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A Framework for the Evaluation of the Cost and Benefits of Microgrids

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A Framework for the Evaluation of the Cost and Benefits of Microgrids

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SUMMARY

A Microgrid is recognized as an innovative technology to help integrate renewables into distribution systems and to provide additional benefits to a variety of stakeholders, such as offsetting infrastructure investments and improving the reliability of the local system. However, these systems require additional investments for control infrastructure, and as such, additional costs and the anticipated benefits need to be quantified in order to determine whether the investment is economically feasible.

This paper proposes a methodology for systematizing and representing benefits and their interrelationships based on the UML Use Case paradigm, which allows complex systems to be represented in a concise, elegant format. This methodology is demonstrated by determining the economic feasibility of a Microgrid and Distributed Generation installed on a typical Canadian rural distribution system model as a case study. The study attempts to minimize the cost of energy served to the community, considering the fixed costs associated with Microgrids and Distributed Generation, and suggests benefits to a variety of stakeholders.

KEYWORDS

Distributed Generation, Distribution Planning, Microgrids, Wind Energy

1. INTRODUCTION

For the purposes of this paper, a Microgrid is considered as a conglomeration of small generation and loads that operate as a coherent system and connects to a wider grid as a single point load [1]. Many sources suggest additional criteria to define Microgrids, for example, that they contain storage devices and controllable loads, and necessarily have the ability to intentionally disconnect from the main power grid and to operate in a disconnected state (islanding mode) [2],[3]. Other researchers add the requirement that Microgrids must be able to provide heat as well as power (Combined Heat and Power–CHP) [4].

It has been suggested that Microgrids may be a way to improve system power quality, reliability, and economics, while reducing environmental impact [5]. Given these characteristics, and the fact that the

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Distributed Generation (DG) or Micro-Sources within Microgrids typically have power electronic interfaces, which permit a great deal of flexibility [6],[7]. Although excellent work has been done to identify individual benefits of Microgrids, the diversity of Microgrid characteristics naturally complicates attempts to quantify benefits and to form a business case around them. Without a clear financial analysis and business case, there is hesitation to invest in Microgrids.

In this paper, the benefits of Microgrids are examined–specifically how they depend on certain high-level characteristics of the system architecture, and an alternative approach to categorizing benefits is proposed, inspired by the UML Use Case paradigm.

2. BENEFITS OVERVIEW

The technical and economic benefits obtained from Microgrids are broadly classified as improved efficiency, reduced emissions, and improved Power Quality and Reliability (PQR) [8],[9]. The direct benefits can be divided into two categories: local benefits that result from a Microgrid's internal operation, and broader benefits resulting from the ways in which the Microgrid interacts with the "macrogrid" or larger utility system.

Local benefits include increasing reliability of power provided to customers within and outside the Microgrid [4],[10],[11],[12], improving power quality by mitigating voltage swells and sags, reducing distortion and unwanted harmonics [13], improving efficiency by reducing distribution losses [14],[15], and by providing Combined Heat and Power (CHP) [9],[16]. Participation of Microgrid loads and sources as one co-operating entity allows additional economic benefits including collective optimization of costs based on participation in the electricity market, provision of ancillary services to the grid (for example, reactive power and voltage control, reserve power [17], and black start capability [18], as well as potentially working on a larger scale to provide frequency control reserves (FCR) [19]), and reducing or offsetting substation and feeder investments by a utility or network operator [20],[21].

Indirect benefits resulting from Microgrid operation can be more wide-reaching in their impacts, but also more difficult to quantify. They include environmental benefits such as a reduction in emissions of greenhouse gasses and other pollutants by integrating clean energy sources into the grid, a reduction of the physical footprint required for power generation, a reduction of reliance on external fuel sources and prices, and the creation of employment in the locality of the Microgrid.

3. USE CASE REPRESENTATION OF BENEFITS

Inspired by the UML Use Case Paradigm, which allows complex systems to be represented in a concise, elegant format, this paper illustrates the benefits of Microgrids in terms of "stakeholders" or "actors", "parameters", and "functions". Stakeholders are all parties with some potential financial interest in the Microgrid, parameters are Microgrid characteristics on which functions are dependent, and functions represent the various benefits that will be considered. An overview of the structure of functions and parameters is shown in Figure 1.

Parties who benefit directly from benefits of Microgrids include the Independent Power Producer (IPP) who owns the Distributed Generation (DG) used in the Microgrid, the end-use Microgrid Customers (MGCs), the Distribution Network Operator (DNO), and possibly the generation utilities or Bulk Energy Suppliers (BESs) (for example in the case of black start support). Customers outside the Microgrid, herein referred to as "Grid Customers" (GCs), are somewhere in between direct and indirect beneficiaries, since they may experience improved reliability as a result of the Microgrid [10]. Society is the last stakeholder we will consider. Society represents every entity not already listed who can be affected by externalities such as the environmental and economic impacts of Microgrids, whether directly connected or not. These stakeholders are summarized in Table 1.

For the purposes of this exposition, IPPs are seen as separate entities from Microgrid Customers (MGCs), though in practice, customers may own the DG in the Microgrid, in which case the benefits to both IPPs and MGCs would be lumped together.

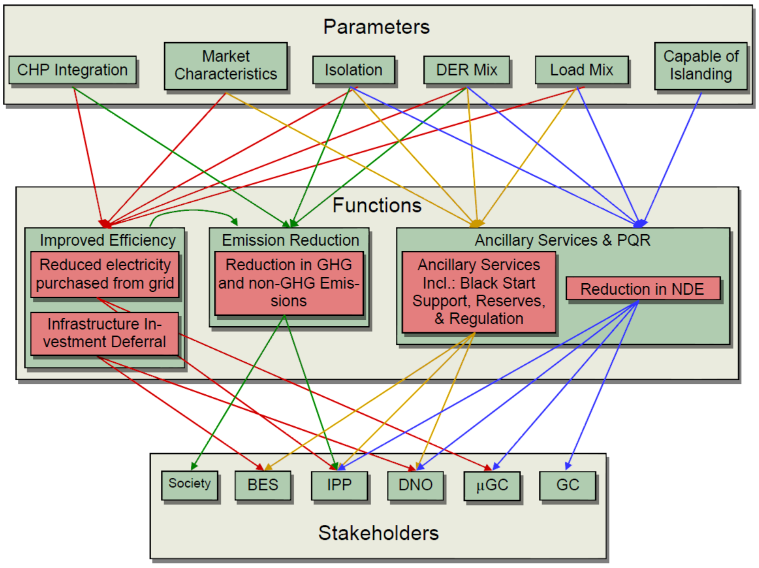

Figure 1: Overview of Relationships between Microgrid Benefit Functions

There are many different types of Microgrids, and quantification of Microgrid benefits is highly dependent on the various characteristics that define the Microgrid. A list of the characteristics or parameters that can fundamentally affect the method of valuation is summarized in Table 2. Parameters with purely numerical effects on valuation, for example gas prices, average wind speeds, or interest rates, are not included in this list.

Table 1: Microgrid Actors/Stakeholders

Actor Name	**Actor Type**	**Description**
Microgrid Customers (MGCs)	People or Corporations	Residential, commercial, or industrial loads within the Microgrid.
Grid Customers (GCs)	People or Corporations	Loads outside the Microgrid.
Independent Power Producer (IPP)	Person or Corporation	Owner of DG in Microgrid.
Distribution Network Operator(DNO)	Corporation	The entity responsible for correct operation of the grid
Utilities or Bulk Energy Suppliers (BESs)	System	The entities outside the Microgrid who supply power to the grid.
Society	People, Corporations, & Other Entities	Everyone who might be affected by Microgrid externalities.

Table 2: Microgrid Valuation Parameters

Parameter	**Description**
CHP Integration	Whether Combined Heat and Power (CHP) is used in Microgrid (MG).
DER Mixture	The combination of Distributed Energy Resources (DER) used in MG. For example, are Microturbines or Renewable Energy Sources (RES) used?
Load Mixture	The mixture of load types in MG. Are dispatchable or critical loads included?
Market Characteristics	Whether energy or ancillary services can be sold to the DNO, whether electricity is purchased at a fixed or varying rate, and whether other tariffs are applied, for example to reduce peak loading.
Isolation	Whether the MG is connected to the macrogrid during normal operation, or instead operates exclusively independently.

Capable of Islanding	Whether the MG is capable of disconnecting from the grid in the event of a fault or other contingency.

Given these definitions of the stakeholders and parameters, the benefits of Microgrids can be viewed in terms of "Functions" that provide value to stakeholders based on the operation of the Microgrid. A representative sample of these functions is detailed in Table 3 - Table 7. The benefits of reduced land use are closely tied to infrastructure investment deferral, so a function related to reduced land use is not given a separate listing here. The connections between stakeholders, parameters, and functions are summarized in Figure 1.

Table 3: Function: Reduced Energy Purchase

Function Name	Reduced Electricity Purchased from Grid
Related Functions	Infrastructure Investment Deferral
Actor(s) Receiving Benefit	MGCs, IPPs
Description	The structure of the Microgrid allows internal DG sources and CHP to reduce total energy purchased from the grid at the Point of Common Coupling (PCC).
Relevant Microgrid Parameters	DER Mixture, CHP Integration, Isolation, and Market Characteristics
Quantification Methodology	In simulation, DER is dispatched by a Central Controller (MGCC) according to a Unit Commitment/Economic Dispatch optimizing value to the MGCs.[1] In non-isolated cases, the grid provides the balance of power if there is a DER shortfall. If local regulations allow, energy is sold back to the grid when economic criteria are met. The value of the IPP's energy sales, and the total cost to the MGCs, are compared with the status quo base case.

Table 4: Function: Investment Deferral

Function Name	Infrastructure Investment Deferral
Related Functions	Reduced Electricity Purchased from Grid
Actor(s) Receiving Benefit	DNO, Utility
Description	The reduction in peak grid loading provided by the Microgrid allows certain distribution network investment/upgrade costs to be deferred. This provides value to the DNO (and potentially the BESs) through the present value of money not spent, as well as potentially through the reduced land required for DG installation, compared with large generation.
Relevant Microgrid Parameters	DER Mixture, CHP Integration, Load Mixture, and Isolation
Quantification Methodology	Reduced peak loading of infrastructure is found through simulation. The deferral time and consequent time value of money savings can be found from known demand growth and interest rates [20].

Table 5: Function: Reduced Emissions

Function Name	Reduced GHG and non-GHG Emissions
Related Functions	Reduced Energy Purchased
Actor(s) Receiving Benefit	Society, IPP, MGCs

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[1] Note that electrical control is not strictly necessary. For example, droop control is viable in certain cases.

Description	The inclusion of renewable DG and natural gas-based CHP in the Microgrid can allow energy used by MGCs to be generated with significantly lower emission of GHGs and other pollutants compared with the status quo.
Relevant Microgrid Parameters	CHP Integration, DER Mix, and Isolation
Quantification Methodology	The amount of GHG and pollutant emissions from energy use within the Microgrid is found through simulation, and this is compared to the base case of national emissions per kilowatt hour of electricity production. GHG emission reduction can be valued using typical GHG or carbon tax rates as a guide. Valuation of other pollutant reduction is indirect, but might be based on medical expenses and agricultural losses from pollutants.

Table 6: Function: Ancillary Services

Function Name	Ancillary Services
Related Functions	Infrastructure Investment Deferral, Increased Reliability
Actor(s) Receiving Benefit	MGCs, GCs, DNO, IPP, Utility
Description	Ancillary Services (potentially including Spinning and Non-Spinning Reserves, Voltage and Frequency Regulation, and Black Start Support) can be provided by the Microgrid, improving local PQR. Reduced Peak Loading and Improved Reliability are treated separately, in Table 4 & Table 7 respectively.
Relevant Microgrid Parameters	DER Mix, Load Mix, Market Characteristics, and Isolation
Quantification Methodology	Ancillary Service valuation is highly dependent on market prices or contracts [22],[23]. For example, an agreed amount of reserve can be held by a BES or IPP and provided whenever needed for a certain value.

Table 7: Function: Improved Reliability

Function Name	Increased Reliability
Related Functions	Ancillary Services, Infrastructure Investment Deferral
Actor(s) Receiving Benefit	MGCs, GCs, DNO, IPP
Description	Microgrids can reduce outages to critical loads within the Microgrid by disconnecting from the Macrogrid in the event of a fault (islanding), and by turning off dispatchable loads, if applicable. In certain cases, they can also provide emergency power outside the Microgrid to supplement reduced grid supply during a contingency.
Relevant Microgrid Parameters	Load Mix, DER Mix, Capable of Islanding, and Isolation
Quantification Methodology	Can consider using a number of standard metrics, including Non-Delivered Energy (NDE) and SAIFI, SAIDI, etc. These values can be found through Monte-Carlo simulation, or analytic calculations, based on reliability values for various grid components. These are then compared to a status quo base case. Monetary valuation of improved reliability is customer dependent, and usually relies on contractual arrangement or market value.

4. METHODOLOGY USED TO QUANTIFY BENEFITS

The Use Case is used to map out which benefits are available and to whom they will apply. Modelling and/or simulation must be carried out to quantify those benefits in detail. Here the method used to determine benefits in the following Case Study is outlined, as illustrated in Figure 2.

A Microgrid Central Controller (MGCC), Load Controllers (LCs), and Microsource Controllers (MCs) were implemented in MATLAB code. These interfaced with Simulink models that described the topology of a distribution feeder both with and without DG and Microgrid infrastructure. The simulation and data collection process is described below:

The following occurs at every time step (time steps are one hour in length, and there are 8766 time steps in a simulation, which is the average number of hours in a year, including leap years):

1. Wind speed and relative load are determined according to standard models. Reliability information is used with a random number generator to determine if there is a system failure resulting in islanding during the current time step.
2. Bidding:
    a. All MCs send generation bids and constraints to MGCC. The bid functions take into account resource (wind) availability, any applicable costs, including fuel, start-up, equipment, and O&M costs, as well as profit margin.
    b. All LCs send load bids and constraints to MGCC.
3. Scheduling: MGCC solves the Unit Commitment (UC) and Economic Dispatch from the bid functions. Additional considerations are taken into account in islanding conditions.
4. The parameters of all Simulink models are set according to dispatch and load information.
5. Steady-state load flow values are extracted from the Simulink models.
6. Repeat.

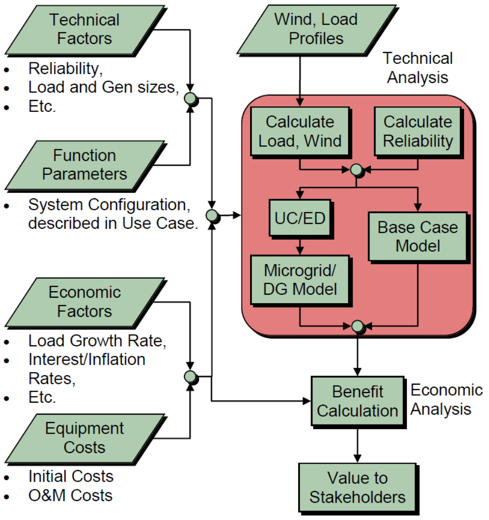

Figure 2: Data flow for the proposed methodology. The technical analysis shown here is repeated a number of times to calculate benefits over a run time of one year.

A note on reliability: faults are determined in Step 1 based on estimated rates of failure. If a fault occurs in a given time step, model parameters are updated to reflect fault conditions. Previous faults are cleared after a set time period has elapsed. The year-long simulation may then be repeated in a Monte-Carlo-style simulation to accurately reflect reliability statistics.

5. CASE STUDY

The methodology was tested using a Microgrid topology based on a typical, large, Canadian, semi-rural feeder, with 10 MW peak load and 6.2 MW average load. Three cases were considered: a base case (Case 0), in which no DG and no Microgrid technologies are installed in an existent distribution feeder; a DG-only case (Case 1), in which DG is installed without Microgrid hardware; and a full Microgrid case (Case 2), in which DG and Microgrid hardware are both installed, and the Microgrid provides the ability to island in the event of an upstream fault, providing partial power to the system. The use case functions examined were Reduced Electricity Purchased, Investment Deferral, Reduced GHG Emissions, and Increased Reliability. In the interests of clarity and brevity, other ancillary services were not considered in this example.

Two large wind turbines of 3 MW peak capacity each were installed in the DG and Microgrid cases, at a cost of $4.5 M/MW. An annual O&M cost of 2% of the investment cost was assumed. In the Microgrid case, additional costs for the Microgrid hardware were taken to be $129,000, including controllers, communications devices, and disconnect switches. Note that the distribution feeder was assumed to already exist. In both cases, all costs were amortized over a project lifetime of 20 years.

Reduced Electricity Purchased was found through steady-state simulation of the distribution feeder for the three cases. For simplicity, the installed DG consisted exclusively of wind turbines. No CHP was considered because of the lack of CHP infrastructure in Canadian homes. This means that the synergistic reduction in heating costs that can be provided by CHP will not apply [24]. The grid was not isolated, and therefore power could be exchanged with the utility grid. The market was assumed to have a constant energy exchange value of $165.50/MWh at the Point of Common Coupling (PCC), which is typical of the Canadian province of Prince Edward Island, an area very conducive to development of wind energy due in part to the good availability of wind[25],[26].The benefit of the reduced cost of purchasing power from the utility was shared between the IPP and the Customers as follows: in both Cases 1 and 2, the IPP sold power to the Customers at a rate which would make up the costs of DG installation and O&M, plus a marginal profit of $3/MWh. Excess DG power was sold to the DNO at the exchange price of $165.50/MWh.

Investment Deferral was found by means of the same steady-state simulation as Reduced Electricity Purchased. The DER and state of CHP integration, described previously, dictate the amount of reduced substation loading which occurs during simulation of Cases 1 and 2, compared with Case 0. In our example, no load is allowed to be shed during normal operation in the Microgrid case. If load were allowed to be shed, the load mixture would dictate the value of incentives needed to shed loads. For example, if the load mixture contained water pumping loads, they would probably be shed first, for a relatively low incentive, whereas life-support-related loads would never be shed, regardless of incentive value. The fact that the grid is not isolated means that power is purchased from the grid, and so we can apply investment deferral economics to components of the utility grid outside the Microgrid feeder. This analysis considered only one investment, that of the substation transformer supplying the Microgrid, though investment deferral could also be considered with respect to generation, and other T&D infrastructure, including the distribution lines within the Microgrid itself.

The feeder substation upgrade costs were taken to be $56,000/MW peak, and it was assumed that the DNO intended to replace the substation transformer with a 50% peak capacity expansion. The average load growth rate was assumed to be 2%.The DNO received all Investment Deferral value.

Reduced GHG emissions were found from the same simulation. The state of CHP integration and the DER mixture dictated the amount of the amount of grid energy offset in Cases 1 and 2 relative to Case 0. The fact that the Microgrid is not isolated allows energy to be sold to the grid, offsetting the emissions of the utility power plants. The average greenhouse gas emission rate of utility-produced energy was assumed to be equal to the Canadian average of approximately 200g CO2/kWh. Its value to Society was estimated based on typical carbon tax rates as $20/ton emitted. All value from this function was assigned to Society. Note that some analysts might take into account the carbon emitted in the construction and installation of the DG and Microgrid.

Increased Reliability was found through simulation and corroborated with analytical calculations. The load mixture determines the value of reliability to each customer (which can be set via contracts). Average costs of Non-Delivered Energy (NDE) were taken to be $2.50/kWh, $10/kWh, and $25/kWh for residential, commercial, and industrial customers respectively [27]. The assumed contract between the utility and customers compensated for half this cost–i.e. the utility paid $1.25 to each residential customer, $5.00 to each commercial customer, and $12.50 to each industrial customer respectively per kilowatt hour of NDE. No explicit economic value was given to the number of interruption events per customer, i.e., SAIFI. In the case of the full Microgrid (Case 2), this contract was offloaded from the DNO to the IPP at the cost of 75% of the expected value of the contract without the Microgrid. The most critical parameter in the increased reliability function is the capability of islanding (Case 2 only), which allows the Microgrid to operate separated from the grid in the event of an upstream fault. The DER mixture dictates how much power can be provided to Microgrid customers while islanding, and the fact that the Microgrid is not isolated means that it is affected by upstream reliability. It was assumed that the Microgrid infrastructure would allow selectively supplying some loads in the event of islanding with insufficient wind capacity to power all loads. A constant upstream failure rate of 1 failure per year was assumed. This paper only considered external failures.

5.1 Results

The results can be seen in Table 8 and Figure 3. The average electricity price seen by MGCs was $165.50/MWh in Case 0, and $160.76/MWh in Cases 1 and 2 (not counting Islanding operation). This reduced energy cost provided a net benefit of $265,536/year to Customers in Cases 1 and 2. The profit margin of \$3/MWh on energy sold to customers provided an annual benefit of \$70,233 to the IPP, and the sale of excess power to the grid increased the benefit to the IPP by \$3,426/year. The load reduction in Cases 1 and 2 allowed the DNO to defer investment in substation upgrades by 2.7 years, worth \$43,431, or \$15,862/year of the deferred time, effectively offsetting over 15% of the upgrade cost of \$287,000. The power produced by the DG in Cases 1 and 2 offset 4,723 tonnes of CO_2 emissions, worth \$94,469 to Society. In Case 2, the Non-Delivered Energy was reduced from 37 MWh in Cases 0 and 1 to 21 MWh in Case 2. The DNO benefit was \$18,967/year from offloading the value of their reliability contract onto the IPP. The IPP gained the difference between what was paid by the DNO and what they had to pay out under the terms of the reliability contract in Case 2, a net benefit of \$42,639. Subtracting the amortized annual cost of the Microgrid infrastructure, the net benefit to the IPP from the reliability function is \$27,486/year. It is notable that the mean cost for the IPP to provide energy during islanding was \$1,060/MWh, taking into account Microgrid costs, which is less than the \$1250/MWh that is paid to residential customers for NDE during an outage. The net benefit to the Customers from improved reliability is \$61,606/year.

Table 8: Summary of Relative Benefits of DG and Microgrid

Benefit Function	**Net Annual Benefits Relative to Base Case (Top number corresponds to Case 1, bottom to Case 2)**			
	To Customer	**To IPP**	**To DNO**	**To Society**
Reduced Energy Purchased	\$265,536	\$85,078	\$0	\$0
	\$265,536	\$85,078	\$0	\$0
Investment Deferral	\$0	\$0	\$15,862	\$0
	\$0	\$0	\$15,862	\$0
Reduction in GHGs	\$0	\$0	\$0	\$94,469
	\$0	\$0	\$0	\$94,469
Increased Reliability	\$0	\$0	\$0	\$0
	\$61,606	\$27,486	\$18,967	\$0
Total	**\$265,536**	**\$85,078**	**\$15,862**	**\$94,469**
	\$327,142	**\$112,564**	**\$34,829**	**\$94,469**

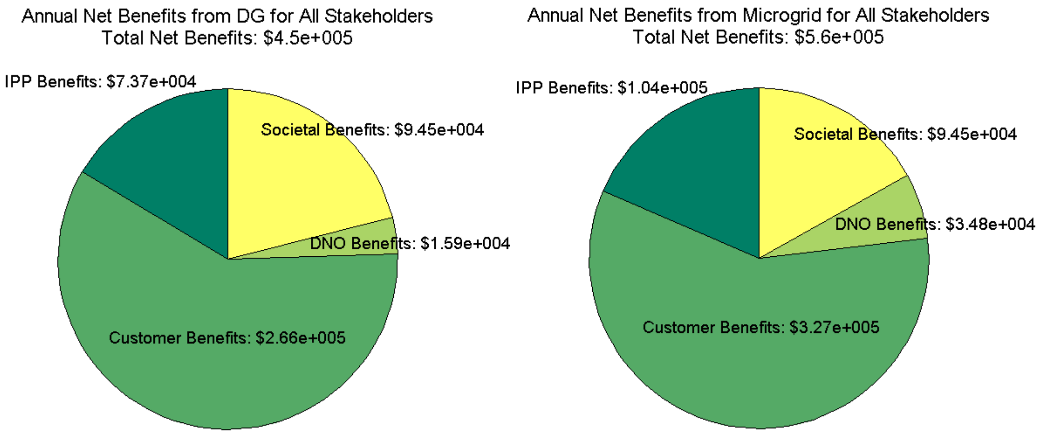

Figure 3: Net benefits to all stakeholders for DG and Microgrid cases relative to Base Case

6. CONCLUDING REMARKS

Given the feeder model and assumptions taken, the installation of DG and Microgrid infrastructure was found to be favourable to all stakeholders considered. It should be noted that these results are strongly dependent on local characteristics, e.g. energy prices, tariffs, load growth rate, and contractual values for reliability improvement or any ancillary services which may be considered.

The Use Case developed may be seen as the first step in providing a framework from which to consider these benefits, and their effects on various stakeholders in a concise, clear manner. Future work on these ideas will include further developing ancillary benefit Use Case functions. We are now also in the position to determine the most critical parameters that affect benefit quantities and distribution to stakeholders. Knowledge of these critical parameters would allow the analyst to focus energy on only the most economically viable Microgrid proposals, or may provide insight to modify proposals to optimize their viability and benefit distribution.

7. BIBLIOGRAPHY

[1] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power and Energy Magazine*, vol. 5, no. 4, pp. 78-94, Jul. 2007.

[2] M. Dicorato, G. Forte, and M. Trovato, "A procedure for evaluating microgrids technical and economic feasibility issues," in *2009 IEEE Bucharest PowerTech: Innovative Ideas Toward the Electrical Grid of the Future*, 2009.

[3] C. Schwaegerl, L. Tao, P. Mancarella, and G. Strbac, "Can microgrids provide a new paradigm for network operation? an evaluation of their technical, commercial and environmental benefits," in *IET Conference Publications*, 2009.

[4] Y. Zoka, A. Sugimoto, N. Yorino, K. Kawahara, and J. Kubokawa, "An economic evaluation for an autonomous independent network of distributed energy resources," *Electric Power Systems Research*, vol. 77, no. 7, pp. 831-838, 2007.

[5] EPRI, "Methodological Approach for Estimating the Benefits and Costs of Smart Grid Demonstration Projects," 1020342, 2010.

[6] R. Lasseter, et al., "The CERTS Microgrid Concept," Sacramento, CA, CEC Consultant Report P500-03-089F for the California Energy Commission, October, 2002.

[7] C. Marnay, et al., "Optimal technology selection and operation of commercial-building microgrids," *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 975-982, 2008.

[8] N. D. Hatziargyriou, A. G. Anastasiadis, J. Vasiljevska, and A. G. Tsikalakis, "Quantification of economic, environmental and operational benefits of microgrids," in *2009 IEEE Bucharest PowerTech: Innovative Ideas Toward the Electrical Grid of the Future*, 2009.

[9] C. Marnay and O. Bailey, "The CERTS Microgrid and the Future of the Macrogrid," Berkeley Lab Report #LBNL-55281, 2004.

[10] P. M. Costa and M. A. Matos, "Assessing the contribution of microgrids to the reliability of distribution networks," *Electric Power Systems Research*, vol. 79, no. 2, pp. 382-389, 2009.

[11] C. Marnay, J. Lai, M. Stadler, and A. Siddiqui, "Added value of reliability to a microgrid: Simulations of three California buildings," in *2009 CIGRE/IEEE PES Joint Symposium Integration of Wide-Scale Renewable Resources into the Power Delivery System*, 2009.

[12] G. Venkataramanan and C. Marnay, "A larger role for microgrids," *IEEE Power and Energy Magazine*, vol. 6, no. 3, pp. 78-82, 2009.

[13] I. Wasiak, et al., "A power-quality management algorithm for low-voltage grids with distributed resources," *IEEE Transactions on Power Delivery*, vol. 23, no. 2, pp. 1055-

1062, 2008.

[14] P. Tenti, D. Trombetti, A. Costabeber, and P. Mattavelli, "Distribution loss minimization by token ring control of power electronic interfaces in residential micro-grids," in *IEEE International Symposium on Industrial Electronics*, 2010, pp. 2377-2381.

[15] P. M. Costa and M. A. Matos, "Avoided losses on LV networks as a result of microgeneration," vol. 79, no. 4, pp. 629-634, 2009.

[16] H. Asano and S. Bando, "Optimization of a microgrid investment and operation: Energy saving effects and feasibility of ancillary service provision," in *Transmission and Distribution Conference and Exposition: Asia and Pacific, T and D Asia*, 2009.

[17] M. H. Gomes and J. T. Saraiva, "Allocation of reactive power support, active loss balancing and demand interruption ancillary services in Microgrids," *Electric Power Systems Research*, vol. 80, no. 10, pp. 1267-1276, 2010.

[18] J. Vasquez, J. Guerrero, J. Miret, M. Castilla, and L. Garcia De Vicuna, "Hierarchical control of intelligent microgrids," *IEEE Industrial Electronics Magazine*, vol. 4, no. 4, pp. 23-29, 2010.

[19] C. Yuen, A. Oudalov, and A. Timbus, "The provision of frequency control reserves from multiple microgrids," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 173-183, 2011.

[20] H. A. Gil and G. Joos, "On the quantification of the network capacity deferral value of distributed generation," *IEEE Transactions on Power Systems*, vol. 21, no. 4, pp. 1592-1599, 2006.

[21] A. A. Chowdhury, S. K. Agarwal, and D. O. Koval, "Reliability modeling of distributed generation in conventional distribution systems planning and analysis," *IEEE Transactions on Industry Applications*, vol. 39, no. 5, pp. 1493-1498, 2003.

[22] D. E. King, *Electric Power Micro-grids: Opportunities and Challenges for an Emerging Distributed Energy Architecture*. PhD Thesis, Carnegie Mellon University, Pittsburgh, PA, USA, May 2006.

[23] New Brunswick System Operator (NBSO), "New Brunswick System Operator Open Access Transmission Tariff," Published on the NBSO website., 2010.

[24] A. S. Siddiqui, et al., "Effects of carbon tax on microgrid combined heat and power adoption," *Journal of Energy Engineering*, vol. 131, no. 1, pp. 2-25, 2005.

[25] Hydro Quebec, "Comparison of Electricity Prices in Major North American Cities," Available: www.hydroquebec.com. Accessed April 10, 2011., 2010.

[26] PEI Department of Environment, Energy and Forestry, "Prince Edward Island Energy Strategy," Available on: www.gov.pe.ca. Accessed April 10, 2011., 2008.

[27] S. Blazewicz, G. Shlatz, F. Small, S. Tobias, and J. Bean, "The Value of Distribution Automation," California Energy Commission, PIER Energy Systems Integration Program. CEC-500-2007-103, 2008.

[28] J. T. Saraiva and M. H. Gomes, "Provision of some ancillary services by microgrid agents," in *7th International Conference on the European Energy Market*, 2010.

[29] C. Schwaegerl, et al., "Report on the technical, social, economic, and environmental benefits provided by Microgrids on power system operation," Available at http://www.microgrids.eu/documents/668.pdf. Accessed February 13, 2011., 2009.