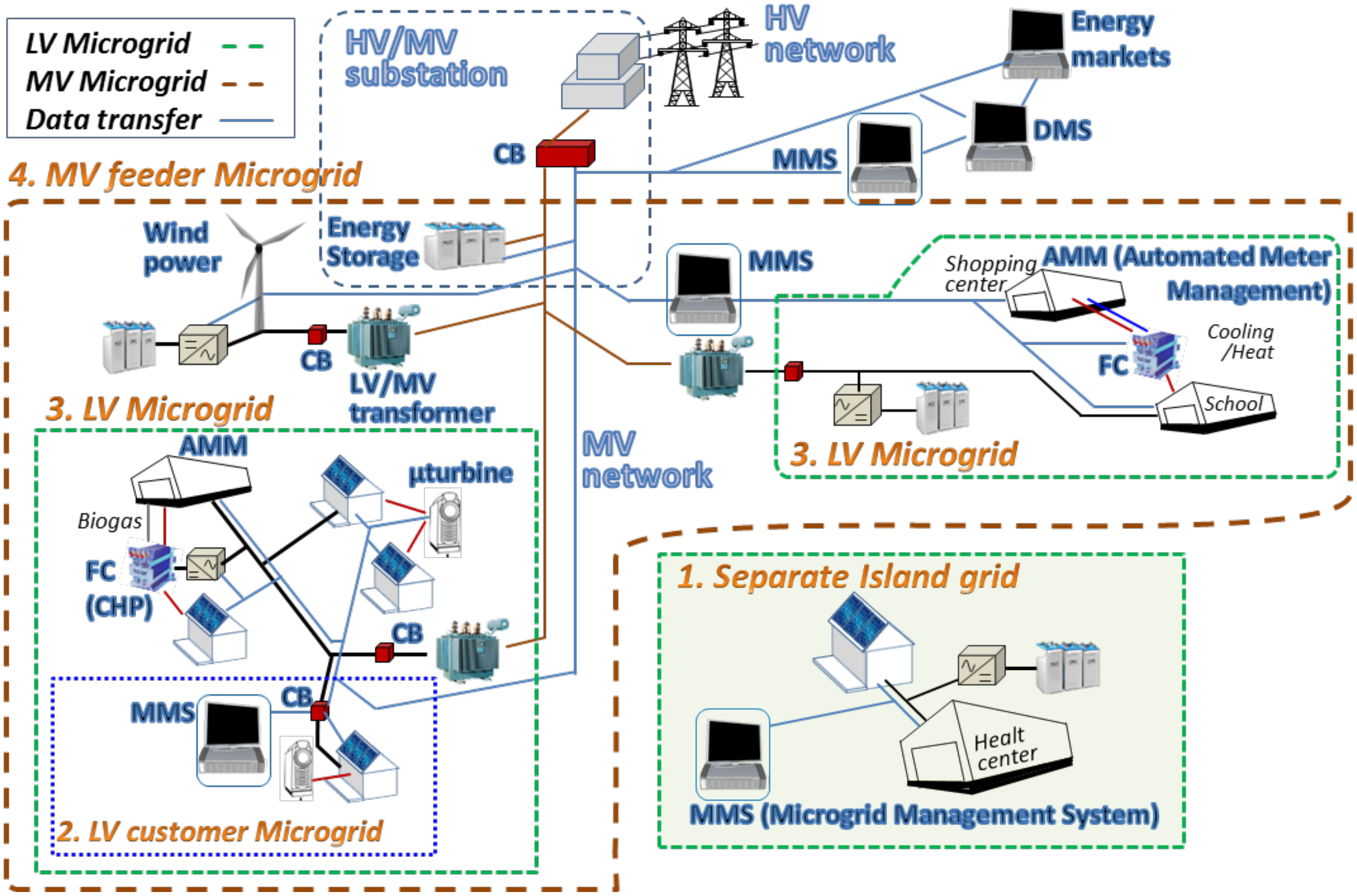

Figure 3. Four different types of microgrids: island microgrid, low voltage customer microgrid, low voltage microgrid, and medium voltage microgrid

These four types of microgrids also imply that a microgrid can appear in a variety of scales. In the case of an LV customer grid, the microgrid size will be in the vicinity of less than 10 kW capacity. Separate island microgrids and LV microgrids, on the other hand, will contain more than one DER, which can widely range from ten to hundreds kW, with total installed capacity below MW range. There can be exceptions to this, but maximum capacity of an LV grid is limited to several MW (in terms of peak load demand). MV microgrids are the largest, yet move into the multi-microgrid territory and are therefore outside the scope of this research. As a microgrid grows in scale, implying a greater number of implemented DG and DS, its balancing capacities and controllability will improve since it will be less sensitive to the intermittency on the load demand and renewable DG supply side [8]. The size of a microgrid is also related to its connection voltage level. An LV customer grid will typically be connected to the low voltage main grid, while LV microgrids that include many DERs and customers may be connected to the medium voltage main grid [7].

Due to the lack of standards and different ownership possibilities, a variety of microgrid models are proliferating. They can take different forms in terms of voltage and scale depending on geography, economically available technologies, and consumer preferences. In some cases they connect to the main grid and in others they function as a completely self-sufficient island separate from the grid. Different types of distributed generation and storage can be applied depending on geographical factors and which technologies are economically viable. The type of applied DER also has implications for the network hardware necessary, particularly in the case of microgrids employing solar and wind power production and/or battery storage, since these require inverter technology. Automatic control, demand response, and communication can also vary depending on the owner's preference of what aspect of their power use they would like to optimize: reliability, security, costs, or carbon emissions. Since microgrids can be optimized to meet a variety of goals and since they are so modular, there will probably always be a range of control approaches. This variety is illustrated in current microgrid cases from around the world, summarized in Table 4 below.

Based on this case comparison, it can be seen that the most real-world microgrids are typically in the MW scale range with a variety of DER, versus the demonstration microgrids in the kW range, which are not yet commercially viable due to a variety of reasons discussed in Section 3. For example, Flores Island microgrid has 1.48MW hydro power, 600 kW wind , and a 600kW reciprocating engine, all backed up with flywheel storage [17,18]. This is due to the fact that more and varied generation capacity ensures sufficient production and maintains power quality. However, exceptions to size do exist, as seen in the Sendai case, which has a generation capacity of 800kW, yet has transitioned from a demonstration to commercial microgrid by proving it can effectively transition to island mode during the Tohoku Earthquake by utilizing the Multi-Power Quality Microgrid System [19]. However, this was also possible due to the fact that 600kW of its IPS capacity was based on reciprocating engines, which are a stable and reliable power source. Other real world cases, like Lolland Island and Johnson & Johnson (J&J), also use more stable and cost effective distributed generation like cogeneration [20,21]. This is also a highly probable reason why the Huatacondo microgrid was able to transition from a demonstration microgrid to a commercial microgrid. It utilizes a 120kW diesel generator for the majority of its power generation and is supplemented by PV and wind turbines [22]. Moreover, it is evident that backup storage is beneficial since eleven out of the thirteen studied cases employed some type of storage technology. This is due to the fact that power storage is a critical factor in enabling continuous and stable power supply, particularly during fault or disaster events. Lastly, this case comparison illustrates the variety in available control and communication mechanisms, which depend on the optimization goals of the microgrid. For example, the Santa Rita Jail uses the CERTS technology in order to allow disconnection from the main grid and transition in island mode, as well as peak shaving through storage scheduling to decrease costs [23,24]. The Sendai case, on the other hand, has a main goal to meet the power needs of vital loads so it utilizes a Multiple Power Quality Microgrid System with Integrated Power Supply (IPS). This system groups loads into 4 categories based on the level of critical demand and prioritizes power supply so that the most important loads are supplied during emergency disconnections from the main grid [19]. Therefore, microgrids do indeed vary significantly depending on location, components, and optimization goals.

This document is a preprint version of the final paper: M. Soshinskaya, W. H. J. Graus, J. M. Guerrero, and J. C. Vasquez, “Microgrids: experiences, barriers and success factors,” *Renewable and Sustainable Energy Reviews*, 2014 – Elsevier.

Table 4. Comparison of demonstration and real-world microgrid cases around the world; ordered by known year of completion. Refer to Appendix A for References. *R=residential, C=commercial, I=industrial

Case	Country	Year	Network type	Grid Connected	Model	Load (R,C,I)*	DG Capacity	Distributed Generation (DG)	Distributed Storage (DS)	Control/Communication
Samsø Island (RW)	DK	-	Mesh	Y	Free Market	R,C	>11 MW	Wind, solar	None	unknown
Lolland Island (RW)	DK	-	Mesh	Y	Free Market	R	11.15 MW	CHP, methane-burning turbine, fuel cells	Hydrogen	unknown
Kynthos Island (D)	GR	2003	Radial	N	unknown	R	17 kW	PV, reciprocating diesel engine	Battery	PV inverters, SMA Battery inverters, intelligent load controllerr (ILC) system with Multi-Agent Software/internet
J&J CHP (RW)	USA	2004	Single user	Y	Prosumer	C	2.2 MW	CHP & absorption chiller	none	Unknown, but can be operated in grid-independent mode to provide high reliability power; no operator, monitored by DSL connection; sensors automatically page technician when necessary
Utsira Island (D)	NO	2004	Radial	Y	DSO	R	215 kW	Wind turbine, hydrogen internal combustion engine, fuel cell	Flywheel, hydrogen electrolyser, hofer compressor, battery	Master synchronous machine/none
Am Steinweg (D)	DE	2005	Mesh	Y	DSO	R	63 kW	PV, CHP	Battery	Bi-directional inverter, Power Flow and Quality Management System (PoMS)/internet
Mannheim-Wallstadt (D→RW)	DE	2006	Mesh	Y	DSO	R	23.5 kWp	PV, CHP	Battery	Inverters, Multi-Agent System/internet
Hachinohe (D)	JP	2006	Radial	Y	Free Market	I,C	610 kW	PV, wind turbines plant & dispersed, gas engines	Battery	4 layer Energy Management System with PV inverter to compensate for imbalances among 3 phases/Energy Mgmt: Private line
Sendai (D→RW)	JP	2007	Radial	Y	Prosumer	R,C	800 kW	PV, fuel cell, reciprocating engine	Battery	Multiple Power Quality Microgrid System with Integrated Power Supply (IPS) & Dynamic Voltage Restorers (DVR compensates voltage dip); 2 switched: PCC & Resale Prevention Relay
Bronsbergen (D)	NL	2008	Mesh	Y	DSO	R	315 kWp	PV	Batteries	Microgrid Central Controller with PV inverters and battery monitoring system/internet
Huatacondo (D→RW)	CL	2011	Ring	N	Prosumer	R	150 kW	PV, diesel generator, wind micro-turbines	Batteries	PV inverters, battery inverter, wind inverter with Energy Management System based on Rolling Horizon Strategy for Isolated Microgrid/internet
Flores Island (RW)	PT	2012	-	N	DSO	R,C	2.48 MW	Hydro, wind, diesel reciprocating engine	Flywheel	Power Store Distributed Control of generators with inverters in combination with flywheel
Santa Rita Jail (RW)	USA	2012	Single user	Y	Prosumer	R,C	2.2 MW	PV, molten carbonate fuel cell	Li-ion battery	Consortium for Electric Reliability Technology Solutions (CERTS)

Currently, the most common models in the EU are DSO Monopolies compared to more Free Market and Prosumer models around the world, although some of these latter cases do not comply with their full definitions since they do not feed power back into the grid. This has implications on the regulatory and market environment that microgrids are entering. Moreover, while Free Market models do exist and incorporate more stakeholders into the ownership of the microgrid, most do not involve the consumers yet, who in turn do not get any economic benefits or decision-making power. This is seen in the Hachinohe microgrid, which was a project supported by Mitsubishi Research Institute, Mitsubishi Electric Corporation, and Hachinohe City with the support of the New Energy and Industrial Technology Development Organization (NEDO) [25]. Samsø Island, on the other hand, is a successful example of a fully functioning Free Market microgrid since it is owned by multiple stakeholders including the municipality, private companies, and consumers, who own shares in 9 of the 11 land wind turbines. However, this has only been made possible with the aid of national and EU funds, in addition to generous, guaranteed fixed prices that Denmark provides for wind-derived electricity, ensuring that the investment costs are paid back over six to seven years [26]. The real world Lolland Island microgrid is another good example of regulatory and financial support since 2006 when the Municipality of Nakskov founded a local energy holding company, LOKE A/S, specifically created for financing future energy related initiatives on the island [27]. Therefore, Free Market and Prosumer models require more regulatory and financial support, rather than DSO Monopolies.

The size and voltage level, but also the network configuration and components will be influenced to a large extent by the load characteristics. The amount of storage, e.g., will depend on the level of peak demand, flexibility (demand response level) of the different loads and requirements for reliability.

3. Barriers & Solutions

While the benefits of microgrids have been thoroughly explored and touted, and some successful microgrids have been implemented, there is still abundant literature about the technical challenges and some regulatory issues for microgrids. Moreover, the international case studies illustrate these and also indicate that financial and stakeholder challenges need to be addressed before microgrids can be smoothly implemented. These sections will explore these issues and attempt to indicate potential solutions to overcome them. The most common barriers were identified and grouped into four categories: technical (3.1), regulatory (3.2), financial (3.3), and stakeholder (3.4), based on the literature and overlying patterns recognized amongst the thirteen case studies.

3.1 Technical

With extensive research efforts and the rapidly increasing number of microgrid pilot projects initiated all over the world, it would seem that all technical challenges associated with the microgrid concept would be resolved. However, technological issues are still experienced by specific elements of the microgrid, dual-mode switching functionality between grid-connected and island mode is still a challenge, power quality is not always reliable, and protection issues are not fully resolved.

3.1.1 Technological Issues

Due to the multi-component configuration of the microgrid concept, challenges relating to specific elements of the microgrid can easily arise. If these constituents cannot be successfully implemented and operated individually, this inevitably undermines the successful operation of the microgrid. These challenges can range from the durability and efficiency of actual generation and storage units to the effective functionality of communication and control software. In the case of Utsira Island, for example, it was found that wind energy utilization was only 20% versus up to the assumed 75% [28], indicating the need for developing more efficient electrolysers & improved hydrogen-electricity. Moreover, they experienced technical difficulties with the fuel cell in the form of leaking coolant fluid and frequent false grid failure alarms, which led the fuel cell to rapidly degrade and need to be replaced after only 3 years [29]. The Santa Rita Jail microgrid in the US underscores the technical issues relating to fuel cell technologies since it was documented that fuel cell outages had a detrimental effect on the life of the fuel cell stack [24]. The Sendai case also indicated issues with the fuel cell technology since it replaced the molten carbonate fuel cell (MCFC) with the phosphoric acid fuel cell (PAFC) after the demonstration phase. Challenges can also be associated with communication and control software, especially since a multitude of programs and algorithms are currently being researched and tested. For example, the Kythnos microgrid was testing the Mult Agent System of communication and control between loads and DER (a.k.a. agents), and reported that it had issues with the negotiation process between these agents [30]. The Huatacondo microgrid also had challenges implementing its Social SCADA monitoring and control system [31]. Therefore, technical issues with specific technological elements of the microgrid can prevent it from operating successfully.

Obvious solutions to avoid these issues are to incorporate technologies (preferably more than one) and communication/control software that are proven and cost-effective. However, a significant amount of research is still being done to improve the durability and efficiencies of certain technologies, like fuel cells. Moreover, demonstration projects need to continue to test and streamline communication and control software on larger scales.

3.1.2 Dual-mode Operation

At the core of the microgrid concept is its ability to transition from grid-connected mode to island mode, either intentionally or due to a fault event, and particularly to have enough generation to provide reliable power. This conversion to island mode can take two forms: black start, which allows a short period of outage before re-energizing the system in island mode, or seamless transition within a very short time after disconnecting from the main grid, which can be very difficult to achieve [32]. The Santa Rita Jail microgrid in the US supports the difficulties associated with transitioning to off-grid mode. These are particularly the energy reliability during the transition to off-grid mode during a blackout and before the back-up generator re-energized the system with black start [24]. This supports the ideal situation of a seamless transition; however, the ability to achieve a black start transition is also important in case seamless transitioning fails.

The second transition state of reconnecting to the main grid also poses challenges. Re-synchronizing the two grids after the fault event has been resolved requires carefully choosing the moment to close the switch between them and may need further voltage and/or frequency controls in the islanded microgrid because these transitions are likely to cause large mismatches between generation and loads [32,1]. However, very few microgrids can achieve this and succumb to continuous grid connection or pure island mode, without having to switch between the two. The Bronsbergen demonstration microgrid in the Netherlands attempted to test autonomous operation and black start capabilities of its PV-battery powered microgrid, yet reported having significant issues operating its inverters in parallel and achieving those two goals without losing power quality [33]. This is because the ability to support these transitions between on-and-off grid modes lies at the individual component level, particularly the inverters and converters needed for DER since the conversions need to occur in a short period of time. Therefore, more research needs to be done on developing a series of dual-mode inverters to fully realize this inherent capability of the microgrid concept. Moreover, further developing droop control methods for currently used inverters are another viable solution that have already seen positive experimental results [32].

3.1.3 Power & Frequency Control

The DSO of the main grid needs to maintain a certain frequency and voltage quality to ensure stable power flow to all consumers. Therefore, they pose certain constraints for microgrids which are connected to the main grid, which are sometimes difficult to meet due to the potentially fluctuating DG power fed from the microgrid. For example, managing the instantaneous active and reactive power balances between microgrid and network becomes difficult under network voltage profiles because the high resistance to reactance ratio of the LV networks leads to the coupling of real and reactive power, which goes against the technically acceptable state of decoupled active and reactive power during operation [1]. Difficulties also arise in the coordinated control of harmonic currents and voltage between a large number of DER with often conflicting requirements. For example, the Hachinohe microgrids experienced problems associated with frequency drop, voltage drop with AC startup, and phase unbalance in its attempt to integrate PV, wind, and dispersed gas engine power generation [34]. Even if just two types of DER are being integrated, as seen in the Bronsbergen demonstration microgrid PV-battery combination, it still reported issues in reducing harmonic currents and maintaining voltage amplitude within the standard [35]. Therefore, power quality issues should be carefully dealt with and matched to network standards, which can be a challenge to actually identify due to the limited direct transparency, accuracy, and availability of network running states.

The power and frequency control problem ultimately lies at the component level, either from intermittent DG like PV and wind, or when there is frequent load switching. One effective solution to this issue mentioned by Toa et al. (2011) is to adopt line current ramp rate limitation algorithms in storage units, which can shift voltage flickers to less critical frequencies [32]. Using a storage unit converter with such functionality will detect large current slopes of a load and inject current in a way that the slopes are smoothened.

3.1.4 Protection & Safety

Short circuit faults, which can harm components, consumer equipment and personnel, are common events in the power system. Therefore, just like the traditional power system, microgrids need protection schemes against not only external faults, but also internal faults. To prevent the microgrid from being exposed to high voltages during external faults, protective relays should be installed to automatically detect abnormal conditions and initiate circuit breakers to isolate the fault. In grid-connected mode, this protection can normally be achieved with a fast semi-conductor switch at the PCC. However, the major issue arises in island operation with inverter-based resources. This is because fault currents in inverter based microgrids may not have sufficient current rates to use traditional over-current protection techniques that rely on high fault currents for detection [3].

The cases studied indicated a lack of reported issues associated with protection and safety, which is partly due to the fact that most of the microgrid cases are still grid-connected and do not switch into island mode for long periods of time, which means they can still use traditional protection schemes for external fault protection. For the microgrids that are perpetually in island mode, like Kythnos Island, Flores Island, and Huatacondo, it is assumed that case-specific solutions were used. This is an assumption due to the lack of information provided about any protection issues in case descriptions and reports.

A variety of proposals for solutions of protection schemes have been researched and presented. For example, adopting an adaptive protection system that can change relay settings online to ensure that the whole microgrid is protected at all times. However, this is limited by the processing speed of the microgrid's communication and control network [32]. Wang et al. (2011) presented another solution based on a Central Control Unit that can coordinate DG and non-critical loads in order to avoid tripping problems [36]. However, none of these are a direct solution for the issue of low short circuit current level in island mode so more research needs to done on differential protection or voltage-based protection mechanisms to complement the current protection scheme proposals [32].

3.2 Regulatory

As already indicated proper regulatory support is a crucial underpinning to smooth microgrid implementation which provides guidance and allows for DER penetration, integration, and main network connection. However, in reality many aspects of legislation actually limit and prevent the use of microgrids. Country-specific legislation in the EU can become a significant issue for microgrid architectures with multiple DGs.

For example in Spain, RD 1663/2000, Connection of photovoltaic facilities to the low voltage grid, prevents electric loads and PV generators from being on the same circuit with the same metering system, and does not allow storage systems or other DG to be installed between PV generation and the metering system [37]. Furthermore, RD 1699/2011, which regulates self-consumption through net-metering, again constrains the microgrid concept since it does not allow the integration of generation and storage systems, and islanded mode is also not permitted. In addition, law 24/2013, article no. 9, self-consumption customers connected to the electricity grid are obliged to pay system costs and services as other consumers. Consequently, a kWh produced by a consumer will accrue the same toll payment as a kWh purchased from the grid (around 6 Eurocents per generated kWh). Thus these regulatory barriers may block the deployment of microgrids in Spain [52].

These regulations essentially undermine one of the key benefits of microgrids to integrate and easily monitor and control DER to optimize the end-users power consumption. However, certain regulatory issues are shared internationally. These limitations particularly arise when the microgrid design requires connection to the main grid. This leads to issues with interconnection rules, and bi-directional power flow and thus the inability to trade locally produced power.

3.2.1 Interconnection Rules

When DG integration into the main power grid began, network operators created interconnection guidelines and codes in order to standardize the process and manage the impacts of DG integration without disturbing the functionality and safety of the main grid. While most of these guidelines do not directly apply to the microgrid concept, anti-islanding and fault regulations do affect microgrid design because they effectively treat DER as a potential source of disturbance to the grid [32]. Therefore, these interconnection rules force immediate disconnection during blackout to avoid operation/protection complexities and prevent potential safety threats to network users and utility field crews. The anti-islanding capability comes in passive protection schemes, utilizing voltage and frequency relays at the installed DER, or active protection schemes in inverter-connected DER. These utilize sophisticated algorithms for detecting loss of grid conditions [23]. These anti-islanding protection schemes ultimately interfere with the microgrid's ability to seamlessly transition to island mode and continue functioning locally since the DER are forced to disconnect before the grid can switch into island mode. This issue was experienced by the Sendai microgrid in Japan, but resolved by consulting with the local utility, Tohoku Electric Company. This helped to design and build the microgrid system within the grid connection guidelines [38].

In addition to working closely with the local utility, this barrier can be overcome with the installation of a control switch at the PCC, where the microgrid connects to the distribution grid, combined with an MCC global control system. This system automatically monitors and detects faults so that microgrids can disconnect from the grid before anti-islanding mechanisms are activated. This switch and control system allows DGs to continue producing power without feeding it back into grid, and thereby preventing potential safety hazards [39]. This would support the communication-based method of anti-islanding functionality solution discussed by Tao et al. (2011) [32]. Therefore, technical solutions can help overcome the issues related to interconnection rules.

3.2.2 Bi-directional Flow of Reactive Power & Ability to trade locally

Once the PCC is established to switch the microgrid on and off from the distribution grid, and the network starts to view the microgrid as one functioning entity rather than a bunch of individual DER and load units, the problem of microgrid control of bi-directional flow of reactive power at the PCC arises.

Ideally, the microgrid should be able to function as an "ideal citizen", which can participate in the electricity market by buying and selling active and reactive powers to/from the grid. However, under current regulatory and market frameworks, microgrids under the "good citizen" policy are preferred, meaning they may import but cannot export active power. This is due to the fact that the DSO prefers no export of power from Microgrids if no clear regulations are in place for who will buy-back the electricity produced from renewable energy sources. Exporting power to the distribution grid can also lead to modifications of the existing MV network protection settings, which utilities prefer to avoid. Moreover, if microgrids cannot export the power produced by their DG units, this has implications for its ability to trade with local consumers via the distribution network. This type of local trading mechanism naturally raises a red flag from local energy suppliers and DSO since local trading would take away from the energy suppliers' daily income and reduce the use of system (UoS) fees charged by the DSO [32].

Therefore, microgrids are still quite limited by these regulatory and market conditions, which abolish any economic gains that would really incentivize and push microgrid implementation forward. For example, the Bronsbergen microgrid was unable to sell and buy electricity from storage [40]. The U.S. J&J CHP case also indicated that no grid-feedback is allowed, and the Japanese cases of Sendai and Hachinohe also had to make an agreement between the microgrid owner/operator and electric utilities which prohibits reverse power flow from the microgrids to the main grid [21,19,34].

Although globally prevalent, the grid-feedback barrier can still be dealt with in the short term. For example, in order to manage power production and flow so that no power is actually fed back to the grid, the Sendai and Hachinohe microgrids set a target for the power flow at the PCC, which the energy management systems ensure that the power flow remains within that scheduled value [19,34]. Moreover, if grid-feedback were allowed, thereby opening the gates for local trading, a common stakeholder interest sharing platform needs to be created to resolve the power trading class between DSO or energy supplier and DG owners. In order to provide sufficient incentives for both existing and new players in the energy retail chain, such a platform would need to transfer some of the local benefits of local retail market to DSO and energy supplier [32]. However, this would require a complicated market clearing mechanism to properly allocate net values created within this business model. Therefore, this solution needs to be further researched on the conditions necessary for such a platform to successfully function since it would need to be case-specific depending on the various demands of stakeholders involved.

3.3 Financial

Even if all of these technical and regulatory barriers would be alleviated, the commercialization of the microgrid concept heavily depends on the reduction of production costs of renewable energy generation, storage technologies, and energy management systems. While some technologies have already become cost-effective, many important technologies like PV, fuel cells, and storage technologies remain expensive without some sort of financial support.

This has been evident in the studied cases. For example, the Bronsbergen demonstration microgrid proved not to be economically viable. This was mainly because the amount of storage, which was donated for the demonstration, needed in order to support the PV installations was too expensive to reproduce at the commercial level [40]. The Utsira Island demonstration microgrid in Norway came to similar conclusions about its wind-hydrogen generation plant that required a 10 kW fuel cell, which proved to be too expensive for the 215 kW scale of the microgrid DG units [39]. The Huatacondo case has also indicated the challenge of replacing DER units, like the expensive battery system, is the responsibility of the community, which is not in an affluent area. For a small isolated village in northern Chile, this is a foreseen challenge. Current project planners are making a plan to improve the community's capacity to manage their economical resources, in addition to identifying several external agents nearby which can help [31]. Therefore, not only do technologies need to become more cost effective through more R&D and learning, but creating a longterm plan to improve the local economy and capacity of the community is necessary. This can include approaching external parties for financial assistance that can mitigate the financial challenges associated with microgrid implementation.

However, the focus of support on purely DER units can still be a problem for microgrid commercialization, which also requires market support for the advanced control functionalities and energy management systems that are integral to the microgrid concept [32]. For example, the demonstration microgrid in Am Steinweg, Germany found that the costs for the Power Flow and Quality Management System (PoMS) must be lowered so that large-scale integration of such systems into DG grids could be feasible [41]. Therefore, differentiating financial support between the DG market and the microgrid market is also a key for the commercialization of microgrids.

3.4 Stakeholder

Due to the indicated regulatory and financial barriers, the entrance of prosumers into the microgrid picture has been limited. However, some microgrids have attempted to incorporate prosumers into the planning and implementation process, which inevitably led to issues with gaining trust, dealing with conflicting self-interest, and managing operations.

3.4.1 Trust of Constituents & Conflicting Self-interest

Due to the novelty and complexity of the microgrid concept, many microgrid planners and designers can have trouble gaining the trust of local consumers to actually implement the microgrid in their area. Creating a microgrid can involve infrastructure and visual changes in the community, particularly if large PV systems and wind turbines are the chosen DG units. These changes can potentially be unwelcome by locals. Moreover, integrating the various components and understanding the ultimate environmental and financial benefits of a microgrid can be very difficult for local consumers to grasp, particularly in relatively isolated areas where many microgrid opportunities exist. Therefore, convincing local residents of benefits of microgrid implementation can be very difficult in addition to getting them to cooperate with a unified attitude.

This was experienced during the planning process of the Samsø Island microgrid by Soren Harmensen. It took Harmensen endless meetings just to get locals on board until the idea took hold to resolve community issues and concerns. For example, Samsø individual who owned a cement factory, proposed a nuclear plant to be built on the island instead of wind turbines so that he could provide the concrete for the reactor [26]. These self-interested conflicts had to be managed and dealt with democratically. The German demonstration microgrid in Mannheim-Wallstadt also found that gaining social acceptance by real prosumers required more effort than expected [42]. Gaining this acceptance can be even more difficult if a similar effort failed in the past. This was the case in Huatacondo, where planners had particular difficulties gaining the trust of the community because the project that was promised in the past was never realized [31].

Ultimately, choosing a qualified person or team that can explain the microgrid vision and convince the community of the benefits that they can gain is a key to gaining trust and social acceptance of prosumers. Having a liaison to explain visionary ideas and effectively resolve community concerns is valuable in gaining the trust of local residents. However, not all communities are the same nor receptive to big changes and visionary ideas. Therefore, more research should be done on how to identify optimal communities for prosumer involvement and how to effectively engage them.

3.4.2 Managing Operations

A lot of research and focus goes into designing the microgrid—choosing the optimal types of generation, storage, network configurations, and computing/communication hardware and software. However, operating the microgrid to achieve the continuous functionality that it was designed for is a point that should not be missed. As seen in Huatacondo, this can be during normal operations, where there were issues managing the change in consumer habits because they had to go from not having any light at night to having to maintain their power devices throughout the night [31]. In this case, the energy consumers were also the intended operators of the system so it was their responsibility to manage the devices, which was an inevitable challenge since they were not electricity or engineering experts. Moreover, running a microgrid during abnormal and unanticipated conditions also pose a significant challenge. For example, when the Tohoku Earthquake hit Japan, the effects of the disaster were greater than anyone had ever anticipated. Therefore no instruction manuals had sufficient guidance on how to respond to such a disaster. Microgrid operators also found it extremely difficult to respond to the situation due to road blockages and lack of functioning communication channels [43]. Therefore, managing microgrid operations under severe conditions, which are unplanned for poses a significant challenge even for experts in the field.

However, with proper comprehensive training of microgrid users and operators and contingency planning, these challenges can be mitigated. In Huatacondo, they overcame the issues managing consumer habits by holding workshops about the implemented technologies, how to use the Social SCADA technical interfaces, and the energy efficiency plans for the community [31]. Operator training also proved integral to the Sendai microgrid success during the disaster [43]. Therefore, operating procedures and training so that operators have a comprehensive knowledge of the system and guide for unanticipated conditions, are important elements in the implementation of microgrids. These are essential for their successful functioning during planned conditions, and particularly for unplanned situations, like times of natural disasters.

3.5 Summary of Barriers

The occurrence of these technical, regulatory, financial, and stakeholder barriers is summarized in table 5 below.

Table 5. Summary of known technical, regulatory, financial, and stakeholder barriers experienced by the 15 cases (some cases had limited information about challenges experienced, so no barriers are indicated here).

Barriers:	**TECHNICAL**				**REGULATORY**		**FINANCIAL**	**STAKEHOLDER**	
	Dual-mode Operation	**Power & Frequency Control**	**Protection & Safety**	**Technological**	**Interconnection Rules**	**Bi-directional flow of power & ability to trade locally**	**High Costs**	**Trust of constituents & Conflicting Self-interest**	**Managing Operations**
General Literature	X	X	X	-	X	X	X	-	-
Utsira Island	-	-	-	X	-	-	X	-	-
Am Steinweg	-	-	-	-	-	-	X	-	-
Bronsbergen	X	X		-	-	X	X	-	-
Kythnos	-		-	X	-	-	-	-	-
Mannheim-Wallstadt	-	-	-	-	-	X	-	X	-
Samsø	-	-	-	-	-	-	-	X	
Lolland	-	-	-	-	-	-	-	-	-
Flores	-	-	-	-	-	-	-	-	-
Sendai	-	-	-	X	X	X	-	-	X
Hachinohe	-	X	-	-	-	X	-	-	-
Huatacondo	-	-	-	X	-	-	X	X	X
J&J CHP	-	-	-	-	-	X	-	-	-
Santa Rita Jail	X	-	-	X	-	-	-	-	-
Case Occurrence	2	2	0	5	1	5	4	3	2

This analysis proves that the greatest challenges to implementation are regulatory barriers, technological issues, high costs, and stakeholder cooperation. However, technological issues have a multitude of potential solutions that already exist or are being researched. Moreover, as research and learning continues to evolve, the expensive DER, like fuel cells and batteries, will ideally become more cost-effective. However, in the short term, this will remain a significant barrier since most prosumers require a high return on investment. Apart from high costs, the greatest barriers to implementation are the regulatory and market environment surrounding the bi-directional flow of power between the microgrid and network and the ability to trade the power generated. It is found that utilities (DSOs) don't want to change nor prioritize microgrid integration into the main network, so they do not allow regulated grid feedback and trading. This also has to do with cultural and financial factors of common end users since any costs that the utility spends on upgrades, ultimately gets passed down to the consumer through an increased electricity price, which end-users naturally do not want to pay [4]. This indicates that regulatory, market, and stakeholder issues are also intertwined, creating another layer of complexity, which makes implementing a microgrid even more challenging.

4. Conclusions & Success Factors

The main aim of this research was to identify the common barriers and success factors to implementing a microgrid in the real world. Utilizing literature research, the essential constituents and ownership models of a microgrid were defined. Moreover, publicly available information about 13 microgrid cases around the world were used to illustrate the variety of challenges and solutions experienced during their implementation and operation.

It was found in the both the literature and case studies, that microgrids vary significantly in terms of ownership models, technologies employed, configurations, and scale. The literature also indicated 3 forms of microgrid ownership based on ownership of the DER units: DSO Monopoly, Free Market, and Prosumer. The case studies also illustrated this division of ownership. However, some cases did not completely fulfill the definition of Free Market or Prosumer Models since they were not allowed grid feedback and therefore were not capable of fully taking advantage of the microgrid's economic benefits by selling power back to the main grid. Moreover, while literature noted that mesh grid configurations are less ideal due to their complexity, the case study analysis illustrated that mesh and radial grid configurations are used the most often rather than ring configurations. This is probably because these microgrids utilized the configuration of the existing grid instead of installing a new network. Lastly, the literature defines a microgrid as having the capability to be connected to the main grid and also transition and function in island mode. However, the case analysis shows that the current regulatory environment and technical difficulties with transition between these phases prevent most current microgrids from fulfilling this aspect of the microgrid definition. Ultimately, the literature and case study analysis confirm that one standard microgrid model is not possible.

The literature research identified the common technical, regulatory, and market barriers as well as possible solutions, which the thirteen case studies confirmed and added to, particularly in identifying the significance of challenges associated with the various stakeholders of a microgrid. There is considerable literature identifying technical challenges in the form of maintaining power quality, have dual-mode switching capability to transition between grid-connected and island mode, and protection challenges during fault events within the microgrid. The case studies added to these challenges by describing technological issues with specific microgrid components. There is a variety of proposed solutions that already exist or are currently being researched for the technical challenges. The main regulatory barriers come in the form of complex and non-transparent interconnection rules to connect the microgrid to the main grid, and restrictions over bi-directional power flow and trading between the microgrid and main grid. The latter is the most significant and common barrier, without neither standard nor readily available solutions. Moreover, although many microgrid technologies have become costcompetitive, the case studies indicate that high investment costs are still a major challenge requiring more financial support until technological durability and efficiency improve. Stakeholder barriers also arise since stakeholders have conflicting interests and don't trust each other. This barrier does not have readily available standard solutions since microgrid community demands and cultural environment vary. Lastly, stakeholder challenges in the form of managing microgrid operation can also arise; however, these can be overcome with proper training and protocols.

Ultimately, this literature and case analysis pinpoint the success factors and/or characteristics that are necessary in order to have a full-functioning and commercially viable microgrid. These success factors can be described as:

- **Stable, reliable, and cost-effective power sources** like CHP, reciprocating engines, hydro power, wind local primary energy, should be a share of the microgrid to supply stable energy during times of outage and/or disaster.
- **Larger capacity and multiple technologies** allow microgrids to meet power demands and maintain power quality more effectively in island mode.
- **Backup equipment**, particularly storage, to maximize peak shaving and facilitate the transition between grid-connected and island mode.
- **Effective power quality and energy management system**, which can seamlessly control and communicate between DER and with the main network operator, in order to optimize consumption, maintain power quality during island mode and switching from grid-connected to island mode.
- **Supportive regulatory and market framework** is critical in order to allow feeding microgrid power back into the grid, which in turn facilitates trading with the main network and between constituents.
- **Stakeholder involvement** in decision-making to foster trust and cohesiveness among consumers and other stakeholders, like manufacturing companies, DSOs, and power producers. Building a cooperative relationship between the DSO/utility and the microgrid system is especially important if the microgrid is to be connected to the grid.
- **Microgrid operator training and user-friendly interfaces** to easily and consistently maintain its normal operation, and particularly during unforeseen events, like faults and natural disasters.

If the majority of these success factors can be employed, microgrid implementation can move forward at a more rapid pace. However, with the currently intertwined regulatory and stakeholder barriers between DSOs/utilities and prosumers, this is an extremely challenging hurdle to jump. Therefore, regulatory frameworks to facilitate grid feedback and stakeholder collaboration methods need to be further researched in order to have proper support and involvement for smooth implementation.

5. Discussion

Most current research on barriers to microgrid implementation focuses on technical challenges during microgrid operation, and only recently has some research begun identifying the regulatory and market barriers surrounding microgrid implementation. However, this has not indicated the gravity of the latter barriers. This research has confirmed and slightly expanded on the technical challenges associated with microgrids. More importantly, it has emphasized the significance of the regulatory and market barriers by identifying which barriers were experienced (and prioritizing how often) by a sample case study of 13 microgrids around the world. This research has also identified stakeholder challenges as another significant barrier, which has not yet been addressed by current literature.

However, this research also has its limitations. Microgrid cases were chosen based on the availability of public information and a variety of geographic location to represent a global sample. It would have been ideal to have at least one microgrid case from each continent, as well as from developed and developing areas. However, due to lack of information, not all continents are represented and only one microgrid case from a remote and underdeveloped area is included. The Huatacondo case in a developing area indicates that those areas have different drivers and barriers than microgrids in developing countries. More research into the differences between microgrids in developing countries versus developed countries could help clarify specific issues for each and delineate solutions for each separately. Therefore, this research could be improved by including a barrier analysis from more developing areas and continents like Africa and India, which will provide a more comprehensive insight into all possible challenges and solutions. Furthermore it must be noted that microgrids can be combined with other energy distribution networks, e.g. for heating or cooling. The combined efficient operation of the heating, cooling and electricity distribution can be an important element in the successful implementation of a microgrid.

Nonetheless, the conclusions indicate that more research needs to be done on how to resolve the barriers that were found. More significant research needs to be done on collaborative business models to stimulate the DSOs/power producers in order to change the regulatory and market environment to be more welcoming to microgrid integration. This can first be done by doing a deeper investigation of the Samsø island case study, which is already successfully selling its power back to the main grid in Denmark, in order to understand the enabling terms and conditions established by the DSO as well as how the market mechanism functions to trade power. Additionally, more research should be done on how to optimally engage end-users in the microgrid implementation and operation. This can be done via an in-depth case analysis from microgrids like AM Steinweg, Samsø Island, and Huatacondo, which have successfully engaged the various stakeholders using different methods and in varying degrees of involvement. This research can potentially provide suggestions for creating platforms and methods for stakeholder cooperation to facilitate microgrid implementation and integration into the current power environment.

Acknowledgements

The authors would like to thank Dr. Sjef Cobben, Hiroshi Irie, and Fernando Lanas for taking the time and energy to respond to the questionnaires and follow-up questions. The insight into their specific cases made them that much more interesting and tangible.

Appendix

Summarized Case References

Case	Sources of Information
Utsira Island	[29, 20]
Kythnos Island	[20, 11, 44, 45, 30]
Am Steinweg	[11, 41]
Bronsbergen	[33, 46, 11, 35, 40]
Mannheim-Wallstadt	[47, 48]
Samsø Island	[26, 20]
Lolland Island	[20]
Flores Island	[20, 17, 18]
Sendai	[20, 19, 43]
Huatacondo	[49, 22, 50, 31]
Hachinohe	[49, 22, 50, 31]
Johnson & Johnson CHP	[21]
Santa Rita Jail	[23, 24]

References

[1] Mittal A., & Agrawal, M. (2011). MICRO GRID TECHNOLOGICAL ACTIVITIES ACROSS THE GLOBE : A REVIEW. *International Journal of Research and Reviews in Applied Sciences* , 147-152.

[2] O'Connell, K. (2012). *Energy for the future*. Retrieved November 8, 2012, from Innovation Trail: http://innovationtrail.org/post/energy-future-micro-grids-explained.

[3] Basak, P., S. Chowdhury, S. HalderneeDey, S.P. Chowdhury, 2012. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. *Renewable and Sustainable Energy Reviews ,* Volume 16, p. 5545–5556

[4] Dohn, L. R., (2011). *The business case for microgrids White paper: The new face of energy modernization,* s.l.: Siemens AG.

[5] Keuffner, J. (1986). WIND HYBRID POWER SYSTEM FOR ANTARCTICA INMARSAT LINK. *International Telecommunications Energy Conference (Proceedings)* (p. 297). INTELEC.

[6] Microgrid Horizons (2012). *ABOUT MICROGRIDS*. Retrieved November 30, 2012, from Microgrid Horizons: http://microgridhorizons.com/Pages%20-%20MicroGrids/PagesAboutMicrogrids.html

[7] Lasseter, R. H. (2002). *Microgrids*. Proc., IEEE PES Winter Meeting

[8] Schwaegerl, C., Tao, L., Pecas Lopes, J., Madureira, A., Mancarella, P., Anastasiadis, A., Hatziargyriou, N. & Krkoleva, A. (2009). "Report on the technical, social, economic, and environmental benefits provided by Microgrids on power system operation." More MicroGrids EU-project. 145 pages. Erlangen, Germany. Retrieved December 7, 2012 from Microgrids: http://www.microgrids.eu/documents/668

[9] Laaksonen, H., (2011). *Technical Solutions for Low-Voltage Microgrid Concept*, 271 pages, Vaasa, Finland. ISBN 978–952–476–345–5

[10] Ihamäki, J. (2012). *INTEGRATION OF MICROGRIDS INTO ELECTRICITY DISTRIBUTION NETWORKS,* Master Thesis, 115 pages. Lappeenranta University of Technology, Finland.

[11] Lidula, N.W.A & Rajapakse, A.D. (2011). *Microgrids research: A review of experimental microgrids and test systems*. Renewable and Sustainable Energy Reviews, Volume 15, Issue 1, Pp186–202.

[12] Lasseter, R.H. (2007). *Microgrids and Distributed Generation*, Journal Of Energy Engineering, 133, 3, pp. 144-149, Academic Search Elite, EBSCOhost, viewed 7 December 2012.

[13] Higgins, N., Vyatkin, V., Nair, N.-K. & Schwarz, K., (2010). *Distributed Power System Automation with IEC 61850, IEC 61499 and Intelligent Control,* Retrieved December 14, 2012, from The Net is Automation: http://www.nettedautomation.com/download/HVNS_SMC_IEEE%20final.pdf

[14] Ihamaki, J. (2011). FEASIBILITY STUDY OF THE AVAILABLE RELAY POTECTION SOLUTIONS FOR MICRORIDS, Bachelor Thesis, 25 pages. Lappeenranta University of Technology, Finland.

[15] Asmus, P. (2010). Microgrids, Virtual Power Plants and Our Distributed Energy Future. The Electricity Journal. 1040-6190. Elsevier Inc. Pp72-82

[16] Pasonen, R. (2010). *Community microgrid - A building Block of Finnish Smart Grid*, Master's thesis, 119 pages, TUT, Tampere, Finland.

[17] Luyster, B. (2012) Deep Microgrid RFP. Retrieved on January 18, 2013 from: http://www.dpuc.state.ct.us/DEEPEnergy.nsf/c6c6d525f7cdd1168525797d0047c5bf/7de9a5e1c321af6b85257a7e00523874/$FILE/ABB%20Microgrid%20Presentation.pdf

[18] Silva, J. M.M. (2005). *THE PROSPECTS OF RENEWABLE ENERGY SOURCES IN THE AZORES ISLANDS*. 100% RES: A challenge for Island Sustainable Development. Retrieved on January 18, 2013 from http://www.unescocan.org/pdf/100RES.pdf

[19] Irie, H. (2012a). Sendai Microgrid - Introduction and Use Case. Retrieved on January 11, 2013 from: http://e2rg.com/microgrid-2012/Sendai_Irie.pdf

[20] Platt, G., Berry, A. & Cornforth, D., 2012. What Role for Microgrids?. In: F. P. Sioshansi, ed. *Smart Grid: Integrating Renewable, Distributed, & Efficient Energy.* Oxford: Elsevier Inc., pp. 185-208.

[21] Pacific Region CHP Application Center (PRAC) (2006*). Johnson & Johnson 2.2 MW reciprocating CHP system: Project Profile*. Retrieved of December 19, 2012 from Microgrids at Berkeley Lab: http://der.lbl.gov/sites/der.lbl.gov/files/dercam_casestudy_johnsonjohnson_v1_2.pdf

[22] Reyes, L. (2011). *Huatacondo's Microgrid and the Social SCADA Concept*. Retrieved January 19, 2013 from Microgrids at Berkeley Lab: http://der.lbl.gov/sites/der.lbl.gov/files/jeju_reyes.pdf

[23] Microgrids at Berkeley Labs (2012). *Current Project: Santa Rita Jail*. Retrieved on December 19, 2012 from Microgrids at Berkeley Lab: http://der.lbl.gov/microgrids-lbnl/santa-rita-jail

[24] DeForest, N., Lai, J., Stadler, M., Mendes, G., Marney, C., Donadee, J. (2011) Integration & Operation of a Microgrid at Santa Rita Jail. Retrieved on December 19, 2013 from Ernest Orlando Lawrence Berkeley National Laboratory: http://eetd.lbl.gov/ea/emp/reports/lbnl-4850e.pdf

[25] Kojima, Y., Koshio, M., Nakamura, S., Maejima, H., Fujioka, Y., Goda, T. (2007). *Demonstration Project in Hachinohe: Microgrid with Private Distribution Line*. IEEE.

[26] McKie, R. (2008) Isle of plenty. Retrieved on January 13, 2013 from The Guardian, The Observer: http://www.guardian.co.uk/environment/2008/sep/21/renewableenergy.alternativeenergy?intcmp=239

[27] Magnoni, S. & Bassi, A. (2009). *Creating Synergies from Renewable Energy Investments, a Community Success Story from Llolland, Denmark.* Energies, Volume 2, pp 1151-1169.

[28] Fuel Cell & Hydrogen Energy Association (FCHEA) (2012). Fact Sheet: Renewable Hydrogen Production Using Electrolysis. Retrieved January 29, 2013, from http://www.fchea.org/core/import/PDFs/factsheets/Renewable%20Hydrogen%20Production%20Using%20Electrolysis_NEW.pdf

[29] International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) (2011). *Utsira Wind Power and Hydrogen Plan* .Retrieved on December 19, 2012 from IHPE: http://www.iphe.net/docs/Renew_H2_Ustira.pdf

[30] Hatziargyriou, N. (2009). The More Microgrids Project. Retrieved on January 11, 2013 from: http://ec.europa.eu/research/conferences/2009/smart_networks/pdf/microgrids.pdf

[31] Lanas, F. (2013) *Centro de Energía, F.C.F.M. - Universidad de Chile* [Email Questionnaire] (19 January, 2013).

[32] Tao, L., Schwaegerl, C., Narayanan, S. & Zhang, J. H. (2011). *From Laboratory Microgrid to Real Markets--Challenges and Opportunities.* The Shilla Jeju, Korea, Institute of Electrical and Electronics Engineers (IEEE), pp. 264-271.

[33] Cobben, J.F.G. (2008a) The first microgrid in the Netherlands. Retrieved on December 27, 2012 from: http://afdelingen.kiviniria.net/media-afdelingen/DOM100000159/Sjef_Cobben_-_The_first_microgrid_in_the_Netherlands.pdf

[34] Kojima, Y (2009). *Operation Result of the Hachinohe Microgrid Demonstration Project*. Retrieved on January 13, 2013 from Microgrids at Berkeley Lab: http://der.lbl.gov/sites/der.lbl.gov/files/Kojima_2009.pdf

[35] Loix, Tom (2009). The first microgrid in the Netherlands: Bronsbergen. Retrieved on December 27, 2012 from Leonardo Energy: http://www.leonardo-energy.org/sites/leonardo-energy/files/root/pdf/2009/article2.pdf

[36] Wang, B., Sun, M. & Dong, B. (2011). "The existed problems and possible solutions of distributed generation microgrid operation", Asia-Pacific Power and Energy Engineering Conference, APPEEC.

[37] Fernandez, G., Trujullo, M., Sanz, J. & Sallan, J., (2010). *Spanish microgrids: current problems and future solutions.* Las Palmas de Gran Canaria, Spain, European Association for the Development of Renewable Energy, Environment and Power Quality.

[38] Irie, Hiroshi (2013) *Consultant at Mitsubishi Research Institute, Inc*. (Email Questionnaire] (23&24 January, 2013)

[39] Guerrero, J., 2013. *Vasquez, J.C.; Guerrero, J.M.; Savaghebi, M.; Eloy-Garcia, J.; Teodorescu, R., "Modeling, Analysis, and Design of Stationary-Reference-Frame Droop-Controlled Parallel Three-Phase Voltage Source Inverters," Industrial Electronics, IEEE Transactions on , vol.60, no.4, pp.1271,1280, April 2013*

[40] Cobben, J.F.G. (2013) *Part-time Professor at Technische Universiteit Eindhoven & Strategy and consulting power Quality, Smart grids, Safety at Alliander,* [Email Questionnaire] (2 & 8 January, 2013).

[41] Erge, T., Becker, R., Kröger-Vodde, A., Laukamp, H., Thoma, M., Werner R., & Wittwer, C. (2005), *Report on improved power management in low voltage grids by the application of the PoMS system, Deliverable 9.3 (DISPOWER project)*; Retrieved on January 11, 2013 from: http://www.iset.uni-kassel.de/dispower_static/documents/del93.pdf

[42] Pickhan, R., M. Khattabi, S. Drenkard, H. Dietschmann, A. Dimeas and P. Moutis (2009). Advanced Architectures and Control Concepts for MORE MICROGRIDS. Report for the European Commission. Retrieved on 7-11-2013 from: http://www.microgrids.eu/documents/661.pdf

[43] Hirose, K., Reilly, J.T., Irie, H. (2013). *The Sendai Microgrid Operational Experience in the Aftermath of the Tohoku Earthquake: A Case Study*. Retrieved on January 11, 2013 from: http://der.lbl.gov/sites/der.lbl.gov/files/Sendai%20paper%20jan%2013.pdf

[44] Dimeas, A.L. & Hatziargyriou, N.D. (2009). Control agents for real Microgrids. Retrieved on January 11, 2013 from: http://labplan.ufsc.br/congressos/ISAP%202009/ISAP2009/PDFs/Paper_146.pdf

[45] Mitra, I., Degner, T., & Braun, M. (2008). *Distributed Generation and Microgrids for Small Island Electrification in Developing Countries: A Review*. SESI JOURNAL. Solar Energy Society of India. Vol. 18 No. 1 January-June 2008, pp. 6-20. Retrieved on December 19, 2012 from http://www.iset.uni-kassel.de/abt/FB-A/publication/2008/2008_Mitra_Sesi.pdf

[46] Cobben, J.F.G. (2008b) More Microgrids Project: The first microgrid in the Netherlands Retrieved on December 27, 2012 from: http://der.lbl.gov/sites/der.lbl.gov/files/Cobben_2008.pdf

[47] Buchholz, Britta (2006). Pilot installation: Residential Area „Mannheim-Wallstadt“, Germany. Retrieved on January 11, 2013 from More Microgrids: http://www.microgrids.eu/documents/061117_MMG_WPF_Mannheim.pdf

[48] Khattabi, M., Drenkard, S., Dietschmann, H., Dimeas, A., & Moutis, P., (2009). Advanced Architectures and Control Concepts for MORE MICROGRIDS. Retrieved on January 11, 2013 from More Microgrids: http://www.microgrids.eu/documents/661.pdf

[49] Saez, Doris (2012). *Modeling and Optimization of a Micro-grid: Huatacondo, Isolated Village in Northern Chile*. Retrieved on January 19, 2013 from University of Waterloo: http://wise.uwaterloo.ca/calendar/wise-lecture-series-modeling-and-optimization-of-a

[50] Palme-Benkhe, R., Ortiz, D., Reyes, L., Jimenez-Estevez, G., Garrido, N. (2011). *A Social SCADA Approach for a Renewable Based Microgrid—The Huatacondo Proje*ct. 978-1-4577-1002-5. IEEE.

[51] Morozumi, Satoshi (2007). *Micro-grid Demonstration Projects in Japan*. IEEE. Pp 635-642.

[52] Sanz, J. F., Matute, G., Fernández, G., Alonso, M. A., & Sanz, M. (2014) Analysis of European policies and incentives for microgrids. International Conference on Renewable Energies and Power Quality (ICREPQ'14).

[53] Brucoli, M., & Green, T. C. (2007, May). Fault behaviour in islanded microgrids. In 19th International Conference on Electricity Distribution (pp. 1-4).