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Simulation Platform for Supply Deficient Microgrids

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Abstract--- **Supply deficiency is a common problem in the Philippines especially in places where connecting to the main grid is not possible, and implementing a standalone microgrid is the proposed solution. However, due to the intermittent output of some renewable distributed generations (DG), it is desired to have a modeling tool that can forecast possible outcomes and effects of these distributed resources to the network. This paper presents a software tool that can perform a one-year simulation of a microgrid with any combination of solar PV, wind, run-of-river hydropower, biomass, diesel or gasoline generator, and battery storage. It can compute and display hourly, daily, monthly-average and monthly-total data of energy supplied by the DG, energy consumed by the load, expected frequency and duration of supply interruptions, and expected energy not supplied. In essence, the tool can help in observing patterns and determining the effects of a DG mix with a given load demand which can be used for designing supply deficient microgrids.**

I. INTRODUCTION

Distributed generations (DG) are now commonly used due to its potential to make a system more efficient and reliable. They are small-scale power generation sources connected directly to the distribution network [1][2]. They have several advantages compared to the centralized models of power generation like the lowered power generation and transmission costs, smaller electrical losses and improved system reliability.

Existing DGs include wind turbines, photovoltaic cells, fuel cells, microturbines, hydropower, diesel engines, gas turbines, biomass generator and combined heat and power (CHP) plants. Diesel engines are usually installed to serve as backup controllable supply should the other renewable energies fail to meet the demand. Batteries, on the other hand, are installed as energy storage in the case of energy surplus.

A localized cluster of these DG, loads and energy storage operating as a single controllable system is called a microgrid [2]. Microgrid can operate in both grid-connected mode and islanded mode. Effect on power quality and stability, additional power balance control policy, and connectivity issues are some of the complications introduced by DG in an isolated microgrid [2], [6], [7].

The Philippines has a big potential for these renewable energy sources. In 2015, ten percent of the electricity requirement of the country is supplied by hydropower generators [4]. For solar technologies, according to a study of DOE Philippines and US-NREL Climatological Solar Radiation (CSR), the annual potential average in the country is 5.1 kWh/ m^2 /day [3]. For wind turbines, according to Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), the country has an average of 31 W/ m 2 of wind power density [3].

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In 1999, the Philippine government started an electrification project to improve quality of life and to provide greater access to basic services and better infrastructures for rural development. However, one of the challenges is to electrify and connect the more remote and disperse villages since it would require more resources, time and effort. For these remote areas, they implement an off-grid or decentralized electrification with battery charging Stations or solar home system, micro-hydro and wind turbine energy systems, depending on the area's feasibility [8]. According to a report of IRENA, there are about 375 MW of installed diesel mini-grids in the country, majority of which are have an operating capacity of below 500kW. Also, majority of these areas are supplied between 6-8 hours per day only. Other areas are supplied between 10-24 hours per day [9].

Due to these issues of supply deficiency, implementing a microgrid system is not a simple task and needs to be planned properly. A simulation tool is necessary in order to achieve an effective microgrid system, especially for supply deficient networks. There are already existing studies and platforms conducting a microgrid simulation. Two of the commonly known available simulation software available in the market are Hybrid Optimization of Multiple Energy Resources (HOMER) [10] and ETAP [11]. Both software can model any hybrid renewable system and optimize which set of combination is preferable while taking into account the cost of the system.

Pochacker et al [12] developed an open-source software, RAPSim, that can simulate the total output power of each DG and do a load flow analysis. However, they only have models for solar panels and wind turbines. Distributed Energy Resources Customer Adoption Model (DER-CAM), developed by the Microgrid Group at Berkeley Lab, focuses on minimizing the cost of operating on-site generation and CHP systems by computing the best combination and operation of the DG for the grid. It outputs the optimal selection of technologies that should be adopted and details how they should be operated based on the specified inputs [13].

This paper focuses in building a software tool that can simulate a standalone microgrid with any DG combination as its energy sources which include solar panels, wind turbines, hydropower generator, biomass power generator, diesel generator and battery storage for backup. The program is able to compare the system’s load demand with the energy supply, forecast how often and how long an interruption might occur, compute the energy deficit of the system and compute each DGs energy output for a year. This is useful to gather information about supply deficient microgrids.

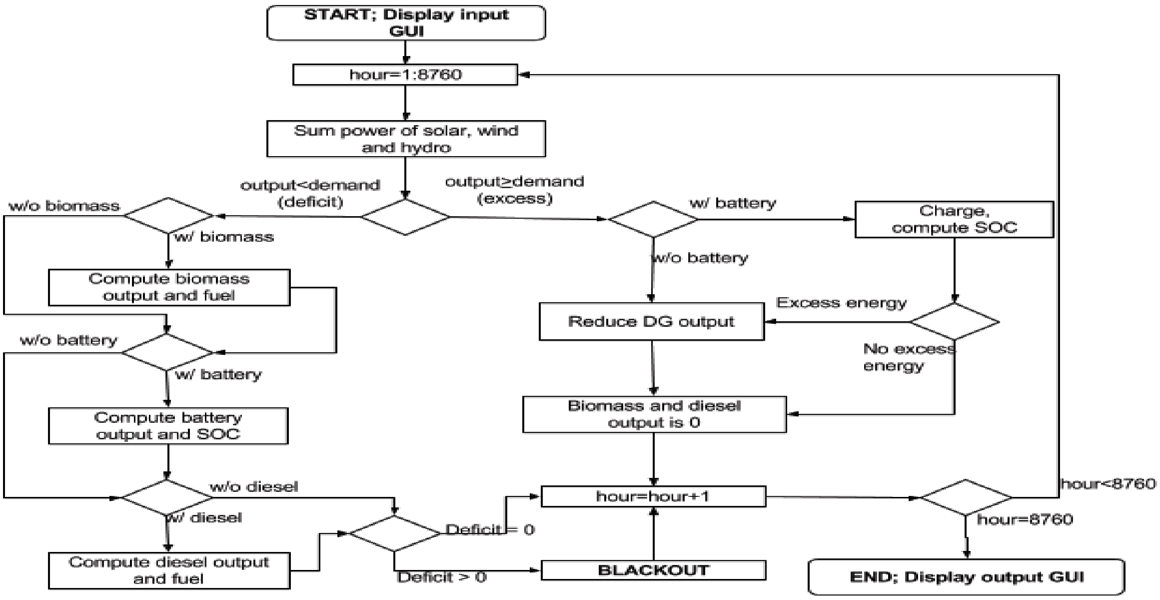

Figure 1. Program Flowchart

II. Simulation Tool

This section describes the different mathematical models used to represent and implement the microgrid components and its energy output.

A. Supply and Demand Balancing

Fig. 1 shows the overview of the program algorithm for the one-year simulation. At the start, the user is asked to input the load profile and the DG mix and its characteristics in the GUI shown in Fig. 2. If a DG is not chosen, its automatic power output is 0 kW.

The program runs 8760 iterations corresponding to the number of hours in a year. The program first sums the output power of the solar panels, wind turbine and hydropower. If there is a deficit from the supply of the solar, wind and hydro, the biomass is the first to supply energy, if it is chosen. If there is still a deficit and a battery is connected, it discharges power within the limits of the stored capacity. If there is still a deficit, the diesel turns on and supply the lacking power with respect to its rated output power. If by the end of the DG output computation and there is still an energy deficit, blackout will occur.

If a battery is part of the system and there is an excess energy, the battery can store it as long as it follows the transition diagram of Fig. 3. If there is still an excess and the user chooses to have a thermal damp load, maximum of 5% of

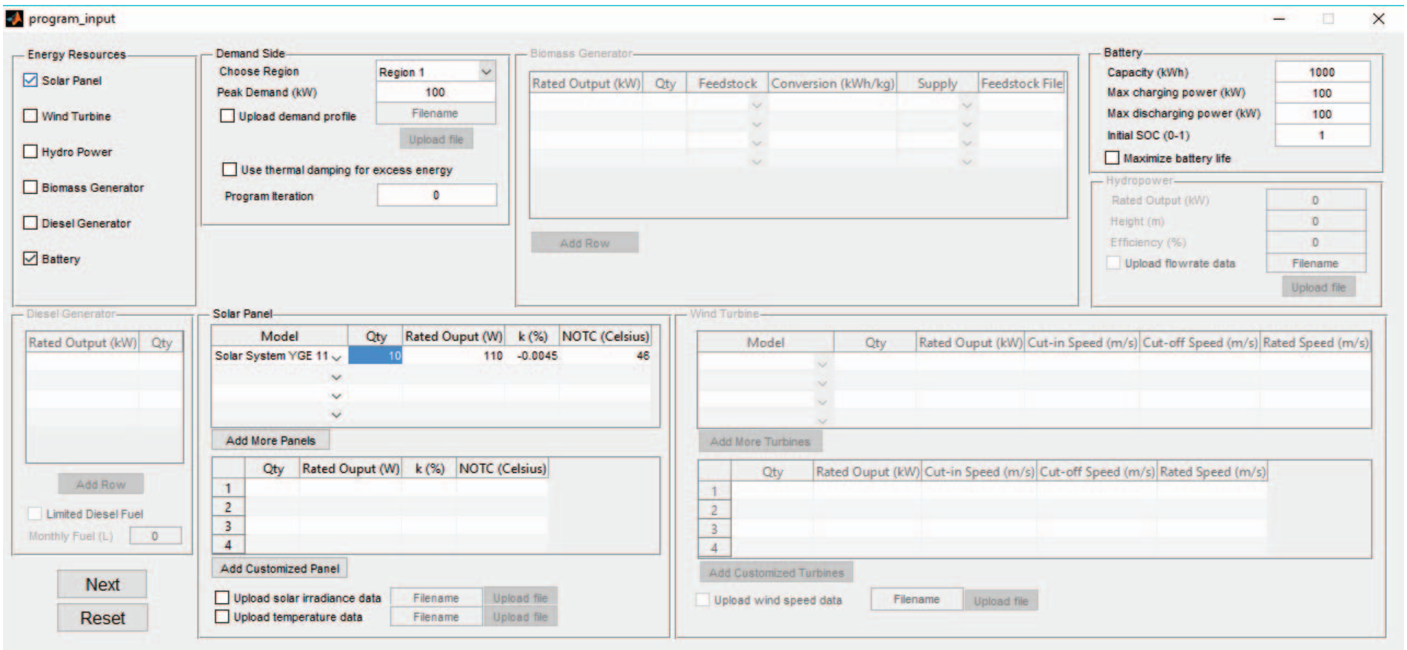

Figure 2. Program Input Page

the peak demand is allowed to be deducted from the excess. If that is not enough, the solar, wind and hydro's output is reduced to match the demand.

The output GUI of the whole program can generate plots for the different power output, display the total energy demand, interruptions and duration.

B. Modeling of Microgrid Components

1) Photovoltaic System

Solar panel energy output is highly dependent on weather conditions, light intensity, position of the sun and altitude. Its output power is computed using (1) [6].

$$P_{PV} = P_{STC}\frac{G_c}{G_{STC}}\left(1 + k(T_c - T_{STC})\right) \quad (1)$$

where P_{PV} – solar panel's power output (W)

P_{STC} – power output at standard testing condition (W)

G_c – irradiance of operating point (W/m^2)

G_{STC} – irradiance at standard testing conditions (1000 W/m^2)

k – power temperature coefficient

T_c – temperature of operating point (°C)

T_{STC} – temperature at standard testing condition (25°C)

The P_{STC}, G_{STC}, T_{STC} and k are all characteristics of a solar panel while the G_c and T_c are dependent on the environment. The default data used for G_c is taken from NREL website [21] while T_c is computed using (2)

$$T_c = T_{air} + \frac{NOCT-20}{80}G_c \quad (2)$$

Where NOCT – nominal operating cell temperature

T_{air} – ambient temperature (°C)

2) Wind Turbines

Equation (3) shows that wind power is related to the cube of the wind speeds [15]. The default wind speed data for a year is taken from NREL's website [19].

$$P_{WT} = \begin{cases} 0 & , V_w < v_c, V_w > v_f \\ P_r\left(\dfrac{V_w - v_c}{v_r - v_c}\right)^3 & , v_c \le V_w < v_r \\ P_r & , v_r \le V_w < v_f \end{cases} \quad (3)$$

where P_{WT} – wind turbine's power output (kW)

P_r – rated power output (kW)

V_w – wind speed (m/s)

v_c – cut-in wind speed (m/s)

v_r – rated wind speed (m/s)

v_f – cutout wind speed (m/s)

3) Hydro Power

The main factors that affect the generated power of a hydropower system are the water's flowrate and the height of the head or intake of the system. This is described by (4) [15]

$$P_h = \frac{\eta\rho g Q H}{1000} \quad (4)$$

where P_h - hydropower's power output

η – hydraulic efficiency of the turbine

ρ – water density (1000 kg/m^3)

g – gravitational acceleration (9.81 m/s^2)

Q – volume flowrate (m^3/s)

H – vertical height difference between the head and the powerhouse (m)

The efficiency and height of the hydropower are taken from the user's input while the default volume flowrate is taken from [21].

4) Biomass Generator

Biomass generator power is derived from the converted energy of feedstock like wood, agricultural waste, etc. Equation 5 shows how biomass' output is computed. Table I shows the conversion factor of the feedstocks used in the tool.

$$P_{bio} = f_{bio}c_f \quad (5)$$

where P_{bio} – biomass's power output (kW)

f_{bio} – fuel feedstock (kg)

C_f – conversion factor (kWh/kg)

Table I Energy Conversion of Different Feedstock

Feedstock	Energy Output (kWh/kg)
Wood	4.5
Dung	3
Straw	4
Charcoal	7

5) Diesel Generator

In this study, diesel generator serves as a backup source. Its power output is limited by its power rating and the deficit from the other sources. Its efficiency in terms of fuel consumption varies with its operation. The conversion table in [16] was used to compute the relationship between a generator size and its diesel fuel consumption based on its operation.

6) Battery

Due to the unpredictable output of renewable energy resources, a battery energy storage system may be implemented in a microgrid to compensate the problem. The state transition diagram shown in Fig. 3 is a modified version of the diagram used in [17]. The minimum state of charge (SOC) for maximizing the battery life is 80%, 30% otherwise. Depending on the output power of the other DGs, it may charge or discharge. Equation 6 shows how to compute for the SOC.

$$SOC_{t+\Delta t} = SOC_t - P_{bat-t}\frac{\Delta t}{C_{bat}} \quad (6)$$

where P_{bat-t} – power output of the battery. Positive when discharging, negative when charging (kW)

C_{bat} – battery capacity (kWh)

t – time (hour)

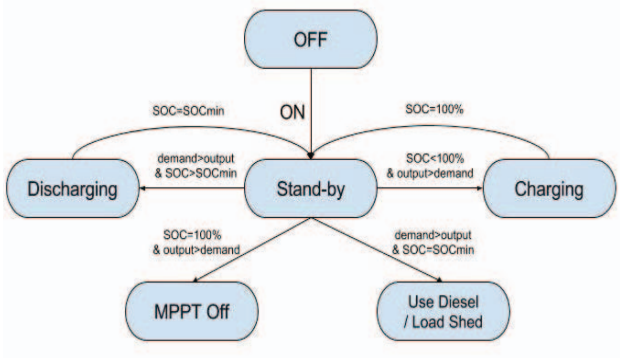

Figure 3. Battery state transition diagram

Table II Results of Case 1 (varying solar rated output)

Solar Rated Output (KW)	no. of hours with inadequate supply	Total Solar Output (MWh)	Total Diesel Output (MWh)	Total Fuel Consumed (L)	Deficit (MWh)
100	5168.2	263.5 (47.9%)	286.1 (52.1%)	97352.2	160.3
110	5088.3	270.2 (49.1%)	280.4 (50.9%)	95399	158.7
120	5024.3	275.9 (50.0%)	275.4 (50.0%)	93653.2	157.0
130	4983	281.2 (50.9%)	271.3 (49.1%)	92149.7	157.5
140	4960.8	286.3 (51.7%)	267.9 (48.3%)	90988.7	156.3
150	4932.7	290.0 (52.3%)	264.6 (47.7%)	89894.4	155.3
160	4915.5	293.7 (52.9)	261.7 (47.1%)	88943.8	154.8
170	4904.6	296.3 (53.3%)	259.2 (46.7%)	88085.2	153.9

When the SOC of the battery reaches SOC_{min} during the discharging state, the battery will shift to standby state. However, when the SOC reaches 100% during the charging state, the battery will shift to standby state and the other DG's output is reduced to match the load demand. The battery is designed to charge or discharge at a constant rate.

C. Meteorological and Load Profile Data

The temperature and wind speed data in the Philippines used in the case studies came from NREL Wind Prospector [19] while the solar irradiance data of 2015 came from NREL MIDC Solpos [20]. There are eighteen sets of data for these three properties where each set corresponds to a region in the Philippines. A user may choose from which region the data to be used. For the case studies, Region I data was used.

This study was not able to acquire Philippine-based data for annual flowrate. Thus, the default flowrate was randomly taken from the USGS water data accessible through their website [21].

At the beginning of the simulation, data on load profile, solar irradiance, temperature, wind speed, flowrate and feedstock are randomized by a value between ±5% using a 3-state Markov chain as shown in Fig 4. The initial data, corresponding to the first hour of the year, is at state B, meaning it would be multiplied by a random number from -2% to +2%. The next data would have a 50% probability of being multiplied by the same range and 25% probability of being multiplied by the range in state A or C. This type of randomization is used to capture the variability of the data.

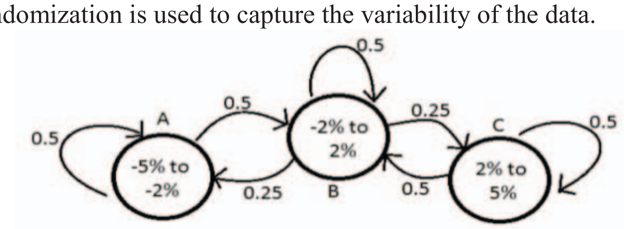

Figure 4. States of the implemented Markov chain for randomizing the data input

D. Data Input

The simulation tool is implemented using Matlab. Upon running the source code, the input GUI will be displayed. Fig. 2 shows the input GUI where the user may enter the data to be simulated. The user may opt to choose the combination of DGs to be simulated. It has different panels dedicated for each DG. The panels for each DG are disabled by default and will only be enabled if the DG is selected in the *Energy Resources* panel. Because the tool is designed specifically for the Philippines, the user may choose the region where the microgrid will be simulated. It has an embedded meteorological data for different regions of the Philippines, as mentioned in the previous section. The user will enter the peak demand and a dummy load curve will be used to model the load profile for the entire year. The user may upload a different load profile, if desired. Under the *Hydropower* panel, the user may enter the rated output, height and the efficiency to be used in the model of the hydro power plant. Only one hydropower plant is assumed to be installed per simulation. A dummy flowrate data will be used if no flowrate data is uploaded. Under the *Biomass Generator* panel, the user will enter the rated output and the quantity of the generator to be installed. The type of feedstock to be used has its own conversion factor that will be used for the model of the biomass generator. The feedstock may be assumed to be unlimited or limited. If limited, a feedstock profile must be uploaded. The user may install different capacities of biomass generator at the same time. Under the *Battery* panel, the user will enter the capacity, max charging power, max discharging power and initial SOC of the battery. The minimum SOC of the battery is designed to be 30% if the maximize battery life is unchecked, otherwise 80%. Like the hydropower plant, only one battery storage is assumed to be installed per simulation. The diesel generator is designed similar to the biomass generator but less complicated. Under its panel, the user will enter the capacity and the quantity of the diesel generator to be installed. Under the *Solar* panel, the user may choose among the models included in the simulator. These models have their own specifications that will be used in the model of the solar PV. The user may still add a customized panel if the desired specification is not among the panels included. The solar irradiance and temperature data of the region selected earlier will be used if no other data is uploaded. The *Wind Turbine* panel is similar to the Solar panel where the user will select a model of wind turbine to be used, add customized panels and upload wind speed data.

III. CASE STUDIES

The following case studies are presented to demonstrate the capabilities of the simulator. It gives the reader an idea how the simulator is working and what results can be generated.

A. Case 1 – Varying Solar Rated Output

For this case, the system peak demand is 100kW with a 50kW diesel generator and solar PV. The total rated output power of the solar PV was varied to see its effect to the energy output of the system.

Table II shows the results for this case. By adding solar panels, the number of interruptions experienced by the system is reduced as shown in Fig. 5. Fig. 6 shows that as the capacity of the PV increases, the energy output of the diesel reduces which also decreases the fuel consumption of the system.

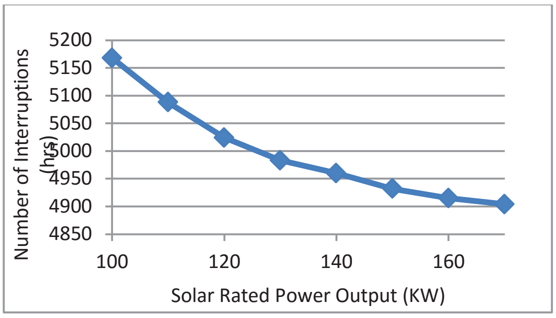

Figure 5. Plot of varying rated solar output versus number of interruptions

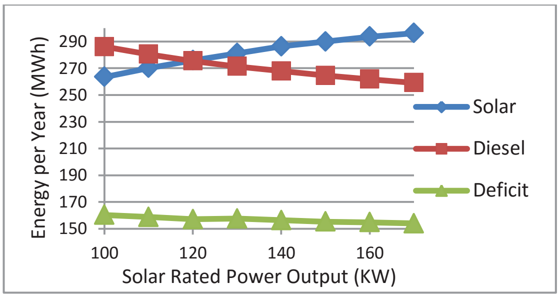

Figure 6. Plot of varying rated solar output versus total energy output and system deficit

B. Case 2 – Varying Battery Capacity

In addition to the components from Case 1, this system included battery storage. The system peak demand is 100kW with a 100kW diesel generator and a 50kW solar rated power output. The battery capacity was varied to see its effect on the system. Its effect is shown in Table III. By adding battery storage to the system, the solar output of the system improved because the excess energy generated by the solar PVs during peak hours was stored in the battery and was used when there was energy deficit. The number of interruptions decreased by improving the capacity of the battery from 100KWh to 250KWh, as show in Fig. 7. However, after reaching a certain capacity of battery storage, further increase in capacity showed no improvement on the solar output as shown in Fig. 8. It can be concluded that there is an optimum solar rated power output for a specific of battery capacity.

C. Case 3 – Limited Monthly Diesel Fuel

For this case, the 50kW diesel generator was assumed to have a limited monthly fuel supply. The diesel generator, combined with 100kW total solar rated power output and 500kWh battery, supplies the microgrid with a peak demand of 100kW.

Table IV shows the results for Case 3. By increasing the fuel available per month gradually, it can be observed that the number of interruptions decreased linearly as shown in Fig. 9. However, after a certain amount of fuel was reach, the number of interruptions remains constant. This is because the rated power output of the diesel generator can be fully used with that amount of fuel. Fig. 10 shows that the solar output is independent of the fuel availability.

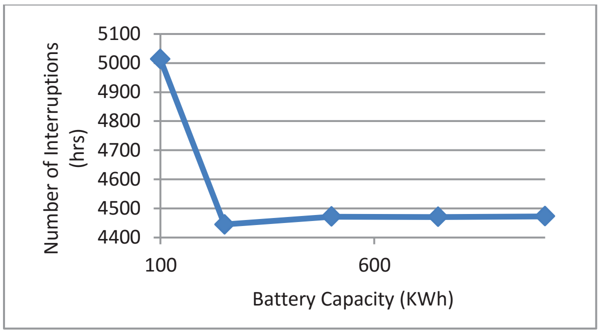

Figure 7. Plot of varying battery capacity versus number of interruptions

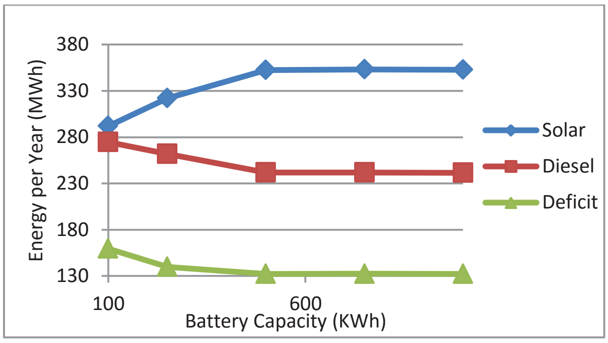

Figure 8. Plot of varying battery capacity versus total energy output and system deficit

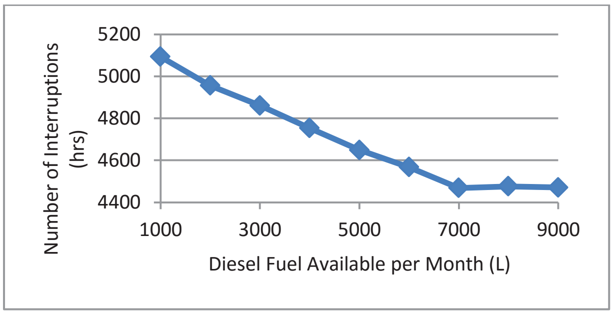

Figure 9. Plot of varying monthly available diesel fuel versus number of interruptions

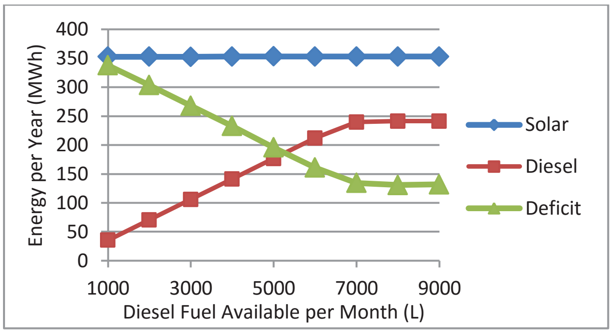

Figure 10. Plot of varying monthly available diesel fuel versus total energy output and system deficit

Table III. Results of Case 2 (varying the battery capacity)

Battery Capacity (KWh)/ Max Charge/Min Charge	no. of hours with inadequate supply	Total Solar Output (MWh)	Total Diesel Output (MWh)	Total Fuel Consumed (L)	Deficit (MWh)
100/25/25	5013	292.0 (51.5%)	274.7 (48.5%)	93543.0	159.6
250/50/50	4445	322.1 (55.1%)	262.0 (44.9%)	89255.9	139.8
500/100/100	4472	352.6 (59.3%)	241.8 (40.7%)	82091.2	132.3
750/200/200	4471	353.2 (59.4%)	241.8 (40.6%)	82053.5	132.5
1000/250/250	4473	352.9 (59.4%)	241.5 (40.6%)	81969.6	132.39

Table IV. Results of Case 3 (varying the monthly available diesel fuel)

Fuel Available per Month (L)	no. of hours with inadequate supply	Total Solar Output (MWh)	Total Diesel Output (MWh)	Total Fuel Consumed (L)	Deficit (MWh)
1000	5093	352.9 (90.9%)	35.3 (9.1%)	12000	337.8
2000	4955.7	352.9 (83.3%)	70.7 (16.7%)	24000	303.5
3000	4861	352.6 (76.9%)	106.0 (23.1%)	36000	267.8
4000	4753.3	353.0 (71.4%)	141.4 (28.6%)	48000	232.7
5000	4649	353.3 (66.7%)	176.7 (33.3%)	60000	195.8
6000	4567.7	352.9 (62.5%)	212.1 (37.5%)	72000	161.0
7000	4468.3	353.2 (59.6%)	239.6 (40.4%)	81328.7	134.5
8000	4475.8	353.1 (59.4%)	241.5 (40.6%)	81970.6	130.6
9000	4470.5	352.9 (59.4%)	241.5 (40.6%)	81955.7	131.8

IV. CONCLUSION

This paper describes a tool that can simulate the operation of energy deficient microgrids. Aside from computing the energy output of the generation assets and fuel requirements to satisfy a given demand profile, it can also predict the natural consequences of supply deficient microgrids: the expected frequency and duration of interruptions, and the amount of energy not served.

The case studies have demonstrated the usefulness of having such a software tool. Various information on system interruption was gathered like the energy deficit and number of incidences. The effects of varying the generation and battery sizes and fuel availability were shown through a sensitivity analysis.

Lastly, the feature where the user can upload a separate file for the input data like solar irradiance, temperature, wind speed, flowrate, and fuel availability is convenient in modeling a more specific network.

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