*Article*

# Advances in Energy Hybridization for Resilient Supply: A Sustainable Approach to the Growing Middle East Demand

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**Abstract:** Energy poverty, defined as a lack of access to reliable electricity and reliance on traditional biomass resources for cooking, affects over a billion people daily. The World Health Organization estimates that household air pollution from inefficient stoves causes more premature deaths than malaria, tuberculosis, and HIV/AIDS). Increasing demand for energy has led to dramatic increases in carbon emissions. The need for reliable electricity and limiting carbon emissions drives research on Resilient Hybrid Energy Systems (RHES) that provide low-carbon energy through combined wind, solar, and biomass energy with traditional fossil energy, increasing production efficiency and reliability, and reducing generating costs and carbon emissions. Microgrids have been shown as an efficient means of implementing RHES, with some focused mainly on reducing the environmental impact of electric power generation. The technical challenges of designing, implementing and applying microgrids involve conducting a cradle-to-grave life cycle assessment (LCA) to evaluate these systems' environmental and economic performance under diverse operating conditions to evaluate resiliency. A sample RHES has been developed and used to demonstrate implementation in rural applications. This system can provide reliable electricity for heating, cooling, lighting, and pumping clean water. This paper's primary focus is the challenges of using resilient energy systems in the Middle East.

**Keywords:** Renewable Energy, Resilience, Hybrid Energy Systems, Life Cycle Analysis

## 1. Introduction

Energy poverty is defined as not having access to reliable electricity and reliance on traditional biomass resources for cooking [Tanaka et al., 2010, 8]. On a global scale, over 1.3 billion lack access to electricity (85% in rural areas), and approximately 2.8 billion people rely on traditional biomass for cooking [Tanaka et al., 2010, 9]. The World Health Organization estimates that household air pollution from inefficient stoves causes 4,000 premature deaths/day (greater than malaria, tuberculosis, and HIV/AIDS) [Tanaka et al.,

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2010, 7]. The need for reliable electricity and our need to limit carbon emissions drives research on Resilient Energy Systems that provide low-carbon electric power through combined wind, solar, and biomass energy and traditional gas-fired systems that increase production efficiency and resilience while reducing generating costs and carbon emissions. Hybrid Energy Systems that combine conventional with renewable energy sources can be designed to provide much-needed reliable electric power to rural areas using available energy resources. Microgrids have been implemented worldwide [Mahapatra et al., 2012; Akanksha and Kandpal, 2010; Del Rio and Burguillo, 2009] with the main focus on reducing environmental impacts [Cook, 2011]. The main technical challenges of designing, implementing, and applying microgrids have been studied by several others [Chowdhury et al., 2009; Lasseter et al., 2002; Hatziargyriou et al., 2007; Infield and Li, 2008; Lasseter and Paigi, 2004; IEEE; 2011]. The US Department of Energy demonstrated the positive economic impact microgrids could provide in rural regions [Melton and Jones, 2016]. Additional work has focused on analyzing microgrid performance and assessing their economic and environmental sustainability [Nagrapurka and Smith, 2019a; Nagrapurka and Smith, 2019b]. This work considered rural locations in the United States with different types and amounts of renewable and conventional energy. This work resulted in an optimized microgrid design for resilient operation and reduced the Levelized Cost of Electricity (LCOE) for each location. Microgrid resilience has been evaluated using a Life Cycle Assessment (LCA) (see Figure 1) using the GREET (**G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation)[1] software package developed by the US Department of Energy. This tool provided data for the microgrid to assess economic performance using wind and solar energy resources available in rural regions.

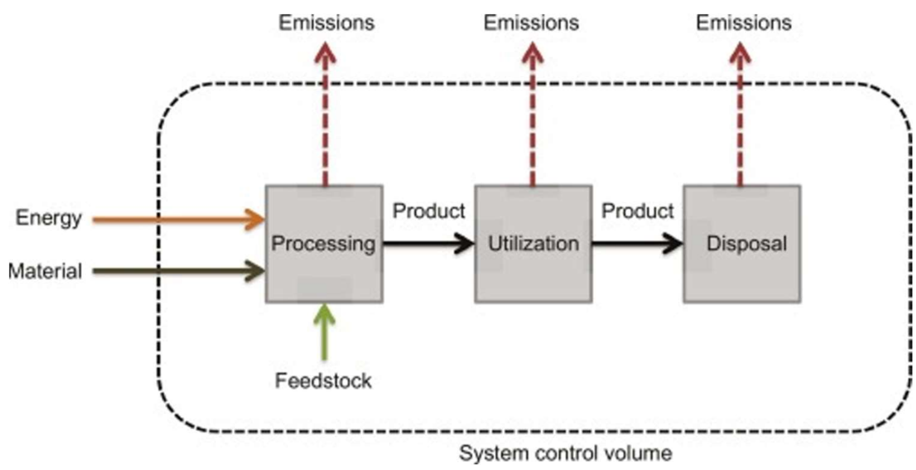


Figure 1 – GREET used to conduct Life Cycle Analysis [Lee et al., 2020, Figure 8.1]

The GREET software tool estimates energy use and emissions for vehicle/fuel systems. It has been used to conduct Life Cycle Analyses of electricity production to assess

[1] See https://greet.es.anl.gov/index.php

emissions during generation, transmission, and distribution, considering various renewable energy resources with their respective technologies and distribution to end-users. Wu et al. 2008 used GREET to assess life cycle energy and greenhouse gas emission from the production of corn-based butanol as a transportation fuel. Wang et al. 2011 studied the energy and greenhouse gas emission effects of corn and cellulosic ethanol using GREET. GREET was used to estimate energy and emissions at every stage in the LCA for the solar microgrid. Emissions data procured from GREET included concentrations of VOCs, carbon monoxide, carbon dioxide, nitrogen oxides, sulfur oxides, methane, and particulate matter. An economic analysis examined the net value of using solar microgrids versus other options for generating electricity in terms of the broader social net benefit of avoided carbon emissions from fossil-fired power plants. Issues such as the availability of other energy forms, including wind and biomass, and the scale size efficiencies of solar microgrids based on the number of homes included in the microgrid, were analyzed to estimate the optimal microgrid-based size hybrid energy system for geographically diverse locations.

Advanced design features considered in the present work included the evaluation of various energy storage technologies, the number of wind turbines and solar PV panels, and smart sensors for monitoring and controlling the microgrid. The LCA examined various configurations considering combinations of specific thermal + PV solar equipment with different battery backup systems and inverter/power management components. Ongoing research involves testing the S&T solar microgrid to optimize dynamic performance. Future work will expand the LCA to consider the full environmental and economic impact of energy/water uses and CO2 emissions associated with manufacturing, transportation, operation, and eventual disposal of all components in the microgrid.

## 2. Microgrid Energy Storage Cost Analysis

An existing microgrid system (see Figure 2) at the Missouri University of Science and Technology (S&T) combines photovoltaic and thermal solar energy with battery storage in rural Missouri. This system has been analyzed by Vikru et al., 2018 to identify the economic performance of the S&T microgrid. As shown in Figure 2, this microgrid includes four small homes equipped with photovoltaic and thermal solar equipment connected to a Li-ion battery backup system operated with smart power management [2]. Recent cost reduction in photovoltaic panels to generate electricity has made this design common. Because of the intermittency of both wind and solar energy, energy storage was also included in this analysis.

[2] For a description of the Solar Microgrid located at the Missouri University of Science and Technology, see https://cree.mst.edu/laboratories/

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- 4 solar houses (2002, 2005, 2007, 2009) connected to microgrid with EV charging station.
  - Individual solar inverters located in basement of each house
  - Each house connected to central microgrid (excess power generation stored/ redistributed as needed)

- Solar Village microgrid can be isolated (islanded) as needed.
- Technical information on existing assets following.

| | Brand | Type | Output |
|---|---|---|---|
| Battery Type | | LifePO4 | 65kW |
| Inverter | | Bi-Directional Integrated | 20kW |
| Switchgear | ELM Fieldsight | Integrated-Time of Use, Peak demand Shaving, Demand response | |

| Solar Village House | Solar Panels Generation Capacity | Inverter | Serial | AC Output |
|---|---|---|---|---|
| 2009 | 8 kW | Fronius IG Plus 7.5-1 | 20161335 | 7 kW |
| 2007 | 7 kW | Fronius IG Plus A 6.0-1 | 24261158 | 6 kW |
| 2002 | 5 kW | Fronius IG Plus A 5.0-1 | 24272088 | 5 kW |
| 2005 | 3 kW | Fronius IG Plus A3.0-1 UNI | 24262772 | 3 kW |
| EV Charging | | Millbank | | 9.6 kW |

Figure 2. Missouri University of Science and Technology Solar Village Microgrid

As shown in Figure 2, the S&T microgrid employs Lithium-Ion batteries for energy storage. Although lightweight, this battery is very expensive and difficult to maintain. For the present study, other types of energy storage devices were considered. Various mechanical equipment can also store energy, including flywheels which store energy by spinning a large disk with the angular momentum of the spinning flywheel converted into electricity. The present study considered a detailed analysis of these energy storage devices.

The "best" storage option can be determined by assessing which provides sufficient energy to operate the microgrid independently from the national grid (e.g., islanding) for up to 24 hours. This factor is closely tied to the power discharge level required to support a nominal load profile for a typical microgrid operation. Additional factors to consider include time to charge the storage device and expected capital cost (CAPEX), and operating cost (O&M) for each storage technology. Lastly, equipment replacement cost and expected operational lifetime, required footprint, system weight, and roundtrip efficiency[3] must also be considered. [Mosher, 2010]

Our initial analysis showed the following results for standard Lead-Acid (Pb-A) battery storage compared to Carbon-enhanced Lead Acid Batteries (Pb-C). More expensive batteries considered included Lithium-Ion batteries (Li-Ion), Sulfur-Sulfur batteries (S-S), Zinc-Bromide batteries (Zn-Br), and Vanadium-Redox flow batteries (V-Redox). Flywheels were also compared to battery storage, as shown in Table 1.

[3] "Energy storage typically consumes electricity and saves it in some manner, then hands it back to the grid. The ratio of energy put in (in MWh) to energy retrieved from storage (in MWh) is the round trip efficiency, expressed in percents (%) (see https://energymag.net)

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Table 1 – Energy storage performance considering four metrics (see Hadjipaschalis et al., 2009; Schoenung, 2011; Mosher, 2011; Chatzivasileiadi, 2011; Yang et al., 2007; Bradbury, 2010; Eyer, 2009).

| Metric | Pb-A | Pb-C | Li-Ion | S-S | V-Redox | Zn-Br | Flywheel |
|---|---|---|---|---|---|---|---|
| Roundtrip Efficiency (%) | 80 | 75 | 85 | 75 | 65 | 70 | 85 |
| Cycle Life | 1,000 | 3,000 | 4,000 | 4,000 | 5,000 | 2,000 | 25,000 |
| Calendar Life (yr) | 6 | 6* | 9 | 14 | 12 | 11 | 20 |
| Self-Discharge (%/yr) | 108 | 52 | 108 | 7300 | 108 | 365 | 36500 |
| *Carbon-enhanced lead-acid battery's lifetime assumed same as lead-acid battery | | | | | | | |

Specific details for each energy storage technology in terms of specific power (W/kg) versus Specific Energy (Wh/kg) are in Figure 3. A comparison of energy production costs ($/kW) is shown in Figure 4.

As shown in Table 1 and Figure 3 and Figure 4, the analysis was conducted to determine the “best” storage technology for the S&T microgrid. The results of this economic analysis are shown in Table 2. Based on Table 1 and Table 2, the economic analysis of the various energy storage technologies considered provided the LCOE in terms of Net Present Value/kWh provided (see Table 3). Lead-Acid batteries, including carbon-enhanced Lead-Acid batteries, represented a significantly more economical energy storage technology than all other types of battery technology considered and flywheel technology.

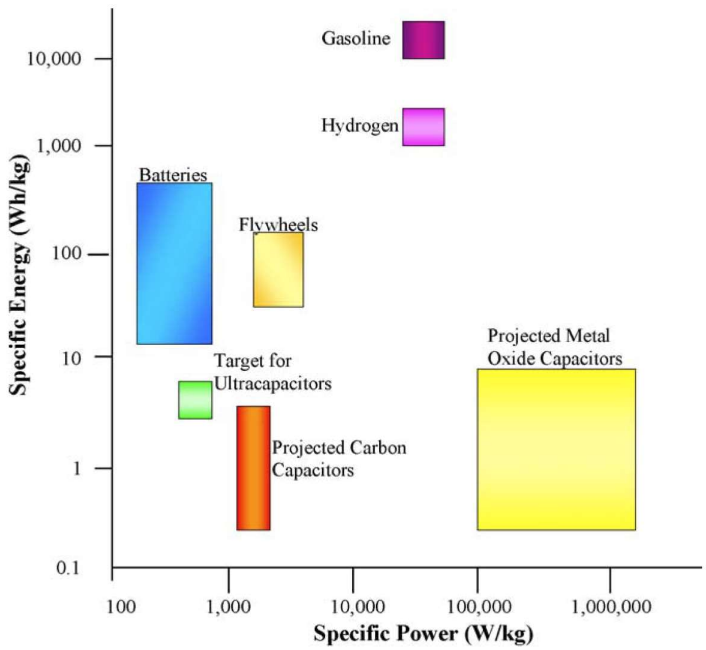


Figure 3 - Comparison of specific power vs. specific energy for various energy storage technologies [Hadjipaschalis et al., 2009]

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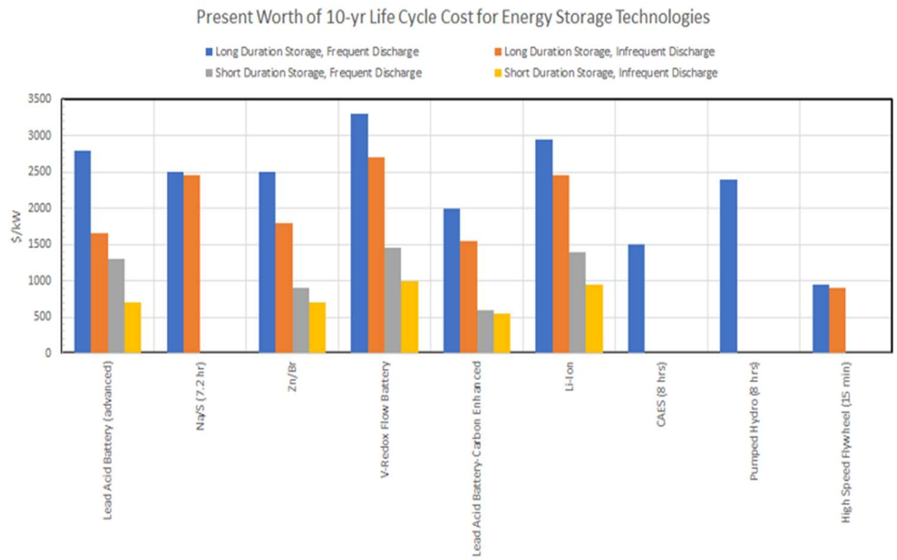


Figure 4 - Cost comparison ($/KW) of various battery technology compared to other energy storage technologies [modified from Schoenung, 2011]

Table 2 - Economic factors for energy storage technology considered in this study (see Schoenung, 2011)

| Metric | Pb-A | Pb-C | Li-Ion | S-S | V-Redox | Zn-Br | Flywheel |
|---|---|---|---|---|---|---|---|
| Energy Cost ($/kWh) | $330 | $330 | $600 | $350 | $600 | $400 | $1,600 |
| Power Cost ($/kW) | $400 | $400 | $400 | $350 | $400 | $400 | $600 |
| Fixed O&M Cost ($/kW-year)* | $1.55 | $1.55 | $0.00 | $9.00 | $4.00 | $0.00 | $11.60 |
| Variable O&M Cost ($/kWh) | $0.01 | $0.01 | $0.00 | $0.00 | $0.00 | $0.004 | $0.00314 |
| *Carbon-enhanced lead-acid battery's Fixed O&M Cost assumed same as lead-acid battery | | | | | | | |

Table 3 – Electric power production cost for various energy storage technologies

| Metric | Pb-A | Pb-C | Li-Ion | S-S | V-Redox | Zn-Br | Flywheel |
|---|---|---|---|---|---|---|---|
| Energy Storage Size (kWh) | 4,688 | 4,920 | 4,329 | 25,808 | 5,847 | 6,391 | 9,884 |
| Average State of Charge (%) | 97.32% | 97.41% | 97.20% | 82.76% | 97.51% | 97.45% | 72.74% |
| Replacement lifetime (yr) | 4 | 3 | 2 | 2 | 1 | 2 | 1 |
| Net Present Value ($1,000) | $1,580 | $1,652 | $2,623 | $9,057 | $3,534 | $2,582 | $15,859 |
| Electricity Cost (NPV/kWh-AC) | $0.459 | $0.481 | $0.763 | $2.634 | $1.028 | $0.751 | $4.612 |

For the S&T solar microgrid, lead-acid batteries were selected as the most efficient energy storage methodology based on this cost analysis. This battery can meet the energy and power requirements for the residential setting of a microgrid. This battery can sustain multiple discharges per day, have low self-discharge and parasitic energy requirements have high efficiency, and most importantly, has relatively low CAPEX and O&M costs. Although they do not have a relatively low energy density, they work well for stationary applications. Also, even though these batteries have a relatively short lifetime, their low-cost offsets this drawback. [Mosher, 2010]

**3. Microgrid Analysis**

To examine various microgrid configurations, a standard methodology was developed and used. Critical assumptions used during this analysis are shown in Table 4.

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Table 4. Assumptions used in Microgrid design analysis

| # | Assumption |
|---|---|
| 1 | Hourly data is sufficient to estimate the dynamic behavior of the microgrid performance |
| 2 | Load profile remains constant throughout system lifetime |
| 3 | O&M costs for microgrid are negligible |
| 4 | Sufficient space exists for both wind turbines and solar arrays to effectively operate (do not interfere with each other) and solar arrays receive full sun during day light hours |
| 5 | Lead acid batteries have 5 year replacement lifetime |
| 6 | Bad year of for solar and wind generation is 90% of 2010 NREL data set (energy generation multiplied by 0.9 to account for reduced generation in this scenario) |
| 7 | Demand data excludes natural gas use for environmental heating and hot water |
| 8 | Transmission and supplemental electrical equipment costs negligible |
| 9 | Wind turbines and solar arrays have 20 year replacement lifetime |
| 10 | Lead acid battery OPEX and O&M costs constant over entire time considered |
| 11 | EU Emissions Trading System price used to estimate cost of carbon credits |

Power demand over 24 hours for a single rural region household was obtained from the Rolla public utility service to establish the required power per home. This can be compared to the standard rate available from the Energy Information Agency, as shown in Figure 5. For simplicity, the load was assumed constant during the year for each home in the microgrid. Though load is known to vary by season, this "simple" approach simplified the microgrid optimization by considering 100 homes with an average load profile for each house of 10,000 kWh/year.

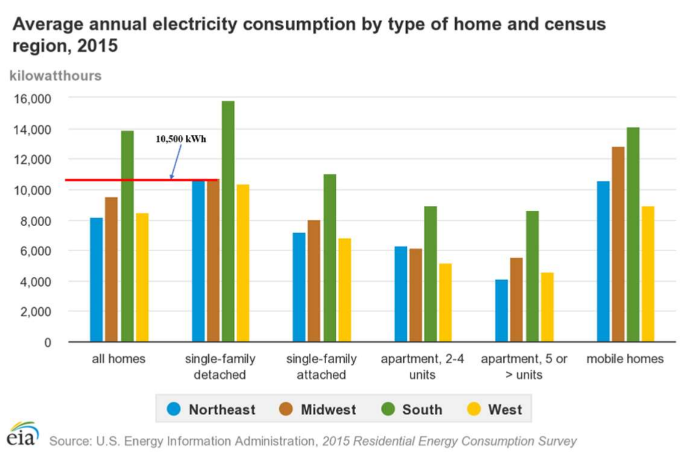


Figure 5. Annual average electric consumption by single household home in rural U.S.A.

## 4. Solar PV Energy

The first factor required in this analysis included the amount of solar energy generated by the solar PV panels in the S&T microgrid. This analysis considered the number of

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"sun-days" during the year based on 2010 data for Rolla, Missouri, obtained from the National Renewable Energy Laboratory's National Solar Radiation database [Wilcox, 2012]. This data is reported regarding sun zenith, sun azimuth, direct radiation, and diffuse radiation. Solar PV generation from diffuse radiation does not depend on the incident angle. In contrast, direct radiation requires components to be fully defined in the angle between the sun and the panel surface (Figure 6).

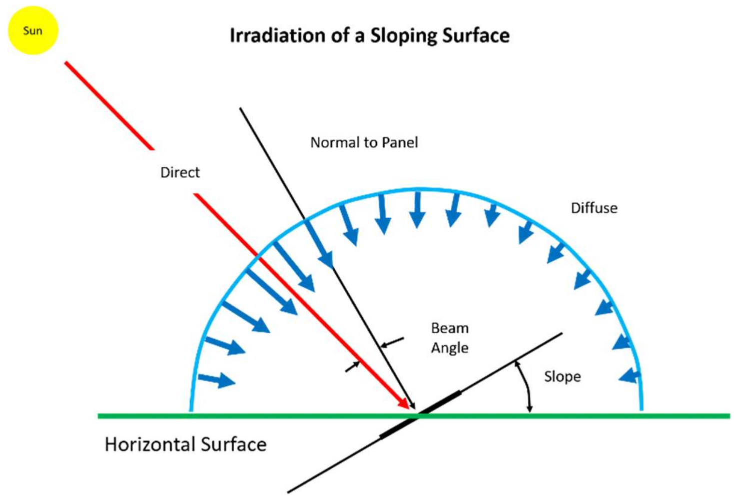


Figure 6. Geometry for estimating solar irradiance on PV panel (from Figure 1, Yenen et al. 2012)

The solar energy generated by the PV panels required the incident Beam Angel as shown above in Figure 6. This was calculated as:

$$Beam\ Angle = arcos[sin\phi_s * sin\phi_p * (cos\Theta_s * cos\Theta_p + sin\Theta_s * sin\Theta_p) + cos\phi_s * cos\phi_p] \quad (1)$$

where $\phi$ is the zenith angle and $\Theta$ is the azimuth angle. Subscripts s and p correspond to the sun and panel. The radiation "incident" on the panel is then found by:

$$Eff\ Rad = Diffuse\ Radiation + Direct\ Radiation * \cos(incident\ angle) \quad (2)$$

Today's efficient solar panels are called "N-type monocrystalline silicon cells," with efficiencies of 15% to 18%. Many things affect cell efficiency, including dust or dirt on the panel surface, ambient temperature, and shading. As a conservative estimate for the present study, we assumed the PV panels have a conversion factor of 14% [Stapleton and Neill, 2021]. Multiplying the Effective Radiation calculated in Eq. 2 by this efficiency factor provided an estimate of electrical energy produced by the solar panels in kilowatt-hours DC electricity per square meter per hour during the year. This number was used in the optimization study to size the required solar power generation source.

Electric power generation from PV panels degrades approximately 0.5% per year [Jordan and Kurtz, 2012, p. 1]. Using this assumption, power generation from the PV panels in the S&T microgrid after ten years will be approximately 90% there initial rated

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value. As a conservative assumption, the solar PV rate was assumed to be 90% of the total capacity over the entire ten years considered in this analysis. The conversion from DC power to AC power in the inverter was assumed to be 84.5%, as suggested in the NREL website PV Watts[4] – which was applied to the estimated power generation rate from PV solar.

5. **Wind Energy**

Like distributed solar systems (i.e., roof-mounted solar PV panels) discussed earlier, distributed wind machines can be used to produce electric power for microgrid use. Unfortunately, intermittent wind speeds are difficult to predict near the ground because wind can be significantly affected by structures and topographical features. Commercial wind machines are typically located approximately 70m from the ground, as shown in Figure *7*.

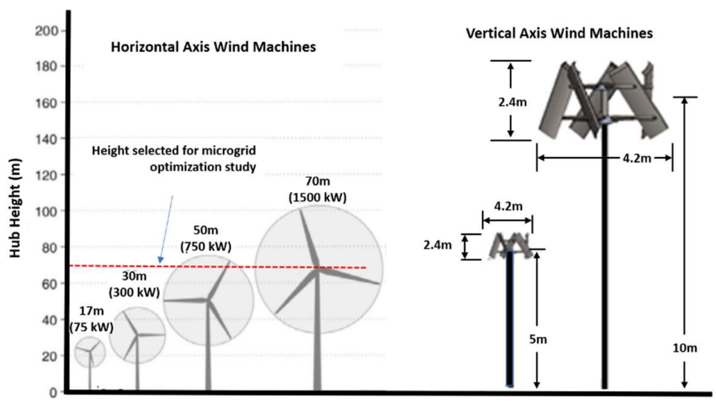


Figure 7. Various wind machine configurations showing scale and power generation

For the microgrid optimization study, wind energy at this height was selected. Missouri's daily wind speed data (see Figure 8) is available from the DOE at 80m elevation. This data was used to estimate the available wind energy available for a wind machine at 70m elevation using the standard "power-law" equation from the literature with the power-law coefficient "$\alpha$" is taken as 0.4 for "small towns and suburbs" (Anjum, 2014, 34):

$$U(z) = U(z_r) * \left(\frac{z}{z_r}\right)^{\alpha} \qquad (3)$$

As shown in Figure 8, rural Missouri has low wind energy with typical wind speeds of less than seven mph (22 m/s). Given wind energy is equal to the wind kinetic energy ($\frac{1}{2}mv^2$) times the wind momentum ($mv$) where $m$ is the mass of air and $v$ is the wind velocity the wind power (kW)[5] is:

$$Wind\ Power\ (kW) = C_p * \rho_{Air} * A_{swept\ area} * v_{wind}^3 \qquad (4)$$

[4] See https://pvwatts.nrel.gov/pvwatts.php

[5] power (kilowatts [kW]) = rate electricity consumed; energy (kilowatt-hours [kWh]) = quantity consumed.

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Where $C_p$ is a dimensionless maximum power coefficient ranging from 0.25 to 0.45 (accounts for turbine efficiency of capturing wind), $I\rho_{Air}$ is the air density (lb/ft3), $A$ is the rotor swept area (ft2) with a rotor diameter D in ft ( $_{Iswept\ area} = \frac{\pi D^2_{rotar\ dia}}{4}$). The wind velocity $v$ is in mph. The air density is based on a reference temperature and pressure of 59°F (15°C) at sea level. To evaluate the annual performance of a horizontal-axis wind machine, Eq. 4 can be transformed to"

$$IEO \ = 0.01328 * D^2_{rotar} * \bar{v}^3_{wind} \qquad (5)$$

where $AEO$ is the annual energy output $\left(\frac{kWh}{yr}\right)$, $D^2_{rotar}$ is the rotar diameter, and $\bar{v}$ is the average wind speed (mph). This form of the equation allows us to analyze the economic performance of wind on the same basis as solar PV.

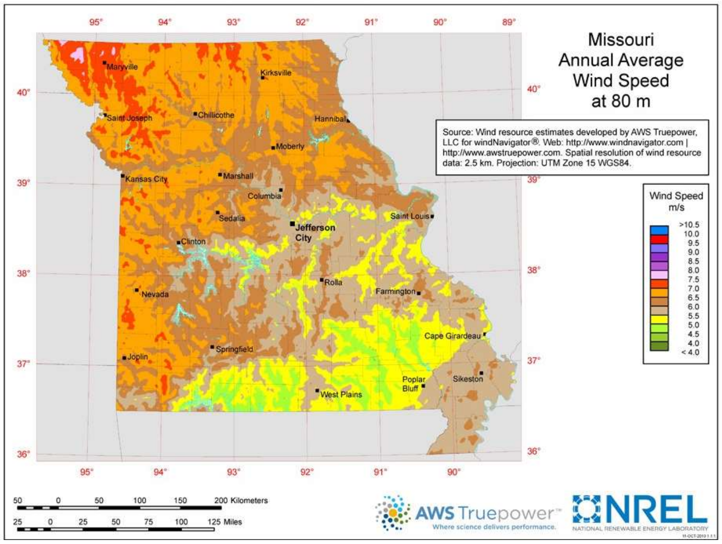


Figure 8. DOE wind speed data for Missouri at 80m elevation[6]

6. **Microgrid Design Analysis**

Based on the information provided in the previous sections on solar and wind energy, plus the assumptions for microgrid design listed in Table 4, an economic analysis of various microgrid designs was conducted. This analysis included solar panel type, wind machine type, and how many solar panels and wind machines are required to meet microgrid energy demand.

For solar panels, according to the US DOE, the price per watt installed was $.0.78 in 2012, which was used in this analysis.[7] Wind costs were estimated using the cost per turbine and the number of turbines required. The estimated energy generation was

[6] Wind resources developed by ASW Truepower, LLC (http://www.awstruepower.com) for windNavigator® (http://windnavigator.com).

[7] See https://www.energy.gov/sites/default/files/2014/05/f15/57957_SunShot_Competitive-USFINAL.pdf

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summed for each wind turbine per year using projected hourly wind speed data. Operation and maintenance costs were estimated as 3% of total CAPEX costs using an estimate of $1,000,000/MW generation CAPEX. Energy storage costs for Lead-Acid batteries were scaled by energy and power needs as

$$Storage\ Capital = max[(C_P \cdot P), (C_E \cdot E)] + BOS_P \cdot P + BOS_E \cdot E \qquad (6)$$

where the $BOS_P$ is the energy needs. For lead-acid batteries, $BOS_P = \$0/kW$ and $BOS_E = \$50/kWh$ [(Mosher) Fixed operating and maintenance costs were found to be $1.55/kW-yr, and variable operating and maintenance costs were found to be $0.01/kWh. [Mosher, 2010]

To optimize the microgrid design, the following objective function was developed in terms of cost per kWh for the solar/wind/Lead Acid-Battery storage

$$\text{Min(cost/kWh)} = (\#\ \text{Solar Arrays}) * \left(\frac{\text{Cost}}{\text{Solar Array}}\right) +$$

$$\sum_{i=1}^{turbine\ design}[(\#\ Wind\ Turbines)_i * \left(\frac{Cost}{Wind\ Turbine}\right)_i] + Wind\ O\&M\ Cost\ +$$

$$Storage\ CAPEX + Storage\ O\&M\ Cost \qquad (7)$$

System constraints included solar array size <100,000 ft$^2$ (<9,290 m$^2$) and # wind turbines <10. Using Eq. (7), the optimal microgrid configuration for rural Missouri in the USA included no wind turbines and 43,500 m$^2$ solar PV panels with 9.45 Mw electric energy storage in Lead-Acid batteries. It is not surprising that no wind turbines were included in the optimal design, given the low wind speeds available in rural Missouri, as shown in Figure 8.

7. **Cost Analysis**

The non-linear reduced gradient method in Excel was used to perform the optimization. The GREET analysis calculated carbon emissions for a combined solar PV and wind system as 45 g CO2/kWh. The carbon emissions for the Lead Acid Battery storage system were taken as 3,200 g CO2/kg, which was divided by battery energy density (0.04 kWh/kg) and multiplied by total batteries in a microgrid (4) and divided by total kWh over microgrid lifetime (20 years * consumption/year) which yielded a value of 32.15 g $CO_2$/kWh for energy storage. No wind generation was included in the optimized microgrid design; thus, the total g$CO_2$/kWh for the microgrid was 77.15 g $CO_2$/kWh. Based on Figure 5, the 100 home microgrid consumes approximately 1,000,500 kWh of electricity per year, equating to about 89 tons of CO2 per year. Assuming carbon emissions are priced at $7.6/ton CO2[8], the relative cost of the $CO_2$ emissions is less than $1,000. For comparison, carbon emissions per kWh for grid-supplied electricity is 792.61 g CO2/kWh[9], resulting in 10x as

[8] Price listed by Regional Greenhouse Gas Initiative (RGGI) on March 3, 2021

[9] Assums Ameren Missouri generated electricity was based on 85.55% coal, 4.22% gas, and 10.23% nuclear power with relative CO2/kWh for each as 1022 gCO2/kWh, 585 gCO2/kWh, and 0 gCO2/kWh (see http://www.eia.gov/electricity/state/Missouri/pdf/missouri.pdf)

much CO2 emissions, but the cost is still less than $10,000 per year for carbon emissions. Based on the current carbon credits markets operating in the US, a carbon cost of $10/ton CO2 was used to estimate electricity costs for the microgrid analysis. Assuming a twenty-year life for the microgrid with a 4.2% annual rate increase for electric power, the estimated cost of electricity, including carbon emissions, is approximately $0.52/kWh for microgrid generated electricity which is significantly higher than grid-based electricity priced at $0.12/kWh for the same cost of carbon emissions. This comparison illustrates why microgrids are not popular in the rural US, given available grid power.

## 8. Discussion

Microgrid systems are designed to provide local electric power to a small set of homes. In regions where grid-based electric power is not available, microgrids are one solution to help alleviate energy poverty and improve quality of life. Microgrid-based Hybrid Energy Systems should be evaluated for use, including locally available energy resources such as wind energy, solar energy, biomass, geothermal energy, hydroelectric energy, and others. Also, various options for energy storage, including batteries, pumped hydro, flywheels, and compressed air, should be considered. In the present study, solar PV and wind energy were considered. Different wind turbine designs were evaluated to find the most optimal for our configuration. Several battery options and flywheels were considered for energy storage. Careful microgrid design ensures the most resilient operation with the lowest LCOE for consumers. We recommend that this type of analysis be carried out to improve the quality of life in rural environments. This technology will also expand economic activity in developing countries by providing a reliable electric power source.

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