# Introductions to compared

## Version 1.

**Introduction**

Micro-grid is defined as a collection of distributed energy resources including power generation and energy storage technologies (e.g., thermal and electric battery) that can serve all or part of electric and heat demand within the same locality. There are several topics as the key value streams of micro grids, such as participation in Demand Response programs, export of on-site generation to the electricity grid, reduced costs due to added resilience against outages and lost loads, participation in local micro-grid energy markets, etc., each of which can be obtained through reliability and power quality improvements brought by micro-grids [1]. On the other hand, there exist dozens of indirect advantages resulting from micro-grids including environmental benefits such as a reduction in emissions of greenhouse gasses [2], decreasing the physical footprint required for power generation [3] and reduction of reliance on external fuel sources and prices [4].

In order to realize the mentioned values, micro-grids should be evaluated in terms of operation and investment. The working combination of micro-grid assets should be additive and follow a well-articulated logic toward delivering its objectives. There are numerous research topics on investigation of value streams for different forms of energy storage and different functional applications [5-7], CHP power plant optimization portfolios [8], optimal selection of technologies and upgrades that can be applied to micro-grids [9, 10], incentive mechanisms to remove barriers to micro-generation development [11], etc. All of these proposed objectives has been realized through saving in energy costs, reliable and secure energy supply, reducing risks for the grid on blackouts and brownouts, and the use of renewables in a generation portfolio.

However, although micro-grids bring considerable benefits to power generation sector, investors and stakeholders wonder if micro-grids are economically profitable due to market volatility and uncertainty. The value of a micro-grid portfolio depends on its projected return of investment and the potential growth in its operating income [12]. Consequently, understanding its costs and benefits is extremely important and involves capacity planning, operations modeling, cash flow analysis, and an integrated solution framework that combines short-term operational objectives and savings with the long-term investment decisions. In other words, higher levels of exposure to the grid and market volatility can be avoided if the portfolio is optimized in response to its short-term load and market conditions.

Literature lacks sufficient work addressing optimal investment uncertainty and optimal operation in enhanced micro-grid portfolios. The long-term value of the micro-grid will also depend on when (in terms of market conditions) investments were made and also on the amount and investment financing costs. Different parameters such as finance charge rate, finance term, and relative relationship between finance rate and discount factor would result in different optimal investment decisions. As shown by Farzan et al. [13], the savings from a micro-grid could be significantly under- or over-estimated if the underlying risks were not taken into account. El Khattam et al. [14] studied the capacity investment in distributed generation (DG) in order to optimize the sizing and siting for DG capacity. Their objective function includes investment and operating costs as well as payment toward loss compensation. There are some elements of investment that are stochastic and ignoring this uncertainty can lead to poor results in investment decisions. Bruno et al. [15] consider the problem of optimal investment portfolio for a company that purchases, sells and distributes gas and owns a network of gas pipelines. They propose a two-stage stochastic programming model to solve the problem with stochastic demand. They also use conditional value at risk to control the variability of the decisions. Real options is another popular approach to address uncertainty and the option to delay an investment. Real options is very powerful in handling uncertainties, but its applications are limited to small-scale problems due to complexities in the solution methodology, unless numerical results are sought. Farzan and Jafari [16] present a real option model for a micro-grid with multiple sources of uncertainties. They show that the underlying partial differential equations can be solved under simple product form solutions and produce results that are close to the results from Monte Carlo simulations. Asano et al. [17] discuss investment strategies in a micro-grid consisting of a cogeneration system and renewable resources under uncertainty in natural gas price. They examine the sensitivity of optimal investment decisions to the level of uncertainty in gas prices.

In this article, we are seeking solutions to optimal investment on a micro-grid power generation portfolio under uncertainty. A micro-grid portfolio includes solar PVs, wind turbine, gas-fired generation, storage (electric battery) and purchase from the grid. We intend to uniquely integrate into a single model the short-term uncertainties arising from micro-grid operation, and the long-term uncertainties due to future natural gas prices, investment in renewable assets, and financing costs. This work extends the current state of art in investment on distributed generation and micro-grids as follows: (i) Larger portfolio of power generation assets with options to purchase from grid or sell to the grid; (ii) Optimal selection of portfolio over the course of planning horizon; and (iii) Optimal incremental investment in each resource over the course of planning horizon. Moreover, the work extends the current literature as it solves for optimal investment decisions while considering a portfolio of electricity generation and storage assets and also captures short-term operational and long-term investment uncertainties.

We are motivated by the fact that a proper mix of power generation resources and timely investment on these resources is an important design and operational planning decision for micro-grids. These decisions can significantly impact micro-grid long-term and short-term objectives, namely saving in energy costs, reliable and secure energy supply, reducing risks for grid on blackouts and brownouts, and the use of renewables in a generation portfolio. Furthermore, higher levels of exposure to the grid and market volatility can be avoided if the portfolio is optimized in response to its short-term load and market conditions. Hence, the model proposed in this article integrates short-term and long-term risks into a single decision-making loop. The loop works as follows: (i) An optimization model of a daily micro- grid operation is run to calculate a functional form of to-be-designed micro-grid, and (ii) The functional form is fed into a stochastic long-term investment model which decides when to invest on micro-grid components and expansions. The operation model is a simplified version of the model proposed by Farzan et al. [13]. The investment model is a stochastic mixed integer program (SMIP). A Monte Carlo simulation approach is taken where several sample path realizations over the course of the planning horizon are generated and a deterministic model for investment optimization for each sample path is solved. At the end, probabilistic characteristics of investment decisions along with optimal cash flows are obtained over all sample paths.

## Version 2.

**Introduction**

There are many practical questions lingering in power community on microgrid economics and factors within the system and the environment that will principally affect its profitability. Investors and stakeholders wonder if microgrids are not profitable now, will they ever be profitable in the future. Or will there be a time that the valuation of a utility owning and operating a cluster of microgrids likely surpasses the valuation of today’s hierarchical grid, burdened by legacy infrastructure, undifferentiated products, and regulatory overheads? The value of a microgrid portfolio depends on its projected return on investment and the potential growth in its operating income[19] so understanding it’s costs and benefits involve at least two complex optimizations (capacity planning and operations modeling) followed by cash flow analysis, and an integrated solution framework that combines short-term operational objectives and savings with the long-term investment decisions. In other words, higher levels of exposure to the grid and market volatility can be avoided if the portfolio is optimized in response to its short-term load and market conditions.

[20] Put forth four topics as the key value streams of micro grids: 1-Participation in Demand Response programs 2-Export of on-site generation to the electricity grid 3- Reduced costs due to added resilience against outages and lost loads 4-and Participation in local microgrid energy markets each of which may obtain through reliability and power quality improvements brought by microgrids. Also, there exist dozens of indirect advantages resulting from microgrids including environmental benefits such as a reduction in emissions of greenhouse gasses [21], decreasing the physical footprint required for power generation [22] and reduction of reliance on external fuel sources and prices [23].

By considering a selection of mentioned benefits against the potential costs come along with microgrids such as specific infrastructure, resource coordination, and information flows as well as added protection and power quality assurance [20] Our contribution in this article is to address the problem by developing an integrated solution methodology that combines a short-term operational model with a long-term investment model that accounts for uncertainties in future natural gas prices, investment in renewable assets, and financing costs.

Our solution approach combines a general binomial lattice with mixed-integer-quadratic model for budgeting and a regression model that estimates the cost of operation and planning micro-grid with its current resources and load. The proposed framework allows us to study the impact of individual generation assets and their interactions on investment decisions.

A microgrids typically has multiple distributed generation sources and energy storage (e.g., thermal and electric battery) that can serve all or part of electric and heat demand within the same locality. The working combination of microgrid assets should be more than additive, and follow a well-articulated logic toward delivering its objectives. For instance, [24], [25] & [26] investigates Value streams for different forms of energy storage and different functional applications, [27]provides a stochastic optimization model to determine the valuation of CHP power plant portfolios and finally [28]and [29]attempts to realize the optimal selection of technologies and upgrades that can be applied to microgrids. On the other hand, aside from available technologies, [30] discuss incentive mechanisms to remove barriers to microgeneration development. All of these proposed enhancements has been done through saving in energy costs, reliable and secure energy supply, reducing risks for the grid on blackouts and brownouts, and the use of renewables in a generation portfolio.

Literature on micro-grids planning and operation is reasonably extensive [8] & [5], Generally speaking, these works evaluate design and operation options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation applications. They also allow for simple cost/benefits analysis in order to optimize sizing and locations. More rigorous investment works, on the other hand, tackle investment planning in a portfolio of physical assets that run under uncertain operational and market conditions. Bruno et al. [3] propose a two-stage stochastic programming model for optimal investment portfolio problem with options to purchase, sell and distribute gas. Conditional value at risk is utilized to control variability of the decisions obtained from the model. Asano et al. [1] discuss investment strategies in a micro-grid consisting of a cogeneration system and renewable resources under uncertainty in natural gas price. They examine the sensitivity of optimal investment decisions to the level of uncertainty in gas prices.

Real option approach in energy investments has been promoted by a number of prominent researchers and many related articles have appeared in the literature [16], [17], [18]. [6] present a real option model for a micro-grid with multiple sources of uncertainties. They show that the underlying partial differential equations can be solved under simple product form solutions and produce results that are close to the results from Monte Carlo simulations. While Real Options approach offers mathematically elegant formulation, it often requires solution to differential equations that are non-linear and can only be solved if significant simplifying assumptions are made.