SIMULATE AND EXPERIMENTALLY EVOLUTE A SPECIFIC PV-BASED MICROGRID SYSTEM FOR REPLICATION IN VIETNAM

By

Phuoc Tri Le

Applied Project for the Requirements of the Professional Master’s Degree Solar Energy Engineering and Commercialization

Academic Advisor: Dr. Govindasamy Tamizhmani

Industrial Advisor: Dr. Devarajan Srinivasan

Arizona State University

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Abstract

Photovoltaic (PV) based microgrid systems are becoming increasingly popular due to the plug-and-play nature of the controller products. A microgrid can be operated independently during the period from grid-connected to grid-off, especially in the emergency mode for hospitals, police stations, and communication towers or to provide power to low-income families in developing countries, such as Vietnam. However, one of the main problems yet to be solved is a validated program to simulate, optimize, and predict the system, which is related to the load profile and power produced by renewable energy systems, depending on weather conditions. This project relates the study of system performance in Arizona operation conditions for an isolated-grid power using a photovoltaic (PV) system and gasoline generator. The electricity produced which isn’t used by the load will be utilized to charge the batteries. A prediction of this system’s performance in Vietnam will be provided by the HOMER Pro simulation program after demonstrating that this tool is validated with Arizona condition performance.
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1. Introduction

1.1. Description of the Industry Issue

Continuously increasing demands for electricity along with an emerging interest in clean technologies has led to the development of distributed power systems using renewable energy sources. However, the integration of a large number of distributed generator into distribution networks is restricted by the capacity limitation of the distribution networks and their unidirectional power flow behaviors. This has motivated researchers to find alternative solutions to enhance the integration of these distributed generators. An alternative approach called microgrid was proposed in 2001 as a means of integrating distribution generations into the distribution networks.

A microgrid unit can be defined as a combination of loads, microgeneration or distributed generation units, storage systems, and associated power units such as photovoltaic (PV) wind turbines that operate as a single controllable system and provide a power load for charging. The microgrid can provide benefits to consumers concerning reliable power supply, efficient power transmission, reduction in transmission system expansion, and enhancement of renewable power penetration.

Off-grid microgrids have traditionally been a highly suitable market and particularly appropriate for applications where less expensive traditional grids could not operate. However, continual improvements in the performance and cost of microgrid technologies (ex. PV, small wind, and batteries) are making them a more attractive option, particularly in developing or remote areas that have not yet invested in traditional grid infrastructure. Microgrids have several advantages over traditional grids: They are scalable and do not require significant capital investment. They are generally environmentally superior to traditional generation. They can be tailored to the particular needs of a community. However, the cost is always an essential factor, and any serious discussion of microgrid technology must effectively address that issue.

The goal of this project is using a simulation tool that has been validated to predict the performance of an existing microgrid unit and to replicate it in Vietnam. This toolkit should provide a vehicle for the available scientific study of grid topologies and application performance issues. The tool requires that it must be validated by comparing experimentation with actual grid testbed because
it can be used to explore a more comprehensive grid resource configuration and scenarios. Further, if application or middleware behavior is challenging to model accurately, the use of direct application execution enables accurate modeling. The microgrid provides reduced setup effort for simulation and increases the observability of application behavior.

HOMER Pro, which was designed at the National Renewable Energy Laboratory, is a global standard in microgrid software based on needs of users in designing and deploying, replicating microgrids and distributed power system in different locations with various purposes. The program can include a combination of renewable power sources, storage, and fossil-based generation (either through a local generator or a power grid). HOMER Pro is chosen as a method of studying because it is commonly used in microgrid education, research, design, advising, and industry. At present, more than 100,000 users in 193 countries have been reported by HOMER Energy [1], the company that administered this simulation program. HOMER Pro has optimization and a sensitivity analysis algorithms function that allows technicians to evaluate different economic and technical respects of a large number of technology options for the variations in technology costs, electricity load profile, and energy resource availability.

HOMER Pro microgrid toolkit provides a detailed rigor f chronological simulation in a model that is relatively simple and easy to use. It is adaptable to many diverse objects. HOMER Pro is accessible to a broad set of users, including both technical and non-technical decision makers. In the performance prediction, chronological simulation is essential for modeling variable resources, such as solar, hydroelectric, wind power, and for combined heat and power applications where the thermal load is variable. HOMER Pro's sensitivity analysis helps determine the potential impact of uncertain factors such as fuel prices or solar irradiance on a given system.
1.2. Problem Statement

As an essential component in the development of smart grid, microgrids have played an essential function in long-term smart grid planning, especially in the reliability evaluation. Although there could be many ways to describe the concept of a microgrid, the most straightforward definition is that microgrid is an association of a low voltage distribution network, distributed energy sources or distributed generation, and load and storage devices which have same local coordinated functions.

In Vietnam, the government has now planned projects to increase the number of distributed generators. The goal was to investigate optimal system design for several types of microgrids in both on-grid and off-grid scenarios. The goal will not only help the people in Vietnam to have a high-quality power supply and but also help the main grid to improve in many respects.

One of the most critical features of to consider in the construction of the system is to design, predict, simulate, and optimize its performance. Among the simulation programs, HOMER Pro is a modeling approach found most effective for system design and deployment, and for replicating microgrids and distributed power system in separate locations with diverse proposes. For that reason, this project seeks to evaluate an existing microgrid PV system at Arizona State University-Photovoltaic Reliability Laboratory (PRL) to replicate in Vietnam using a validated HOMER Pro simulation model.
1.3. Background and Industry Issue

Today, electricity is critically important in daily life. Electricity can be generated from various sources of energy and then distributed through grids to consumers and factories. For decades, most countries relied on large grids to fulfill their electricity needs. However, with rapid technology development in the recent years, there has been a significant contribution from smaller grids all over the world, primarily to fulfill increasing demands in remote areas.

In Vietnam, a developing country in Southeast Asia, the electrical demand has increased by an average of 14.5 percent annually over the last 15 years. Although the electricity used per person is only approximately 900 kWh (compared to 2680 kWh in Thailand), the growth in electrical demand will become a major challenge for Vietnam in the future. According to the General Planning Energy Scheme of the government, the prediction in annual energy used in 2021 will be around 263000 GWh and grow to 350000 GWh in 2025 [2].

In 2015, Vietnamese Prime Minister, Mr. Nguyen Tan Dung - approved the first national strategy of renewable energy development in Vietnam to be implemented by 2030 and visioned to 2050 [3]. This strategy indicates a clear target and pathway for commercial development at large scale of a wide range of renewable energy subsectors: solar, wind, hydroelectric, geothermal, biomass, etc. This renewable energy development strategy has shown the government's persistent determination and efforts to give priority to clean energy and build comprehensive supporting policies based mainly on market mechanisms. Historically, the development of renewable energy in Vietnam has been firmly attached to the implementation of the government's objectives, which are specific to energy-sector policy and plans. These plans address the need to accelerate rural electrification, enhance energy supply security through fuel diversification and optimize energy efficiency and savings by providing energy at affordable prices to citizens.

Geographically, Vietnam has mountainous areas, dense forests, and remote islands. This has brought the opportunity to develop microgrids or smart grids as part of the effort to increase the electrification ratio in isolated areas and islands. The daily solar energy potential in Vietnam is characteristically below 4 kWh/m² in the north to above five kWh/m² from the central and southern regions. An Asian Development Bank (ADB) study on renewable energy development and potential in Vietnam indicated that approximate 220,000 km² of land area (excluding island areas) is suitable for solar power generation installable capacity of 0.6 kW/m², the average installed
capacity per area based on current technologies. ADB likewise cited that the technical solar potential is approximately 18 TWh/year, with more than 60 percent coming from the southern half of Vietnam.

The first large-scale grid-connected solar PV power plant with a capacity of 19.2 MW was initiated in Quang Ngai Province, central Vietnam on August 29, 2015 and is expected to be commissioned by mid-2016. The feed-in-tariff rate for solar power is currently drafted and tariff rates of 11.2 US cents/kWh and 13-14 US cents/kWh are projected for ground-mounted and rooftop installations, respectively. Some aggregate capacities of 900 MW are targeted by 2020 and increasing to 3200 MW by 2050.

The government's attractive incentive packages led to the establishment of solar PV assembly factories that include the following: Redsun at 12 MW/year capacity in Long An Province; IREX – Solar BK at 150 MW/year capacity in Da Nang City; and Bo Viet / Boway at 150 MW/year capacity in Bac Giang Province. These facilities primarily serve the international market (export) with a small quantity of local/domestic supply.

Although the public electric company - Vietnam Electricity - has completed many power generation projects as those mentioned above to make sure the whole nation can have enough power supply for socioeconomic development, total electricity production still cannot meet the demand of the country. The majority of the Vietnamese population is currently living in the rural areas in low-income households. Some families are so impoverished they cannot afford to pay for basic living expenses, let alone electricity. Additionally, the electrical grid in rural areas is frequently unreliable and unstable. Moreover, Vietnam has 54 ethnic groups. Members of these ethnic minorities often live on isolated reservations outside the reach of the national grid with no access to electricity. One of the available solutions now is the extensive use of small-scale electrical power generation technology that can provide electric power a short distance from the load site and connects to the distribution system, or directly to the customer's facilities, or both.

For that reason, the government has planned a project to increase the amount of distributed generators.

The appearance of the microgrid will not only help solve the energy problem for people in Vietnam both in quality and quantity, but also can help the main grid improve in many aspects. For the off-grid model, one of the most important features is the active and reactive power flow control of the
microgrid. The microgrid can produce the exact amount of energy to the load when needed and retain the remains in the storage system to use in the future. In order to function as described, the proposed microgrid uses an inverter system to control the power flow between the energy sources (generators, PV, wind turbines, batteries) and the main loads. This project will focus on studying the performance of a microgrid inverter system from the company OutBack Energy for a 2.25-kW scale unit.

Moreover, the model predictive control, which has recently become a common control method, is also applied to improve the performance of the system. The power flow control of this grid-connected inverter is the numerical simulation by the HOMER Pro simulation program and experimental verification by tests in the Photovoltaic Reliability Laboratory (PRL) – Arizona State University (ASU). This robust model predictive control method along with different constraints in the cost function will also optimize the smart microgrid performance by reducing its operational cost.
2. Project Plan

2.1. Approach and Scope

This project is focused on integrating the performance of an existing microgrid PV model in ASU-PRL and comparing it to the prediction data from the simulation program to validate it. Once the toolkit is validated, a prediction data of the model unit in Vietnam weather conditions will be provided. The approach of the project is described as follows:

1. Real-time performance collection: the operation performance of the microgrid unit will be collected at ASU-PRL for evaluation. The data collected will include: PV power production, load profile, inverter power, batteries voltage, etc. The period for this collection is estimated to be one week.

2. Modeling and integrated prediction data by HOMER Pro: The microgrid component specifications will be modeled precisely into the simulation program before the evaluation. Arizona weather conditions will also be collected from the weather station and input to the program. Once these steps have been completed, an output of the performance prediction of the microgrid will be provided.

3. Validate the simulation tool: A comparison will be made between the real and prediction performance to test the reliability of the program.

4. Predict system performance in Vietnam: Once the program has been validated and combined with the weather data from Vietnam, a predicted performance will be given under Vietnam conditions.

2.2. Top Five Success Project Success Factors

1. The top reason that makes the project successful is that has the expert guidance from two professors who have experience on reliability and simulation standards: Dr. Govindasamy Tamizhmani and Dr. Devarajan Srinivasan.

2. The project supports the Vietnamese government’s Smart City Project goals in developing the distribution generations by providing low-income people access to a high-quality power supply and also to more fully develop an economical and reliable national grid.

3. The project also meets the need of providing energy to low-income families and minorities who live in places that are not serviced by the main grid.

4. The project has support from Vietnamese government in providing necessary data for the prediction in Vietnam conditions.

5. With a clear assessment of the scope of the project’s tasks to be completed and an actionable timeline the project is scheduled to be completed by July 2018.
3. Project Implementation

3.1. Introduction of microgrid

3.1.1. Definition

There are many definitions of microgrid systems utilized in various reports by organizations throughout the world since the use of the systems became widespread. The Department of Energy in USA has defined microgrid as a group of distributed energy resources (PV modules, wind turbines, pump hydro, etc.), and energy storage devices (batteries, fuel cells) [4]. All these parts are controlled by energy management and coordination control to make sure the energy sources provide power that meets the demand in various sizes of the load. The hold system may or may not connect to the utility grid, and performs with the on-grid and off-grid system. In another definition, a microgrid can be seen as a smaller version of the traditional electric grids. Very similar to a traditional grid, a microgrid system has power generators, distribution, and control systems for voltage regulation. Because of the convenience of this system and the advancements in renewable energy technologies in recent years, microgrids have gained much attention in all residential, commercial and utility scales.

3.1.2. Literature Review

The microgrid concept is now an essential approach to solve the problem of integrating a significant amount of microgeneration without interrupting the utility network's operation. The microgrid or distribution network subsystem will create less disruption to the utility network since it has profound connections to generation and loads. In case of disturbances on the primary network, a microgrid could potentially disconnect and continue to operate individually, which helps in improving power reliability to the consumer.

Several advantages offered by microgrids to the end-consumers, utilities and society can be identified. First, the microgrid can support the existing grid infrastructure by adding resilience, compensating for local variable renewable sources, and supplying ancillary services such as reactive support and voltage regulation to a part of an Electric Power System (EPS). In addition, microgrid also helps ensure an uninterruptible power supply meets the needs for critical loads, maintains power quality and reliability at the local-level line, and minimize losses by locating generation near demand. From an environmental perspective, the system integrates the distribution of renewable energy resources to reduce carbon emissions at peak load consumption.
Figure 3.1 includes power sources such as PV arrays, wind turbines, utility grid (grid-tied mode) and energy storage devices, which illustrates a definition of microgrids. The generators in this case can be used as a backup power supply or as a regular power source running parallel to the renewable energy sources and charging batteries. The control system denoted is used as a means to regulate the power from various sources to the load and/or batteries.

Figure 3.1. A microgrid system using solar energy and wind energy

As the definition shows, the size of microgrids is mostly smaller when compared to the traditional utility grids, which are generally sized at megawatts. Microgrids include many different energy resources such as PV arrays, generators, etc. for one-unit goal is providing power for the load for which it is designed. In the last 20 years, due to the improvement in renewable energy technologies, more renewable energy sources are applied to the microgrids [4].

Figure 3.2. Categorization of microgrids based on size
Figure 3.2 has defined various sizes of grids and shows possible metrics to determine the size of PV based microgrids. On the graph, it is stated that the microgrid size can be up to a few hundred kilowatts (kW) of electric power. The graph is categorized into large, medium and small systems based on their size. The size of the microgrid is mostly dependent on the load and availability needs of the load. In general, this size can be designed to a few hundred kilowatts of power for rural electrification or on a commercial scale.

3.1.3. Microgrid structure
A microgrid mainly consists of distributed generators, energy storage devices, power electronics, and a control system to manage the power supply from the generators. The primary grid source, on the other hand, can be either in grid-tied mode or off-grid mode [5].

1. Distributed generators (DG) are the primary source for generating electric power in a microgrid. Distributed generators can be categorized based on their technologies and the size such as renewable energy DG and non-renewable energy DG, portable generator, or commercial generator. Renewable energy sources such as wind and solar are being applied quite extensively in microgrids.

2. Energy storage devices have become an integral component of a microgrid. In the system, energy storage devices can be batteries, fuel cells, flywheels, and super-capacitors. Due to the increased implementation of renewable energy technologies and their intermittent nature, storage devices such as batteries became more widely used than the others.

3. The electrical load in microgrid systems plays a vital role in its operation and stability, because in specific applications, prioritizing the supply to critical loads is essential. Microgrids can be used to supply power for both residential and industrial loads, which can be further classified into sensitive and non-sensitive loads.

4. Power converters are required devices in most distributed energy resource microgrids to convert the generated power from DC sources such as PV modules and wind turbines to compatible AC power for the appliances. The role of power converters includes power conversion, power conditioning, and protection of output power from electric sources to appliances. Most microsources also require a manager power electronic device for the microgrid to control the power flow in the system.
3.1.4. Microgrid operation

The microgrid mainly operates in two modes: On-grid mode and off-grid mode. On a large scale, most of the microgrid operation is a combination of both modes [5].

On-grid mode: the microgrid is connected to the upstream network. The microgrid can receive entirely or partially the energy from the main grid (depending on the power-sharing). On the other hand, when the total electric production more than the consumption, the power excess will be returned to the main grid.

Off-grid mode: when the grid network has some specific failures due to the weather or system errors; or when there are planned actions such as maintenance, the microgrid can smoothly move to islanded operation. Thus, when the microgrid operates autonomously, it is called island mode, in a similar way to the electric power systems of the physical islands or stand-alone systems in residential scale.

Furthermore, the operation of the microgrid may depend on conflicting interests among different stakeholders involved in electricity supply such as system/network operators, distributed generation owners, distributed energy resource operators, and energy suppliers as well as customers or regulatory bodies. Optimal operation of a microgrid is usually based on three factors: economic, technical, and environmental aspects.

![Figure 3.3. The microgrid operation strategies](image-url)

The goal is optimal microgrid operation along with the economic objective of minimizing the total costs of energy distributed resources, rebates, and revenue. In this option, the loss and emission
costs are negligible. The constraints are shown as the physical constraints of distributed energy resource and energy balance.

In the technical option, the power loss in the system is considered as the objective function. The voltage variation and device loading, distributed energy resource physical limits, and energy balance are the constraints.

If the system is optimized in the environmental aspect, the distributed energy resource units with the lower emission levels are the target of choice without considering the financial or technical aspects. The emission cost is given as the objective of this case.

In fact, an optimal microgrid system is not defined in any single way, but can be determined by combining all the options which called combined option. A combine option is an approach solving the multi-objective issue to meet all the environmental, technical and economic requirements. The critical constraints in this option are voltage variation and loading; distributed energy resource physical limits; and the balance energy.
3.2. Literature review of microgrid components
3.2.1. PV modules design

The function of the PV cell is to convert sunlight into DC electricity through the photovoltaic effect. A PV module consists of several connected PV cells. A PV module only works and produces electricity when adequate irradiation is supplied. A PV system is an interconnection of modules, which in turn, is made up of many PV cells in a series or parallel. Since the electric power produced by a single module is not sufficient to meet the requirements of the applications, the modules are connected to form an array to supply the load. In an array, the connection of the modules identical to the cells in a module. The modules in a PV array are usually first connected in a series to obtain the desired voltage. The individual modules are then connected in parallel to allow the system to produce more current. In common uses, the arrays are usually mounted on a rooftop. PV array output can directly feed to a DC motor in agricultural applications.

In manufacturing, the ratings of PV modules are available in wide variety from 100W and up to 300W power depending on the user goals. In addition, many manufacturers are now applying a way to produce AC by PV modules by attaching an inverter, called a micro-inverter, into the back set-up of the module that can convert directly from DC to AC and connect to the bus [6]. A slight economy of scale can often be noted for the different panel sizes up to 100W power; however, after that size, the costs will increase linearly with size. The main disadvantage of PV is it has a high capital cost now, but it is believed that panel costs might come down in future. PV can become cost-effective for small power requirements in areas remote from the existing electricity grid.

In the solar installation, the PV module is connected to the grid or the isolated grid through inverters to convert from DC to AC. Currently, there are three main groups of PV modules and inverters as shown in below figure:
1. The centralized system uses a single inverter to transfer the total power. It is useful for small installations.
2. For the modular system, several inverters are connected to a series of PV modules.
3. System integrated inverters are useful for PV modules with high power installations.

The PV sizing is presented in this subsection. This will be used in next chapter to determine the optimal sizing of microgrid. The PV sizing variables are given as the PV panel number and the amount of string in a PV array. The required number of PV panels in series is estimated by the number of panels needed to match the bus operation voltage. Thus, the PV panel number in series is calculated as follows:

\[ n_{PV\ in\ series} = \frac{U_{bus}}{U_{module}} \]

Where:
- \( U_{bus} \): the bus operation voltage
- \( U_{module} \): the PV module voltage
- \( n_{PV\ in\ series} \): the number of PV panel in series

Each PV string includes modules connected in series. In order to match the current requirement of the system, this PV string is must be installed in parallel with other strings. The parallel string number is the sizing variable that needs to be optimized. The parallel PV string number relates to
the amount of the available output current from the overall PV array. Thus, when the values of the strings are changed in parallel, the value of the output current is also changed. Therefore, in the optimal sizing system, the parallel PV string number is handled as a variable value to be found through the optimization algorithm. The current output of PV array at time $t$ is calculated as follows:

$$I_{PV\ array\ output}(t) = I_{PV\ module}(t) \times n_{strings\ in\ parallel} \times (mismatch\ factor)$$

Where:

- $n_{strings\ in\ parallel}$: number of PV strings in the array
- $I_{PV\ array\ output}(t)$: the PV array output current at time $t$
- $I_{PV\ module}(t)$: the PV module output current at the time $t$

The output power of the PV array is calculated as follows:

$$P(t) = I_{PV\ module} \times U_{PV\ module} \times n_{strings\ in\ parallel} \times n_{PV\ in\ series} \times (mismatch\ factor)$$

3.2.2. Temperature dependence in output power

The power rating of a panel is defined at standard test conditions (STC) which is at cell junction temperature of $25^\circ C$ and irradiance of $1000 \text{W/m}^2$. The maximum power output, in this case, is the theoretical peak power that can be produced by the module. The PV module has a specific voltage-current relationship, which is depicted in an IV-curve. The maximum power point (MPP) operation is where the maximum module output power is obtained with given irradiation and temperature levels.

Electricity generation from solar cell depends on operating temperature which is the temperature measured in the back of the module. Through an increasing the temperature of solar cell while the short-circuit current ($I_{SC}$) marginally increasing and open circuit voltage ($V_{OC}$) significantly decreasing. According to Krauter et al., about 2.3 mV for each 55 K leading to electrical yield reduction ratio of 0.4 percent per K to 0.5 percent per K for mono and multi-crystalline silicon solar cell [7].

Manufacturers typically provide IV curve specifications at different levels of irradiance and keep other variables such as temperature and wind speed constant. The PV module generates at constant irradiation levels, a roughly constant current from the short-circuit current to just before the current values very near the open circuit voltage. If irradiance increases, the PV module output current will increase linearly. The maximum power voltage module is still retained by the level of
irradiance, through the open circuit voltage changes slightly.

Considering the effects of temperature on the performance of the module, manufacturers will usually give IV curves for various temperatures while keeping irradiance levels constant. When increasing temperature, the open circuit voltage will decrease while the short circuit current increases slightly. This leads to the decreasing power production of the module. The effect of temperature on PV model is given in Figure 3.5.

Figure 3.5. The dependence of PV power output on irradiance and temperature

3.2.3. Generator

Generators can run based on a variety of fuels, including diesel, petrol, propane, and biofuels. Compared to renewable energy installations, generators have low capital costs and can produce electric power on demand. The disadvantages of generator operation are fuel dependence; high transport and storage costs; high maintenance costs; exposure to toxic fumes and noise.

Diesel and gasoline generators are the most common generators used as remote power systems in the world. They can provide a dependable AC output. Diesel and gasoline generators are available in sizes ranging from under 1kW to over a megawatt. Compared to diesel generators, gasoline generators have a less expensive and cheaper to maintain but are shorter-lived. The typical lifetime of gasoline generator is around 20,000 hours compared to 25,000-30,000 hours for a diesel generator. The fuel consumption of a generator depends on the manufacturer and the size of the generator. Gasoline generators are available for smaller microgrids (from 2-5kW) and are most suitable when loads are small and only seldom powered.
A generator should be designed such that it meets the load reliably requirements but also runs on average at very high-load levels.

If a battery for short-term storage is installed in the generator system, it can help to overcome peak loads and thereby reduce the design capacity of the generator and system costs if the inverter is sized accordingly. The generator will charge the battery through a battery charger controller that converts AC to DC electricity. The battery bank allows the generator to operate at a rate close to its rated power, so it can help reduce the start and stop cycles of the generator. This results in a decrease in fuel consumption and the cost of maintenance.

A drawback of a generator when operating at peak output power is that it is a very high-rate charging source for the battery. The battery bank, on the other hand, requires lower charging rates close to the full state of charge to protect the batteries from overcharging.

A battery charger can be installed that can taper the current output of the generator when it is close to the full-charge state, however, some energy will be lost. Thus, in general, a solution to solve the energy loss problem is to use the generator primarily for high-rate battery charging after the batteries have been deeply discharged. This can be done by turning on the generator only when the batteries are at an acceptable low level of state of charge, which is enough to require a vast amount of current for charging, allowing the generator to run at the full efficiency.

Nowadays, most of the generators used for microgrid systems have the Auto-Generator Start Controller (AGSC). This controller is one of the reasons people consider the microgrid as a part of a smart-grid system. The AGSC automatically starts and stops the generator by sending the signal the auto-start function of that generator. The Auto Gen Start Controller continuously monitors the power system and starts the generator if the battery voltage or state of charge reaches preset limits, or the air conditioner or heater needs to be run. It also starts the generator to assist the inverter/charger when power demands are high. When correctly configured, the Auto Gen Start Controller ensures that power requirements are met and that batteries stay charged [8].

3.2.4. Battery

Batteries are electrochemical devices that store energy in chemical form. They are used to store excess energy for later use. Most batteries used in small-scale microgrid systems are required for the deep-cycle type and sufficient installation cost. There are several types of lead-acid, nickel-cadmium, nickel-iron, iron-air and sodium-sulfur, absorbent glass mat. In general, the lead-acid
battery is commonly used in the small- and middle-scale of microgrids. The lead-acid battery in the market has three varieties: wet cell (flooded), gel cell and absorbent gall mat. Among them, absorbent glass mat battery (AGM) has higher reliability and higher efficiency than the others.

Absorbent glass mat technology became popular in the early 1980s as an applicant in military aircraft, vehicles, and UPS with the requirement of reducing weight and improving reliability. Inside AGM, the sulfuric acid is absorbed by a high-quality fiberglass mat that makes the battery spill-proof. This enables shipment and using the AGM battery without hazardous chemical restrictions.

AGM has little internal resistance, is capable of delivering high currents on demand, and offers a long reliable lifetime cycle, even when deep cycled. AGM is maintenance free, provides good electrical reliability and is lighter than the flooded lead acid type. While regular lead-acid batteries require a topping charge every six months to prevent the buildup of sulfation, AGM batteries are less prone to sulfation and can sit in storage far longer before a charge becomes necessary. Besides, the AGM battery stands up well at low temperatures and has a low self-discharge [9].

The principal advantages of AGM is that the charging time is up to five times faster than the flooded battery and they have the ability to deep cycle. In particular, AGM offers a depth-of-discharge (DoD) of 80 percent; the flooded, on the other hand, is specified at 50 percent DoD to attain the same cycle life. The negatives are slightly lower specific energy and higher manufacturing costs than the flooded, but cheaper than the gel battery.

When selecting a battery type, usually lead-acid type batteries are chosen. In general, AGM batteries are more cost-effective than other batteries (flooded, gel cell) among lead-acid batteries.

Selection of battery voltage depends on the size of the system design, the inverter and generation controller equipment generally available.

The battery bank often comes in specific voltages from 12V, 24V, 48V and can up to 120V or 240V in DC and thus batteries must be selected and combined in series to meet this voltage and current requirement. The number of batteries in strings that can be connected in parallel is limited to five without higher precise safety monitoring and higher maintenance costs.

In system design, it’s essential that the system depth of discharge (DOD) must be made between an acceptable value where the battery will be less affected by sulphation, but may face frequent
load interruption and will be cycled more often. Although the supply may be more reliable and the cycling reduced with a high deep of discharge, the battery life may be shortened due to increased sulphation.

Various requirement points needed for the battery can then be set for battery levels such as the minimum and maximum state of charge (SOC), boost charge interval, float voltage, bulk voltage, etc., and these can be applied via a charge controller or system monitor which will be mentioned in the next chapter.

Batteries should be installed in an enclosed area such as a bank that can protect them. The battery bank must also have a vent to protect it from overheating. Within the system, batteries are connected in strings to increase the battery bank voltage and/or in parallel to increase the capacity. All batteries in the bank should be the same brand, model, age, and capacity.

3.2.5. Load
Most residential loads are 12/24V DC appliances or 220/230V or 380V AC appliances. The DC devices can be slightly more expensive than similar AC appliances. From DC supply to AC loads needs inverters with the corresponding power range and efficiencies for the expected load factors. The microgrid also needs a charge controller to convert from AC to DC for charging the battery bank. In the past, there were two separate components with two separate functions of converting between AC and DC, but now many manufacturers have made a bi-directional inverter which replaces both the charge controller and traditional inverter.

3.2.6. Energy Management System
The energy management system (EMS) is used to control energy consumption and ensure the distributed energy resources produce enough power to meet demand. The EMS can also optimize power flow in the system so the consumer can save money during peak hours by discharging batteries and charging it in the low-peak hours. In general, the goal of energy management system to increase the reliable and stable performance of the microgrid to ensure optimal battery storage management and the best utilization of energy resources.
The first thing needed to do, in evaluating how energy is managed in a microgrid is to calculate balance as load profile. The balance load is evaluated as the difference between the power consumption and power producing by PV modules. Next, a comparison is made whether balance load is greater than zero. If the balance load is not greater than zero, which means a connected load, then the excess power from the solar source has to be judiciously utilized. For this reason, the SOC of the battery is checked. If the SOC of the battery is less than 90 percent, then we charge the battery with the surplus power. If SOC is greater than 90 percent, it has more economic efficiency if we send the electricity back to the grid. In the event the balance load is positive, which means the total load is higher than the combined power from solar generations, the availability of the generator is checked. If available, the generator is run until the balance load is greater than zero. The energy management system will check whether the power available from the generator is higher than the balance load. If power producing from the generator is higher than the balance load, then the excess is used to charge the battery or send to the grid. If biogas-generated power is insufficient to meet the balance load, the management system goes for the battery power insertion. In this case, the SOC of the battery is checked by MGCC through the inputs available from battery power measurement units. If the SOC of the battery is higher than 40 percent, the battery for supplying the balance load is deployed. When the SOC of the battery is not higher than 40 percent, then the microgrid will connect to the utility grid availability for supplying the balance load.
3.3. Test-bench system design

3.3.1. PV modules

The PV based microgrid system was set up in the Photovoltaic Reliability Laboratory (ASU-PRL) located in Polytechnic Campus of Arizona State University in Mesa, Arizona. Nine PV modules, which was composed of three strings, were mounted on a mock rooftop, facing to the south with a tilt angle of 20° and a 3-inch air gap from the roof, which is closely simulates the settings commonly followed by PV installers in Arizona. The equipment needed to record the weather parameters was installed, wired, and set.

![Figure 3.7. A 2.25kW PV modules used in the project](image)

Poly-crystalline Si PV modules were used with top surfaces made of glass. All the modules had the same nameplate and rating. The electrical specifications for those PV modules are shown in the table below. Each module is 1.64m long and 1m wide and has 60 cells. The temperature coefficients of the voltage, current, and power respectively are -0.34 percent/°C, 0.04 percent/°C, and -0.44 percent/°C.

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Model Type</th>
<th>ET-P660250WB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power (Pmax)</td>
<td>250W</td>
<td></td>
</tr>
<tr>
<td>Module Efficiency</td>
<td>15.37%</td>
<td></td>
</tr>
<tr>
<td>Maximum Power Voltage (Vmp)</td>
<td>30.34V</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1. Electrical specifications of the test PV modules [10]
<table>
<thead>
<tr>
<th>Maximum Power Current (Imp)</th>
<th>8.24A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit Voltage (Voc)</td>
<td>37.47V</td>
</tr>
<tr>
<td>Circuit Current (Isc)</td>
<td>8.76A</td>
</tr>
<tr>
<td>Tolerance</td>
<td>0 to +5W</td>
</tr>
</tbody>
</table>

3.3.2. Battery
The batteries used are AGM batteries which have a nominal voltage of 6V. The battery bank includes eight batteries connected in a series to perform a 48V bank. The bank is connected to the thermal sensor for measuring the battery’s temperature. All the batteries are put into a bank and placed in a clear space to prevent the electrical hazard.

![Battery Bank](image)

*Figure 3.8. A 48V DC battery bank used in the project*

The specifications of the AGM battery are as follows:

*Table 3.2. Electrical specifications of a battery used in project [11]*

<table>
<thead>
<tr>
<th>Model Type</th>
<th>CB6-224</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cells Per Unit</td>
<td>3</td>
</tr>
<tr>
<td>Voltage Per Unit</td>
<td>6</td>
</tr>
<tr>
<td>Capacity</td>
<td>224Ah</td>
</tr>
<tr>
<td>Max. Discharge Current</td>
<td>2050A (5 sec)</td>
</tr>
<tr>
<td>Float charging Voltage</td>
<td>6.8 to 6.9 VDC</td>
</tr>
</tbody>
</table>
Equalization and Cycle Service | 7.3 to 7.4 VDC
---|---
Recommended Maximum Charging Current Limit | 61.5 A
Weight | 31.5 kg
Operating Temperature Range | Discharge: -20 – 60°C
| Charge: 0 - 50°C
| Storage: -20 – 60°C

3.3.3. Generator and Auto Start Device

The microgrid test bed using a Dual-Fuel Generator right out of the box on gasoline or propane, can easily switch fuels with a quick turn of the fuel selector dial. In the test, gasoline was used mainly. The 192cc Champion Engine produces 3400 starting watts and 3100 running watts, and will run for 7.5 hours at 25 percent load with gasoline fuel. The output voltage is 120V and the running current is 28.3A and 25.8A respectively.

*Table 3.3. Electric specifications of the gasoline generator [12]*

<table>
<thead>
<tr>
<th>SPECIFICATIONS</th>
<th>DIMENSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline Starting Watts</td>
<td>3400W</td>
</tr>
<tr>
<td>Gasoline Running Watts</td>
<td>3100W</td>
</tr>
<tr>
<td>Propane Starting Watts</td>
<td>3060W</td>
</tr>
<tr>
<td>Propane Running Watts</td>
<td>2790W</td>
</tr>
<tr>
<td>Gasoline Starting Amps at 120V</td>
<td>28.3A</td>
</tr>
<tr>
<td>Gasoline Running Amps at 120V</td>
<td>25.8A</td>
</tr>
<tr>
<td>Propane Starting Amps at 120V</td>
<td>25.5A</td>
</tr>
<tr>
<td>Propane Running Amps at 120V</td>
<td>23.3A</td>
</tr>
<tr>
<td>Volts</td>
<td>120</td>
</tr>
<tr>
<td>Frequency</td>
<td>60Hz</td>
</tr>
</tbody>
</table>

The function of the generator is to charge the battery when it is in a low state of charge and provide electricity to support the load when needed. The generator is connected to a Generator Start Control Module (GSCM) device. This device can control the generator to kicking on or turning off automatically by sending a specific control signal. In the design, the GSCM is set up in a way that the generator will turn on at the low state of charge (60 percent) and turn off when the voltage of battery bank is at float voltage.
3.3.4. Energy Management System

The FLEXpower ONE FXR system was used as a management system for the microgrid’s test model. The system is available for 120VAC or 230VAC application, ranging from 2500W to 3600W, 50Hz/60Hz selectable for regional diversity [13]. The system is often used for residential and commercial applications including cabins, vacation homes, farm buildings, remote communications sites, and backup power systems, with all necessary components integrated into a compact hang-on-the-wall system such as an inverter, charge controller, communication hub manager, system display, and controller, battery monitor.

![Diagram of FLEXpower ONE FXR components](image)

**Figure 3.10. The FLEXpower ONE FXR and its components used in the project**
The inverter/chargers are designed to use a battery bank to store energy and work with power from the utility grid or from different renewable energy sources. These sources charge the battery, which in turn is used by the inverter. The inverter's settings can be changed to meet the requirement of many applications. Changes are made with the system display. The inverter has one set of terminals for a single AC source. However, it can use two different AC sources (for both generator and grid-tied) when an external transfer switch is installed. The inverter can be set independently for each source. It is common to use utility grid power and a gas, diesel or biomass generator. Other combinations of AC sources are possible.

*Figure 3.11. The power flow diagram of FLEXpower ONE FXR system*

In Figure 3.11, the inverter uses a bidirectional AC input to sell power back to the utility grid. The power being delivered to the grid is excess AC power not being used by the AC loads. Selling requires an inverter/charger with Grid-Tied mode available and active.
3.4. Simulation Software

This project aims to check the performance of PV based microgrid systems. The reference system was designed and installed at Arizona State University - Photovoltaic Reliability Laboratory (ASU-PRL). As the study focuses on the performance of PV based systems, sufficient software is required to simulate the outcomes of a DC-based PV system regarding the PV plant in PRL by using the HOMER Pro simulation software. The proposed system for a microgrid will have a PV array for generating power, storage batteries to supply the loads when there is no solar irradiation, a gasoline generator which produces energy for charging batteries or supporting the load when needed, and a manager for controlling the microgrid.

HOMER Pro was developed by National Renewable Energy Laboratory (NREL), USA and it is mainly used to find out the best combination of renewable energy hybrid systems that can be both economically beneficial and satisfy the needs of the microgrid for which it is designed. It can be considered as the only software currently used to design systems specifically for microgrids. The main advantage of HOMER Pro is the flexibility it offers to the users. Both off-grid, as well as grid-connected systems, can be designed and simulated in HOMER Pro. It has a lot of renewable energy technologies in its libraries which can be utilized to find the best system which is economically agreeable.

Figure 3.12. Microgrid model has been modified by HOMER Pro
To use HOMER Pro, the program requires a model with inputs, which describe technology options, component costs, and resource availability. HOMER Pro uses these inputs to simulate different system configurations or combinations of components and generates results that can be analyzed as a list of feasible configurations sorted by net present cost. HOMER Pro also displays simulation results in a wide variety of tables and graphs that help to compare configurations and evaluate the results on their economic and technical merits. The results can be exported as the tables and graphs for use in reports and presentations.

If the system wants to explore the effect that can change in factors such as resource availability and economic conditions, which might have on the cost-effectiveness of different system configurations, the same model can be used to perform different sensitivity analyses. To perform a sensitivity analysis, sensitivity values have been provided to HOMER Pro that describes a range of resource availability and component costs. HOMER Pro simulates each system configuration over the range of values. The different results of sensitivity analysis can be used to identify the factors that have the most significant impact on the design and operation of a power system. These HOMER Pro sensitivity analysis results can be used for answering general questions about technology options to inform planning and policy decisions.

The mission of HOMER Pro is simplifying the task of designing distributed generation (DG) systems - both on and off-grid. HOMER Pro's optimization and sensitivity analysis algorithms allow evaluating the economic and also technical feasibility of a large number of technology options and accounting for variations in current technology costs and energy resource availability. Working effectively with HOMER Pro requires the understanding of its three core capabilities - simulation, optimization, and sensitivity analysis - and how they interact.

Figure 3.13. Three capabilities of HOMER Pro simulation program
3.4.1. Simulation

HOMER Pro can simulate the operation of a system by making energy balance calculations in each time step of the year. For each time interval, HOMER Pro compares the load and thermal demand to the energy that the system can supply in that same time step, and calculates the energy flows to and from each component of the system. For microgrid systems that are using batteries or fuel-powered generators, HOMER Pro also decides in each time step how to run the generators on and when the batteries need to charge or discharge.

HOMER Pro performs these energy balance calculations for each of system configuration that the designer wants to consider. It then determines whether a configuration is available, (i.e., whether it can meet the electric demand under the conditions that the designer specify), and estimates the cost of installing and operating the system for all over the lifetime of the project. The system cost calculations account for costs such as capital, replacement, LCOE, operation and maintenance, fuel, and interest.

3.4.2. Optimization

HOMER Pro has two optimization algorithms. The original grid search algorithm simulates all of the possible system configurations defined by the Search Space. The new HOMER Pro Optimizer uses a proprietary derivative-free algorithm to search for the least cost system. HOMER Pro then displays a list of configurations after the calculation and sorted by net present cost or LCOE, that can be used to compare system design options.

3.4.3. Sensitivity Analysis

When defining sensitivity variables as inputs, HOMER Pro repeats the optimization process for each sensitivity variable that the owner specifies. For example, if the user defines wind speed as a sensitivity variable, HOMER Pro will simulate the same system configurations for the range of different wind speeds that can be specified.

3.4.4. Interaction in simulator [14]

HOMER Pro simplifies the task of designing distributed generation (DG) systems - both on and off-grid. HOMER Pro's optimization and sensitivity analysis algorithm options allow the engineer to evaluate the economic or technical feasibility of a vast number of technology options and to account for variations in technology costs and energy resource availability. Working effectively
with HOMER Pro requires an understanding of its three core capabilities - simulation, optimization, and sensitivity analysis - and how they interact.

Simulation: At its core, HOMER Pro is a simulation model. It will attempt to simulate a microgrid system for all possible combinations of the equipment that the designer wishes to consider. Depending on how to set up the problem, HOMER Pro may simulate hundreds or even thousands of systems.

Optimization: The optimization step follows all simulations. The simulated systems are sorted and filtered according to criteria that the designer defines so that they can see the best possible fits. Although HOMER Pro fundamentally is an economic optimization model, the system's designer may also choose to minimize the fuel usage.

Sensitivity analysis: This analysis includes an optional step that allows the designer to model the impact of variables, such as wind speed, fuel costs, etc., that are beyond their control and see how the optimal system changes with these variations.

3.5.1. Energy Situation in Vietnam

Vietnam is a lower- to middle-income country with a population of over 90 million and a territory of more than 330,000 square kilometers. Almost 65 percent of the population is rural based. Numerous ethnic groups live in remote, mountainous regions with limited access to markets and basic services. Vietnam is considered one of the most dynamic and stable countries in Southeast Asia, both regarding political systems and economic development. Its economy is growing steadily at an average rate of 6.2 percent per annum, and from 2005–2016 its gross domestic product (GDP) per capita increased from $699 to $1770, while its poverty rate dropped from 15.5 percent to 8.4 percent. Vietnam’s gross domestic product in 2014 was $202.6 billion [15].

Vietnam has vast reserves of primary energy resources, such as coal, oil, natural gas, and water for hydropower generation. Vietnam also has a high potential for renewable energy resources, such as biomass, solar, and wind. In 2012, the total national primary energy supply was around 58.0 million tons of oil equivalent (Mtoe), of which noncommercial energy accounted for 14.0 Mtoe. The share of total national primary energy by fuel type was coal (26 percent), crude oil and petroleum products (27 percent), gas (14 percent), hydropower generation (8 percent), and non-commercial energy (25 percent). In addition, 10.7 Mtoe of petroleum fuels and 0.2 Mtoe of electricity were imported in 2012. Figure 3.14 shows the primary energy supply mix in 2012.

![Figure 1: Primary Energy Supply 2012](image1)

![Figure 2: Final Energy Consumption by Sector in 2012](image2)


*Figure 3.14. Energy access in Vietnam in 2012*
Vietnam’s national energy development strategy for 2020, which was approved in 2007 and includes an outlook to 2059, has the following objectives: ensure national energy security; supply sufficiently high-quality energy for socioeconomic development; exploit and manage domestic primary energy resources efficiently; diversify energy investments and business models; establish and develop a competitive energy market; promote new and renewable energy sources; and develop energy resources productively and sustainably with consideration for environmental protection.

3.5.2. Solar Potential in Vietnam

3.5.2.1. Climate and Geography

Based on its favorable geographical conditions, Vietnam has a high potential for solar energy production, with 1,600-2,700 sunlight hours per year and an average direct normal irradiance of 4-5 kWh per sqm per day. Theoretically, the potential for solar in Vietnam is 60-100 GWh per year for concentrated solar power and 0.8-1.2 GWh per year in case of photovoltaic systems [16], especially in the central and the south, where sunshine remains almost throughout the year.

Solar energy is proved to be the most abundant and stable renewable energy in Vietnam for present and long-term use. However, this energy source scatters unevenly throughout the country due to the topography. Besides, the radiation intensity of solar energy remains insignificant in Vietnam and changes randomly. Therefore, the potential of solar energy varies across regions, as shown in Table 3.4 below.

<table>
<thead>
<tr>
<th>Region</th>
<th>Hours of sunshine/year</th>
<th>Radiation kcal/cm²/year</th>
<th>Application possibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Northeast</td>
<td>1500-1700</td>
<td>100-125</td>
<td>Low</td>
</tr>
<tr>
<td>The Northwest</td>
<td>1750-1900</td>
<td>125-150</td>
<td>Medium</td>
</tr>
<tr>
<td>Northern Central</td>
<td>1700-2000</td>
<td>140-160</td>
<td>Good</td>
</tr>
<tr>
<td>Central Highlands, Southern Central</td>
<td>2000-2600</td>
<td>150-175</td>
<td>Very good</td>
</tr>
<tr>
<td>The South</td>
<td>2200-2500</td>
<td>130-150</td>
<td>Very good</td>
</tr>
<tr>
<td>Average</td>
<td>1700-2500</td>
<td>100-175</td>
<td>Good</td>
</tr>
</tbody>
</table>

Table 3.4. Solar potential in different regions in Vietnam
Figure 3.15. Average solar irradiance and sunshine hours in northern Vietnam

From the statistics, it appears that Vietnam has a high stability of radiation intensity, especially in the south, thus having a high potential of solar energy, which can be used to provide heat and electricity to the remote areas, help dry agricultural products. In addition, the average temperature in this region in the hottest month is 30°C and in the closest month is 27°C. This temperature allows the PV modules operating at a high coefficient and results in less power loss.

Figure 3.16. Annual global horizontal irradiance and ambient temperature in Vietnam
3.5.2.2. Solar Policies

Despite the geography potential, there are only a few small projects in operation to date, mainly due to the fact that a no feed-in tariff was put in place for solar projects before April 2017. There are, however, thousands of small off-grid solar power systems in operation, mainly in rural and remote areas.

In March 2016, the Vietnamese government revised its Seventh Power Development Plan (PDP VII), which was formulated in 2011. The Revised PDP sets out a government objective to increase energy supply from solar power (as a percentage of total power generation capacity) from the current negligible rate to 0.5 percent by 2020 and 3.3 percent by 2030, or, 850MW solar capacity by 2020, increasing to 12GW by 2030.

To support the government’s ambitious target, the prime minister issued on 11 April 2017 a decision regarding feed-in tariffs for solar energy (the “Solar Decision”), valid until 30 June 2019. The Solar Decision contains several incentives for solar power investment [16]:

Figure 3.17. Milestones for Renewable Goals in Vietnam

**EVN off-take obligations and duration** – Vietnam Electricity Corporation (EVN) will have an obligation to purchase all solar power generated returned to the grid for a period of 20 years from the commencement of operation, based on a standard Power Purchase Agreement.

**Tariff** – The electricity price that applied for the on-grid solar project is set at VND2,086 which is equivalent to 9.35 US cents per kWh, based on the VND/USD central exchange rate set by the State Bank of Vietnam on April 10, 2017, excluding value-added tax (VAT). It will also apply to
excess power generated from rooftop solar installations beginning commercial operation before 30 June 2019 and sold to EVN.

*The standard Power Purchase Agreement (PPA) and bankability concerns* - On September 12, 2017, the Vietnamese Ministry of Industry and Trade (MOIT) issued Circular 16/2017/TT-BCT for implementation of the Solar Decision on solar power projects in Vietnam. Valid from October 16, 2017, Circular 16 includes detailed guidelines on the formulation and approval of national and provincial solar power development plans, technical requirements, and tariff structure for both grid-connected projects and rooftop projects. In addition, Circular 16 includes a set of three templates of model power purchase agreements for grid-connected projects ("Solar PPA"), residential rooftop, and commercial/industrial rooftop projects.

The Solar Decision treats the tariff adjustments for on-grid and excess roof-top power differently. For on-grid solar projects, the Solar Decision provides that the rates will be adjusted in accordance with the model PPA (as discussed below). However, this does not appear to have been dealt with in the current PPA (please see the comments on this in the Appendix). For excess roof-top power, it provides that the MOIT will review the purchase price annually, based on the VND/USD central exchange rate of the last day of the preceding calendar year.

Corporate income tax, import duty, and land-related incentives – The Solar Decision confirms that the existing incentives in relation to corporate income tax, import duty and land generally applicable to renewable projects, as set out above, shall apply to the solar sector.
4. Results and Discussion

4.1. Experimentation test bench

A microgrid test bend has been developed to validate the model as design above. The microgrid system is composed by: electronic load (air conditioner, fan and four light bulbs), a 2.25kW PV power supply, a 3.4kW gasoline generator, a fully pre-wired single inverter system FLEXpower to convert AC to DC and DC to AC, a battery bank composed by eight 6V/220Ah AGM batteries and used in the 40percent to 100percent SOC range to preserve its State of Health. The Battery pack is connected through the inverter to the AC bus and connected to the PV modules through the charge controller. The battery bank voltage may range between 48 and 58V (maximum and minimum battery allowed voltage).

![Microgrid System Diagram](image)

*Figure 4.1. The microgrid system used in the project*

For the simulation model, the base data is extracted from the demonstration test bench and introduced into the model to create the real environment in which to conduct the simulation. The needed data are weather data and load power consumption by the electric appliances. The weather data includes ambient temperature, and solar irradiant which are collected from Scientific Campbell’s weather station. The load profile is from the experimental microgrid model that has two bulbs always on. Besides the bulbs, the air conditioner is set at automatic mode to reflect the effect of temperature in the day.
With the base data extracted from the weather station and the experimental model, the behavior of this system needs to be validated by comparing the measurement results with the simulation results. The performance of Photovoltaic array, the inverter and battery bank are both validated to ensure the reliability of the off-grid microgrid system.
4.2. Operation Validation

Solar power is an essential part of the demonstration project since it is the primary power supporting for the load. The size of the array is 2.25kW so that it can produce energy needed for lighting, cooling and charging phones, etc. The harvest electricity from PV will go through the charger controller and charge the battery bank. The incorporated solar power output data are shown in the Figure 4.4 for every hour data set measure at ASU-PRL. The simulation output solar power is calculated from the ambient temperature and solar irradiance by HOMER Pro simulation software. The results have been shown as the figures below.

![Figure 4.4. PV output power profile](image1)

![Figure 4.5. Inverter output power profile](image2)
In the microgrid, one function of the inverter is converting from DC to AC and support to the load. It can be seen from the Figure 4.5 that the output power from the inverter is closely matched with the load power requirement. It is an essential point since it proves that the inverter has worked with high efficiency and didn't waste the energy. Another function of the inverter is making DC from AC to charge the battery from generator or grid. Figure 4.6 shows the simulation verse actual
power that is going into the battery bank. The salient point in Figure 4.7 is that the charging power isn't only from PV but also from the generator, which makes the input power is more prominent than 2.25kW.

The state of charge of the battery bank plays a crucial role in identifying when it needs to be charged. Usually, the battery needs to be charged at the night time when the load is high and no sunlight. On cloudy days, the generator can only turn on and charges the battery so that it reaches the maximum state of charge faster. In Figure 4.8, the appearance of the generator has helped the battery go up to 100percent state of charge faster than just using PV modules to charge the battery bank.

![State of Charge of Battery Bank](image)

**Figure 4.8. State of charge of battery bank profile**

In summary, a real-time microgrid with a gasoline generator, a PV array model, and a battery inverter system models were developed, simulated, and quantified on a real-time platform using HOMER Pro simulator. With the system’s testing time at 72 hours, it can be seen in the above figures that the output results from HOMER Pro are close to the experimentation data from the microgrid model at ASU-PRL at Arizona State’s weather conditions. The microgrid performances were observed as expected from the calculations of the load in the microgrid by the software. As a result, both the HOMER Pro program and the microgrid system have proved its reliability. The microgrid model can be used to implement in different countries with different conditions. Hence,
the second part of this chapter will focus on using the validated HOMER Pro simulator to predict the same microgrid in Vietnam’s weather data.

4.3. Model prediction

4.3.1. Available resources

For the prediction, three resources, namely solar PV, ambient temperature, and load profile have been considered. The hourly data for solar irradiance and ambient temperature are taken from the solar measurement station sponsored by World Bank Group. Based on the latitude and longitude information, at the Southern side, the annual average solar insolation is 5.12 kW/m²/day. The irradiance increases from January to May and then decreases through the monsoon season (June to September) as shown in the Figure 4.9. The annual average temperature in the southern part of Vietnam is 25.4°C, and the maximum monthly average temperature is 28°C. This is close to the standard operating temperature of the modules so they can produce almost the maximum electric power.

![Figure 4.9. Monthly based average solar irradiation (kWh/m²/day)](image1)

![Figure 4.10. Monthly based daily ambient temperature](image2)
Traditionally the demand in Vietnam is restricted during the evening hours, mostly for lighting. With socio-economic improvement, electricity demand is also increasing, especially in summer for cooling purposes. However, since ceiling fans and air conditioners are generally not operated in the winter, the winter load is typically 60 to 70 percent less than the summer load. The peak load of the system with a household considered as 2.4 kW in the hot season and 1.5 in the cold season and daily energy demand about 11.27 kWh/day.

![Image](image1.png)

*Figure 4.11. Individual 12 months electrical load profile*

4.3.2. Prediction output

Figure 4.12 displays a typical daily power output in kW of the PV modules in the simulation scenario correlated to hours of a day over a period of 12 months. It is indicated the output of power during the day steadily varies and reaches its maximum in the middle of a day. Due to seasonal variations, solar power output begins decreasing during the month of June, July, August, September and early October. Figure 4.13 illustrates that the PV output can almost support enough to the demand in general.

![Image](image2.png)

*Figure 4.12. Solar power output over a year*
As the concept of microgrid is becoming more pervasive, a mixed-power system makes the best use of the different types of local generators. Since the electricity supply and demand is not always balanced at every instantaneous time. It tends to fluctuate depending on the time of the day and the time of a year. More specifically, solar energy depends on the physical locations and the weather patterns. The energy storages implemented in microgrid need to be able to store up sufficient electrical energy at low electricity consumption and provide the required power back into the power system when demand increases. In this case, the storage devices are represented by batteries.

The daily profiles of the excess electrical production over a sample period of one month are shown in the Figure 4.14. The battery state-of-charge is affected by power output fluctuation. The storage device provides bursts of power as a generator essentially when the load increases sharply at peak load period, while it absorbs the excessive energy at low load period. The daily profiles of battery state-of-charge in the Figure 4.15 show high correlations with the excess electrical energy. In the summer period, consumer demand goes higher, and the battery bank needs to discharge harder than in the winter, which means the SOC meets the lower limit more frequently in summer than in winter. It is also vital that the microgrid needs to set up the lower limit SOC of the battery at 35 to 40 percent to protect them from over discharging.

![Figure 4.13. Electricity produces by PV and household load](image)

![Figure 4.14. Load power vs SOC of batteries](image)
Figure 4.15. SOC of battery over a year

Figure 4.16. Electricity produced by generator and household load

Figure 4.16 shows the gasoline genset's daily power output over a given year compared to the total AC primary load. With the load following dispatch regimes, the output power doesn't meet with the load consumption since it will kick on only when the state of charge of the battery is low (35 percent) or when the load goes high. Usually, the operation frequency of the generator is higher in summer than in the winter. In addition, the Figure 4.17 shows that in a day, the gasoline generator might have produced 5.7 kWh, mostly when there is no sunlight for PV. Early in the evening, the power consumption goes up, and the generator must work harder to do both charging the battery bank and supporting the load.

Figure 4.17. Generator output power over a year

Figure 4.18. Gasoline consumption over a year
The total fuel used for generator operation is indicated in the Figure 4.18. According to this DMap, it usually takes four liters of gasoline in per day, mainly for charging the battery bank. After 6 p.m., the load goes up and the generator needs to increase the output power so it needs more fuel. The fuel needed for the daytime can be as much as six liters per day.

In summary, the configuration considered with the capacity of 2.25 kW of PV and 3.4 kW gasoline generator produced 3,239 kWh electricity and 2,079 kWh electricity by PV and generator respectively. Among them, almost 61 percent of electricity produced by PV, and 39 percent of electricity produced by the generator as presented in the Figure 4.18. The PV module with a capacity factor 16.4 percent and produces a maximum 1.95 kW, with an average of 8.88 kWh per day. PV modules operate 4322 hours per year at a maximum of 78.9 percent PV penetration into the system. On the other hand, the generator has the capacity factor of 7.4 percent, which produces 2,078 kW/year with the maximum output power 2.32 kW. The total fuel consumption in one year is 2,240 liters (594 gallons).

With the same weather conditions and load profile as the previous simulation, if the PV size increases to 3.25 kW and two more batteries are added to the bank (60V), the new system has much better results: the contribution of PV gains to 84 percent while the operation time of the generator decreases dramatically to only 16 percent.

Figure 4.18. Electric summary of the experimental test bench (2.25kW PV, 48V battery)

Figure 4.19. Electric summary of an extended test bench (3.25kW PV, 60V battery)
5. Conclusion

The applied project has the objective to answer the research question of how a typical microgrid works in different conditions. In order to answer this question, an experimental microgrid model, which has a gasoline generator, a PV array model, a battery bank, and inverter system models were developed and simulated on a real-time platform was built in Arizona State University - Photovoltaic Reliability Laboratory (ASU-PRL). The performance data from the test bench was validated with the output results generated by HOMER Pro software to simulate the conditions of solar irradiance and ambient temperature using data provided by the local weather station. After validation, the prediction of the microgrid’s performance in Vietnam’s weather conditions is demonstrating for the implementation process in the future.

In the validation process, HOMER Pro has shown its reliability in indicating the output results that are close to the experimentation data from the microgrid and the microgrid’s performance is also observed as expected from the calculations of the load in the microgrid by the software. The comparison concerning standard control logic has been provided. Results obtained show how the microgrid’s components, when properly managed, can actively interact with each other. This validation has proved that this simulation model software can be implemented in different countries to increase the number of people using renewable energy in places that have solar energy’s potential.

The validated configuration and design was used to analyze the potential to introduce energy access from locally available stand-alone PV system integrated scheme for the single-family home in Vietnam. With the origin configuration with 2.25kW PV modules, 46V DC battery bank, 3.2kW gasoline generator; the microgrid produces 3,239kWh/year of renewable energy, and covers 61 percent of total energy. During daytime, the system offers 100 percent of renewable power generation and consumption. The generator supports 2,078kW/year, mainly for charging the battery bank to meet the peak load in the summer. The total fuel consumed by the generator in one year is 2,240 liters (594 gallons).

Studied an extension configuration, when increasing the PV size to 3.25kW and the battery bank is 60V DC, the system produces and storages more energy. The new system offers about 84 percent of the renewable fraction. The generator operating status is also lower and produces less power to the system. The system, hence, becomes almost zero CO₂ emission. In both cases, there is a small amount of excess energy, which is roughly 15 percent. This energy can be used if the model is multi-single families.
6. Recommendation

In the modern power system, the number of distributed sources increases simultaneously with the complexity of the system, but the performance of the system is always complemented by the energy management system. It is essential to study the reliability and stability of these systems while the distributed sources in power system enhance flexibility in operation. Further research and analysis can be conducted to study the results of replacing the gasoline/diesel generator with the biomass-fueled generator. Since Vietnam is an agricultural country, the biomass potential is very high, and this model can also be implemented there.

Using a simple microgrid model based purely on DC power system modeling and configuration, including solar and wind turbines, DC loads can be constructed to analyze the performance and reliability. While a new configuration of DC microgrid is less used by electronic devices, DC network helps to decrease the loss of energy, which increases the efficiency since the inverter is no longer appear. The system model integrated with renewable sources as intermittent from DC to DC; modeling and simulation will also consider both dynamic load and dynamic pricing. The new configuration system will be modeling with the same strategy as load flow supply to meet the load of the end users.

The research can also focus on the planning of poly-generation system and storage system for a community. Moreover, the objective function could be modified to ensure maximization of profits where a grid-connected microgrid is analyzed with the possibility of providing energy and auxiliary services; buying or selling energy from the utility grid; and including variable energy prices and feed-in-tariffs. If the studied of microgrid includes the means to power electric vehicles, the designed energy management system could be used for smart charging of EVs.
References


SIMULATE AND EXPERIMENTALLY EVALUATE A SPECIFIC PV-BASED MICROGRID SYSTEM FOR REPLICATION IN VIETNAM

Faculty Advisor: Dr. Govindasamy Tamizhmani
Industrial Advisor: Dr. Devarajan Srinivasan
PSM Student: Tri Phuoc Le

Problem Statement

• A microgrid, as an important component of a smart grid, has played an increasingly important role in long-term smart grid planning

• Vietnam’s government aims to investigate optimal system design for types of microgrids in particular scenarios,

• HOMER is a modeling approach for most system components to simulate, optimize and predict the performance of the system before construction.

⇒ Evaluate an existing microgrid PV system at ASU-PRL to replicate it in Vietnam using a validated HOMER Pro simulation model.

Source: The Green Optimistic
Microgrid Definition

“A group of distributed energy resources and energy storage devices. All of these parts are controlled by energy management and coordination control, provide the power that meets the demand in various sizes of the load.” – Department of Energy

A microgrid can be considered as a smaller version of the traditional electric grids. The difference is the distance between the energy resources to the end user is shorter.

- Application: Military, villages, communities, industrial buildings, industrial centers, industrial parks, mines, hospitals, fire stations, etc.
The Microgrid Categories

Size of the PV array (kWc)

- Grid-connected PV systems
- Large hybrid systems (M W range)
- Medium-size hybrid systems for a village with productive activities (250 kW - 700 kW)
- Small hybrid systems for a remote village with very few activities (40 kW - 250 kW)
- Micro hybrid systems for one client (typically an institution) (10 kW - 40 kW)
- PV / diesel systems without storage

The microgrid mainly operates in two modes: On-grid mode and off-grid mode. In a large scale, most of the microgrid operation is the combination of both modes.

Microgrid Operation

The microgrid mainly operates in two modes: On-grid mode and off-grid mode. In a large scale, most of the microgrid operation is the combination of both modes.

Strategies:
- Economic
- Technical
- Environmental
- Combining
The energy management system (EMS) is used to control the energy consumption and make sure that the distributed energy resources produce enough power to meet the demand. The EMS can also optimize the power flow in the system so that the consumer can save money in peak hour by discharging batteries and charging it in the low-peak hours. The goal is increasing the reliability and stable performance of the microgrid to ensure the storage devices’s safety and best utilization of energy resources.
What does management system do?

- Monitoring
  - Energy usage
  - Power quality
  - Equipment status

- Control
  - Equipment operation
  - Equipment set points
  - Automated control features
  - Firmware updates

Microgrid Model in ASU-PRL

- 250W PV modules
- 2.25kW total (3 strings of 3) in series
- 3.6kW Inverter/Charger
- 48V battery bank (6V each) in series
- 3kW Inverter Generator (gasoline)
- 30A AC/120V load panel
Complete Microgrid System in ASU-PRL

Figure 1. 2.25 kW PV system
Figure 2. 48V battery bank connected to inverter
Figure 3. FLEXpower ONE FXR connected to combiner box
Figure 4. PV combiner box
Figure 5. Batteries and its bank

Simulation Program

• HOMER Pro is software developed by HOMER Energy, in the US and remains a global standard for microgrid software based on user needs in designing, deploying, and replicating microgrids using renewable energies.

• HOMER Pro has optimization, and sensitivity analysis algorithms function, allows people to evaluate different economic and technical aspects of a large number of technology options

• Can help determine the potential impact of uncertain factors such as fuel prices or solar on a given system

• Requirement: Real-time weather data, load profile, specification of components, prices…
Results and discussion:
Part 1. Simulation program validation

Light Bulb: 150W x 2
Fan: 40W
AC: 1.2kW
**Input Parameters**

**Load power profile**

- **Power (kW)**
  - 0.0
  - 0.1
  - 0.2
  - 0.3
  - 0.4
  - 0.5
  - 0.6
  - 0.7
  - 0.8
  - 0.9
  - 1.0
  - 1.1
- **Time (hours)**
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
  - 40
  - 45
  - 50
  - 55
  - 60
  - 65
  - 70
  - 75

**Legend**
- Light bulbs & Fan
- Air conditioner
- Total load

---

**Solar Irradiance and Ambient temperature profile**

- **Irradiance (W/m²)**
  - 0
  - 500
  - 1000
  - 1500
- **Temperature (°C)**
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60
- **Time (hours)**
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
  - 40
  - 45
  - 50
  - 55
  - 60
  - 65
  - 70

**Legend**
- Solar Irradiance
- Ambient Temperature
Validation Results

Photovoltaic Power Produced

Inverter Output Power
Validation Results

Battery Bank Input Power

- Actual
- Simulation

Validation Results

Battery input power breakdown

- Total power
- PV charging
- Gen charging
Summary

- For the validation input data, the simulation output is similar when compared to the experimentation data.
- The HOME Pro program has been validated and can be used to predict the system performance in the next section.
PART 2. SYSTEM PREDICTION

The daily solar energy potential in Vietnam is characteristically below 4 kWh/m² in the North to above 5 kWh/m² from central to Southern part.

- Total of sunlight hours are 1,600 - 2,700 hours/year.
- Regions with highest potential: Southern, and Central Vietnam.

Source: SOLARGIS

Source: VIETNAM BRIEFING
Input Parameters

Average monthly solar irradiance at Ho Chi Minh City

Average monthly ambient temperature at Ho Chi Minh City

Load profile for 12 months in a single-family home
Prediction output

PV output vs Load consumption

SOC vs Load Consumption
Prediction output

![Graph showing power output over time]

Generator output vs Load consumption

System Summary

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<th>Production</th>
<th>kWh/yr</th>
<th>%</th>
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<tr>
<td>Champion 3400-Watt Gas Inverter</td>
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<td>Total</td>
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<tr>
<td>DC Primary Load</td>
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<td>Capacity Shortage</td>
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</table>

Monthly Average Electric Production

Electric summary of the experimental test bench (2.25kW PV, 48V battery)
**CONCLUSIONS**

For a small family in the South side of Vietnam using a 2.25kW PV System:

- Total renewable energy produce in 1 year: 3,239kWh, the system offers about 61% of renewable energy
- During daytime, 100% power generated from PV is consumed.
- The systems excess electricity is about 600 kWh per year. The surplus power can be delivered to the other houses if the microgrid connects multiple homes or a community based water pump for irrigation for development purposes

**FUTURE RESEARCH**

- Research on grid-tied microgrid systems using PV and generator as an emergency back-up energy source.
- Develop the microgrid system from single-family to multi-family.
- Change the generator from gasoline to biomass.
THANK YOU FOR YOUR ATTENTION!

System Configuration

ASU-FRL 3.6 kW Microgrid Design Plan