Microgrids for Fun and Profit

The Economics of Installation Investments and Operations

By Farnaz Farzan, Sudipta Lahiri, Michael Kleinberg, Kaveh Gharieh, Farbod Farzan, and Mohsen Jafari

A VISION SHARED BY MANY EXPERTS IS THAT FUTURE COMMUNITIES (residential and commercial developments, university and industrial campuses, military installations, and so on) will be self-sufficient with respect to energy production and will adopt microgrids. With power generation capacities of 10–50 MW, microgrids are usually intended for the local production of power with islanding capabilities and have capacity available for sale back to macrogrids. A typical microgrid portfolio includes photovoltaic (PV) and wind resources, gas-fired generation, demand-response capabilities, electrical and thermal storage, combined heat and power (CHP), and connectivity to the grid. Advanced technologies such as fuel cells may also be included. This article describes the problems encountered in analyzing prospective microgrid economics and environmental and reliability performance and presents some results from the software tools developed for these tasks.

Integration of Microgrid Operation and Investment

The value of a microgrid portfolio depends on its projected return on investment and the potential growth in its operating income. For a portfolio of financial assets, valuations are based on projections of the market prices of those assets, using historical data about prices, industry trends, and futures prices as a basis for the projections. For a microgrid, the investment payoff is directly linked to the operation of the physical assets, and return on investment depends on how these operations will be optimized and utilized in the short term. The long-term value of a microgrid depends on when (in terms of market conditions) investments were made and also on the amount of the investment and its financing costs. Grid energy and fuel costs, the price of the necessary technology (e.g., PV equipment, wind turbines, or storage), state incentives, and parameters such as finance charge rates, finance terms, and the relationship between the finance rate and the discount factor could all affect the optimal investment decision.

Typical investment models for infrastructure assets utilize assumptions about the short-term average performance of the assets and further assume that the underlying system operates

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optimally (as computed on the basis of some average function). Operational dynamics driven by endogenous factors (i.e., asset reliability and degradation, demand prioritization, resource allocation, and risk management) and exogenous factors (i.e., weather forecasts, natural gas prices, and external demand) are usually ignored or captured only on the basis of discrete choices or simple variance analysis. At the same time, any modularized approach to long-term investment, where assets are acquired and generation capacity is increased in stages, would affect short-term operational dynamics. Short-term returns from the microgrid will in turn influence long-term decisions about when to invest and what to invest in.

Figure 1 illustrates a model developed at DNV KEMA for evaluating investments in different configurations of a microgrid, taking into account economic and environmental metrics. This model simulates the microgrid operating optimally in parallel with the grid. It also simulates operation in islanded mode when the grid is down, when maximizing reliability criteria is key. On the resource side, different generation, storage, energy efficiency, and automation technologies are considered. On the demand side, buildings and respective end-use load are modeled in detail.

Energy Economics

The operation of a microgrid is closely tied to energy economics. This includes both the financials of interacting with the utility and macrogrid and the cost of self-generation. Various resources contribute to the economic benefits of a microgrid:

- ✔ Energy efficiency upgrades on equipment will lower the overall load baseline.
- ✔ On-site generation, possibly in conjunction with energy storage, can be utilized to avoid peak energy costs and even create revenue streams by selling energy back to the grid once price signals justify it economically.
- ✔ Enrollment in demand response programs can be regarded as a means not only to reduce energy costs but also to generate revenue by reducing load on the grid. Demand response can be provided by both self-generation and curtailable end-use load.
- ✔ While grid energy transactions and fuel costs dominate the economics, microgrid participation in capacity and ancillary services markets can also be important incremental revenue drivers.
- ✔ The reliability improvements obtained through islanding capability and sufficient local resources can be valuable—quite valuable, depending on the mission

of the facility and the critical load served during islanded operations.

The marketplace in which the microgrid is playing significantly affects the amount of savings realized. For example, many commercial end users are charged time-of-use rates, and switching to a different tariff scheme—such as one based on real-time data or on hourly locational marginal pricing (LMP)—could be beneficial to them. The decision to switch might not be a trivial one, however, as different schemes impose different risks on the microgrid, based on price volatility and penalties for failing to deliver energy to the grid as scheduled if local resources, especially renewables, come up short. It should be noted that a microgrid has limited options for mitigating its risks. The options vary from relying on self-generation to locking in both its cost and revenue streams by means of long-term agreements with respective parties.

An example of a microgrid's daily control process is shown in Figure 2, where decisions regarding energy purchase, CHP production, and the use of battery storage are optimized against the day-ahead electricity price and the available PV production. Less expensive on-site generation is utilized not only to avoid the higher cost of purchasing energy from the grid but also to gain revenue by selling energy back during morning peak times. The annual savings from self-generation, efficiency upgrades, and demand response participation is shown in Figure 3. Finally, Figure 4 demonstrates cash flows, reflecting investments in various technologies and the savings generated by the microgrid. Note that the energy bought from the grid is, in this case, extremely nonconforming, as the microgrid optimizes around renewable production, native demand, and grid hourly prices. This is not an extreme case; on an annualized basis, there is no net sell-back to the grid. In this example, load grows over time as occupancy of the facilities increases despite the energy efficiency measures imposed. The cumulative cash flow for energy investments and operations shows an approximately eight-year payback.

Interaction of the Elements in Overall Energy Economics

While individual resources contribute to a microgrid's benefits, broader value can be achieved from the interaction of individual elements. Renewable resources introduce uncertainties in operations due to intermittent availability, for example as a result of varying patterns of wind speed and solar irradiation. These uncertainties become important because they can cause shortages or excesses of energy compared with what was planned for, and they therefore can lead to variation in costs and revenues. Adopting appropriate strategies to mitigate the risks associated to such uncertainties requires operational decision-making tools that account for such uncertainties while scheduling different generation and storage resources.

Energy storage devices (either thermal or electrical) can be considered as buffers within the system that enhance flexibility in responding to fluctuations due to renewable resources. But the effectiveness of such storage applications depends heavily on how the devices are controlled. The control strategy should

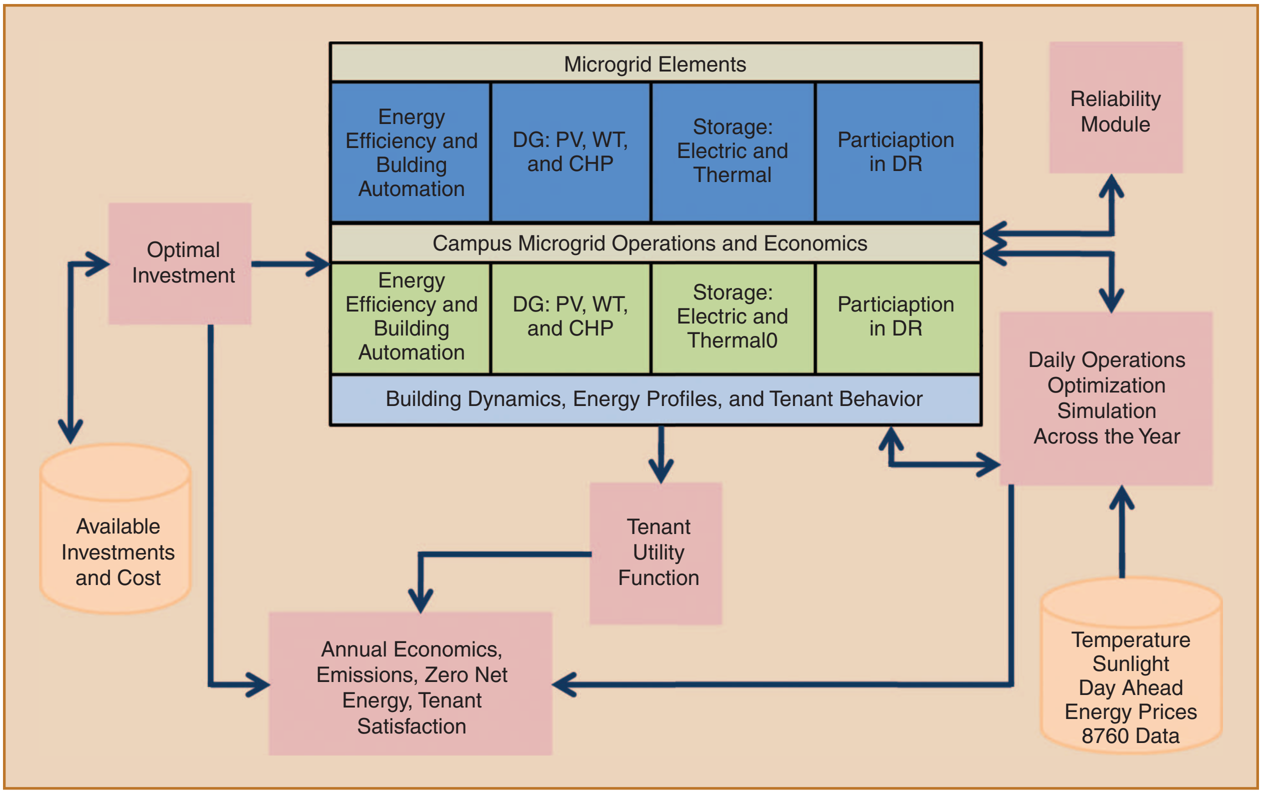


figure 1. Overview of the DNV KEMA model.

be designed to make sure the storage devices are available when they are expected to provide service. Moreover, the storage control needs to take into account the cost of energy for charging and technical constraints around charging, discharging, and performance degradation of the device. In the model results shown, the storage resource is co-optimized with energy production and demand response in a mixed-integer programming formulation. The examples shown are based on "real data" in the sense that typical Los Angeles–based building information, energy prices, and renewable performance are used. In this instance, investments in energy efficiency are the single most valuable option. Electrical storage is still too expensive to make sense on its own, but when coupled with significant investments in PV generation, storage starts to show benefits. Thermal storage is economical purely in terms of shifting air-conditioning load from peak to off-peak. The investment portfolio optimization is complicated by current policies around rebates and tax incentives for different energy efficiency investments and renewable technologies. For instance, if a continued decline in PV costs is projected, it may make sense to delay major PV investments until the last year incentives are available.

Noneconomic Benefits

The benefits from microgrids are not only economic. Microgrids can be viewed as a means of creating zero-net-energy communities and meeting other environmental goals established by states or regulatory agencies. Moreover, microgrids can operate in islanded mode and sustain the power supply in the event of a grid outage. This is in particularly crucial in order to resume the operation of critical infrastructure such as military facilities, hospitals, ports, public transportation, and emergency-response facilities. With the aging of grid infrastructure and restrictions on new investments in transmission and distribution networks, microgrids can serve as an alternative solution to intense investment in the centralized grid. Figure 5 shows how a microgrid can supply a portion of load during a grid outage. In this configuration, PV and battery storage (BS) are sufficient to supply all critical and uninterruptible load for each hour of the outage, and storage level decreases with the duration of the outage. Uninterruptible load experiences a momentary outage (not represented on plots), because no uninterruptible power supply (UPS) is installed and

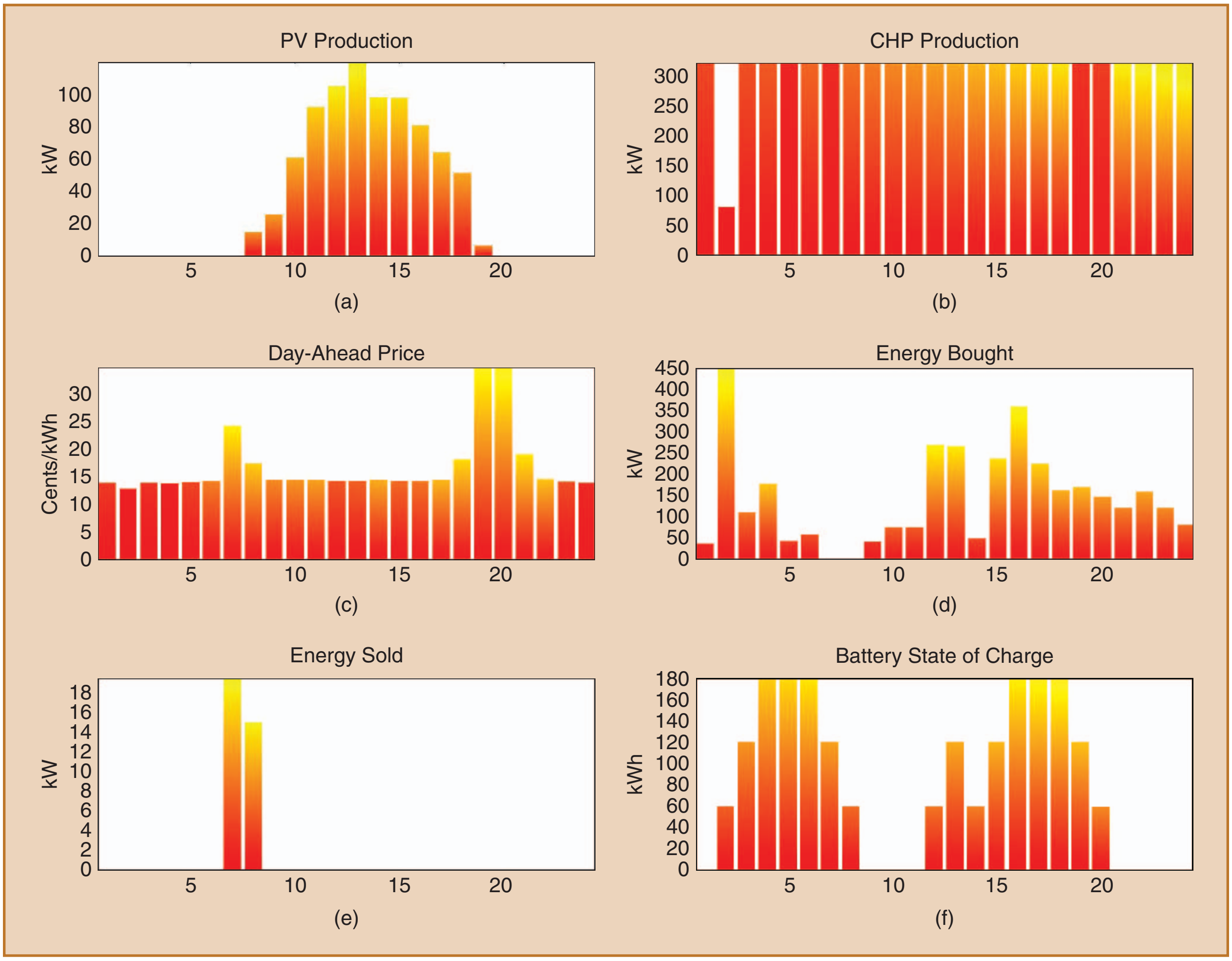


figure 2. (a) PV production, (b) CHP production, (c) day-ahead prices, (d) energy purchased, (e) energy sold, and (f) battery storage state of charge for a sample microgrid.

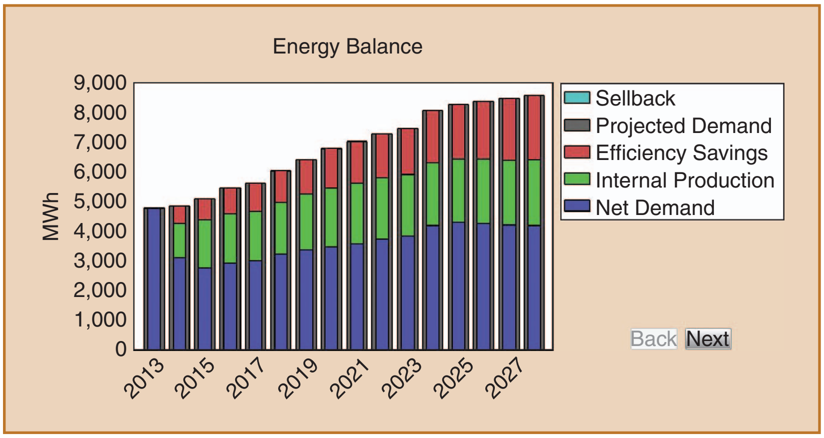


figure 3. Sample microgrid energy economics.

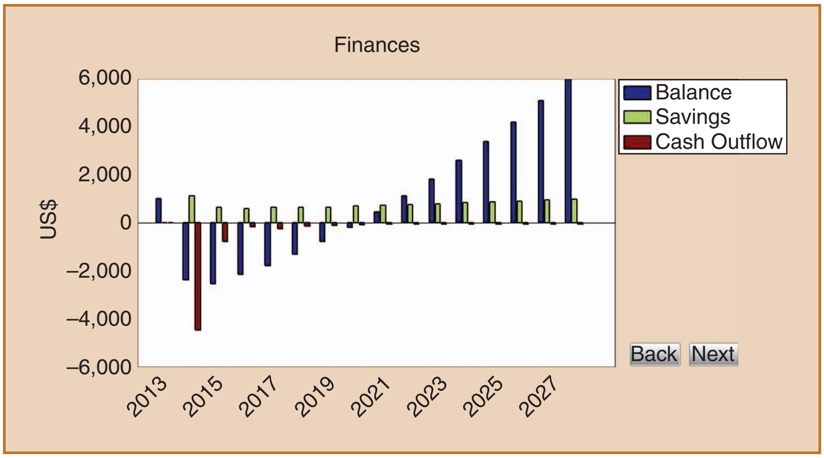


figure 4. Sample microgrid cash flow diagrams over 15 years.

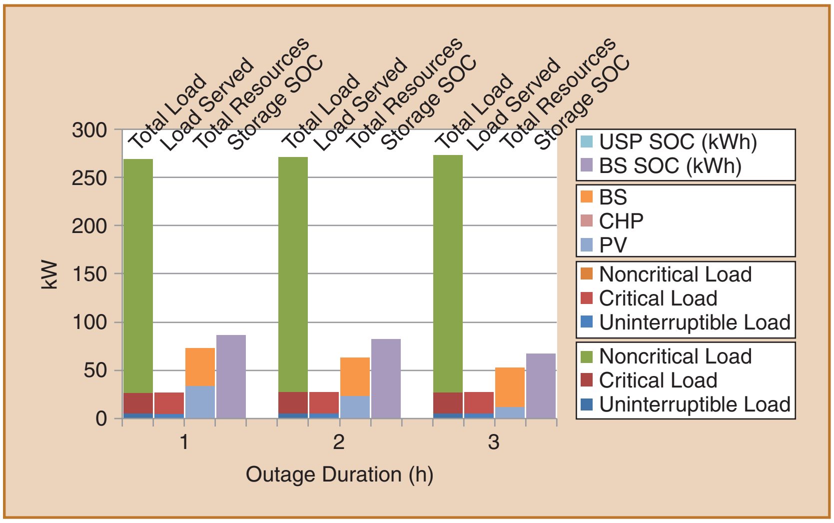


figure 5. Operation of a microgrid in islanded mode during a grid outage.

insufficient resources are available to supply noncritical load.

Stochastic Operation

Traditionally, the wholesale electricity market uses reserves and load-following capacity to hedge against shortage risks and load variations. Moreover, the size and abundance of generation resources and ancillary services such as LMP protect macrogrids against market volatility in prices, demand, and generation capacity. Microgrids are quite vulnerable to these risks, however, due to their smaller size and the volatility of their internal generation resources. Their only hedging mechanisms against shortage risks are to purchase energy from the grid at spot prices, which can be quite high at times of peak load or in an emergency, or to contract with energy service companies.

A typical microgrid will most likely be owned by a community or small group of public and private investors. The investment on microgrids will be very different from a traditional power grid since, due to their size and distributed nature, a small- to medium-sized investment will be more common. Furthermore, to be attractive for private investors, a faster return on investment compared to the traditional grid will be expected. It is also very likely that these investors are motivated by the energy and cost savings that can be realized from the local generation of power and by the security and reliability that microgrids can offer, especially at times of peak loads and during unusual events like natural or man-made disasters. Like any other financial investment, risks will play major role in the operation and control of microgrids. The risk is present in both the design of a microgrid and its daily operation. By appropriately sizing the microgrid and minimizing the risks from energy economics, the microgrid's owners and investors will be able to maximize their savings while ensuring higher levels of energy security and reliability. By doing so, the microgrid will also be able to help mitigate the risks of the larger grid, especially at times of emergencies and high peak loads.

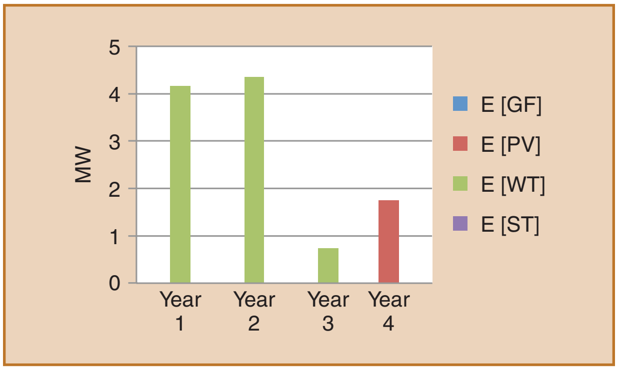


figure 6. Deterministic investment model.

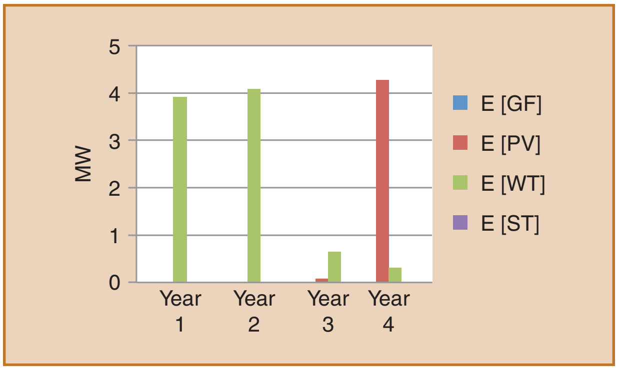


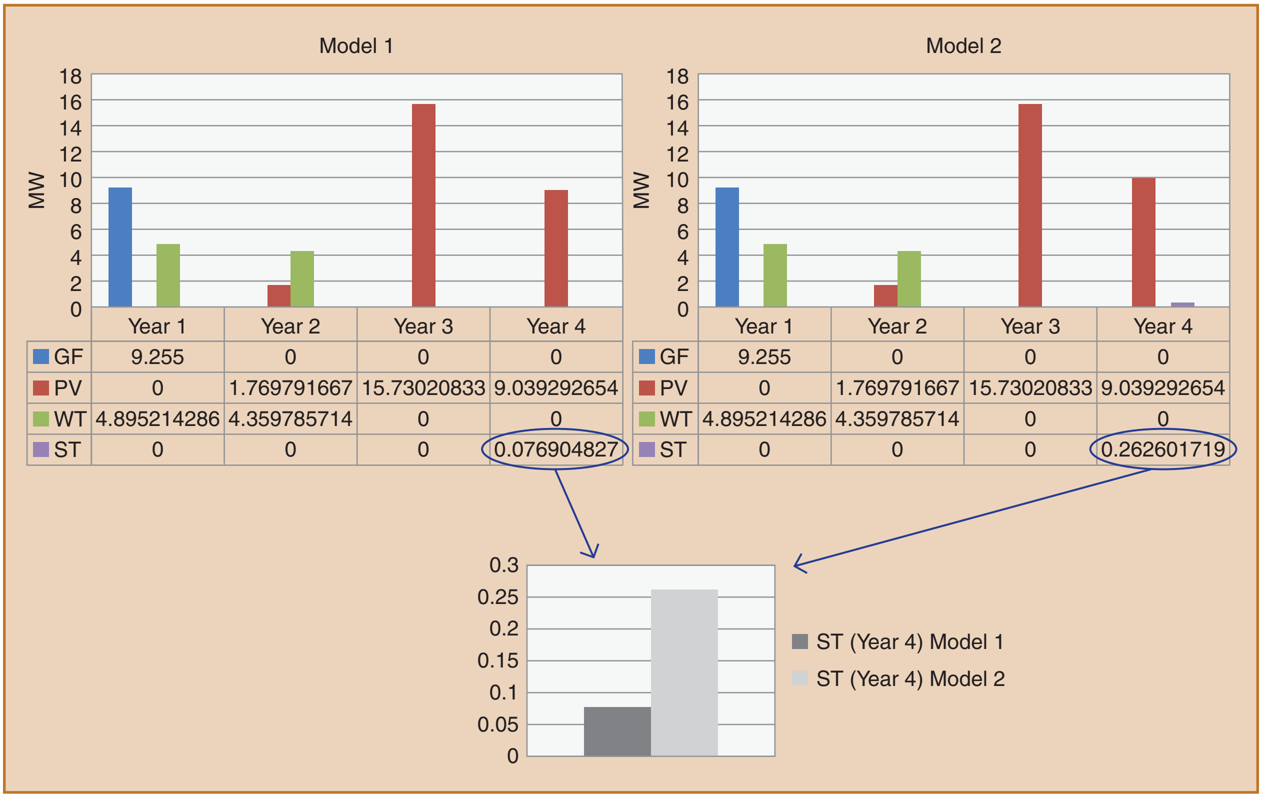
figure 7. Stochastic investment model.

To account for risks in microgrid operation, uncertainties should be formulated using a stochastic optimization model. It is interesting that as we move from deterministic to stochastic models, the planning decision moves toward more prior commitments and less spot purchasing, leading to lower expected cost and variance. (This is a function of expected volatility in energy prices.) As expected, the difference in the way deterministic and stochastic models make decisions depends on several factors, including a microgrid's configuration and the variability of its resources. Therefore, a careful examination of existing settings will help the decision maker choose the appropriate model for planning and operation so as to make sure that ignoring uncertainty (i.e., choosing a deterministic model) does not have an adverse impact in terms of increasing the variation of planning decisions and to make sure that taking uncertainty into account does not lead to a more complicated and costly model without creating a noticeable benefit for the decision maker.

As a microgrid's on-site capacity increases, its cost distribution (in terms of both the average and standard deviation) becomes less sensitive to risks and uncertainties. Risks and uncertainty in cost distribution increase with more renewable penetration and decrease with more fuel-fired generation within the microgrid.

Stochastic Investment

Models developed at Rutgers University are able to balance the risks and outcomes associated with microgrid investment



Model 1

	Year 1	Year 2	Year 3	Year 4
GF	9.255	0	0	0
PV	0	1.769791667	15.73020833	9.039292654
WT	4.895214286	4.359785714	0	0
ST	0	0	0	0.076904827

Model 2

	Year 1	Year 2	Year 3	Year 4
GF	9.255	0	0	0
PV	0	1.769791667	15.73020833	9.039292654
WT	4.895214286	4.359785714	0	0
ST	0	0	0	0.262601719

figure 8. Incremental investment with and without interaction.

and operation. The microgrid cost savings function is calculated from a model that optimizes day-ahead planning and the same-day operation of the microgrid under a host of stochastic variables. This functional form is fed into a stochastic long-term investment model, which decides when to invest in microgrid components and expansions. The investment model captures long-term market and financing volatilities, such as the investment costs of PV and storage, natural gas prices, the availability of investment funds, and the correlation between peak electricity prices and natural gas prices.

The analysis is performed on the basis of cash flow, reflecting actual outflows and inflows of monetary values. It requires proper identification of the costs and benefits resulting from the investment, including any marginal values introduced to the system by the investment. The analysis includes the sunk cost incurred by a new investment as well as its opportunity cost (the benefit forgone if the investment is undertaken). An opportunity cost is also incurred if the asset or resource can be used in some alternative way and with some positive return. Cash flow at the end of the planning horizon plus the value of beyond-horizon cash flows at the end of the horizon is the investment criterion to be maximized within the investment optimization model.

We look at incremental investment decisions over a specific time horizon to evaluate microgrid investments. Decisions regarding how much (if any) capacity of each type of resource, i.e., gas-fired generation (GF), PV, wind turbine (WT), and electricity storage (ST), should be purchased at the beginning of each one-year time period.

Figures 6 and 7 show investment strategies using deterministic and stochastic investment models. In this example, uncertainty exists in future PV capital costs. Therefore, a stochastic model would suggest a strategy that is more distributed over the horizon. This could be viewed as a hedging mechanism against the future uncertainty.

Results may not match expectations if interactions between assets exist in the actual microgrid but operation and investment models ignore them. For example, PV and ST have interaction effects on the cost savings of the microgrid. Depending on the value that it generates, the interaction between PV and ST may make investment in these assets more or less attractive. The incremental investment decisions about various resources are shown in Figure 8. The interaction between PV and ST forces the investment to allocate more capacity to these assets in the fourth year in comparison with the same case without such an interaction. PV dominates the investment because of its higher contributions to the savings generated by the microgrid. Allowing for interactions between the two assets permits the use of storage not only for arbitrage but also coupled with PV production. Therefore, at some point in time (here, in the fourth year), the value of storage exceeds its costs and thus becomes more attractive as an investment. This observation tends to verify our hypothesis, and it necessitates the use of an appropriate model in cases where such interactions exist.

Future Work

Participation in capacity markets and ancillary services markets are attractive revenue streams for microgrids. Inclusion of ancillary market commitments in day-ahead and intraday operations is a well-understood problem; the mathematics is very similar to that used for the co-optimization that independent system operator (ISO) market operations practice when scheduling grid resources today. As with ISO-level market operations, incorporating significant storage in the formulation and obtaining co-optimized solutions are challenges. Incorporating ancillary participation into investment decisions is more complicated, however, as bidding strategies come into play. In the examples shown above, the microgrid is a simple "price taker" in the market that optimizes its resources once market prices are known. But to participate in the ancillary markets, the microgrid operator must make informed decisions about what ancillaries and what energy to offer the markets as a bidder. This complicates the decision process and the investment decisions required to enable that participation.

There is also interest from very large facility operators in co-optimizing energy operations across multiple microgrids. This is an area being intensively investigated at Rutgers.

For Further Reading

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Biographies

Farnaz Farzan is with DNV KEMA Inc., Chalfont, Pennsylvania.

Sudipta Lahiri is with DNV KEMA Inc., Chalfont, Pennsylvania.

Michael Kleinberg is with DNV KEMA Inc., Chalfont, Pennsylvania.

Kaveh Gharieh is with Rutgers University, New Brunswick, New Jersey.

Farbod Farzan is with Rutgers University, New Brunswick, New Jersey.

Mohsen Jafari with Rutgers University, New Brunswick, New Jersey.

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