100 percent Renewable Electricity Plan for Leelanau County, Michigan

by
Leona Liu
Abhijeet Walchale

A project submitted in partial fulfillment of the requirements for the Master of Science degree (Environment and Sustainability; Sustainable Systems) at the University of Michigan

30 April 2019

University of Michigan
School for Environment and Sustainability

Faculty Advisors:
Dr. Gregory Keoleian, Professor (Chair)
Dr. Geoffrey Lewis, Research Specialist

Abstract

Across the United States, 120 cities, 11 counties and 6 cities have made commitments to transition to 100 percent renewable energy. Leelanau County in Northwest Michigan has a small community comprising approximately 20,000 people and Northport Energy asserted a target to transition the electricity consumption for the entire county to 100 percent renewable energy by 2040, with the use of wind energy, solar energy and battery storage system. Potential for renewable electricity generation in the county was estimated by using geospatial data about land use in the county and the available solar and wind energy resources. 35% of the county land areas has a Class II wind power and 18% has a Class III. Annual solar energy resources have a potential of 3.75 to 4.0 kWh/m^2 per day. Considering land use and environmental concerns, 14.1% of land area (95.41 km^2, or 23,576 acres) is suitable for wind turbine installations, while 31.5% (213.41 km^2 or 52,735 acres) is suitable for solar panel installations. Electricity consumption predictions were made for the year 2040 by analyzing the electricity consumption patterns for 2018 based on data provided by the utilities operating in the county. Impacts of Electric Vehicle Adoption and Low Demand Growth were accounted for in scenario analysis. Size of the Battery system was estimated based on the maximum energy flow required to be handled by energy storage. Fraction of demand met, energy sold to the grid, and economic considerations were taken into account to ensure the feasibility of the 100% goal. While there is potential for deployment of solar and wind energy generation to meet 100 percent electricity demand within the County, it is essential to consider the implications of capital and operating expenditures and surplus electricity generation in order to decide the most optimum combination of resources. Six combinations of solar photovoltaics, wind turbines and battery storage were evaluated which met 88.9-100 percent of the annual electricity consumption with renewable sources. Total renewable electricity generation ranges between 0.26-1.32 TWh/year. For these combinations, the capital expenditure, operating costs and net annual revenue range between $0.129 - $0.443 billion, $60 - $163 million per year, and $6 - $157 million per year respectively. Levelized cost of electricity for the three 100-percent renewable electricity scenarios was found to be in the range of $0.194-0.224/kWh.

Acknowledgements

Our client, Northport Energy

This group of volunteers has been an inspiration for us, dedicating their time and energy toward an ambitious 100% renewable energy goal. The pursuit of the larger goal hasn't come at the expense of the day-to-day efforts needed to tackle renewable energy and efficiency projects. We hope that our (future) children will be able to visit Northport someday to see Michigan's first renewably-powered town.

Our advisor, Geoffrey Lewis, PhD.

Dr. Lewis was supportive enough to help the group find necessary resources and help with the modeling process in both the GIS and Battery storage parts of the project.

Our advisor, Gregory Keoleian, PhD.

Dr. Keoleian's extensive knowledge of renewable energy systems and overall experience in the field of sustainability were foundational for the development of this project.

Electric Utilities, Consumers Energy and Cherryland Electric Co-op

Both the utilities provided the electricity consumption data for the Leelanau County. That was essential for our analysis of renewable energy feasibility and demand projections.

List of Figures

List of Tables

Table of Contents

1. Introduction

1.1 Renewable Energy Overview

In 2017, the total energy use in the US was 96.8 quadrillion Btu. About 80% of the nation's energy comes from fossil fuels, 8.6% from nuclear, and 11% from renewable sources (Fig. 1). Wind is the fastest growing renewable source but contributes only 2.4% of total energy used in the United States. Energy generated from solar was only 0.8% in 2017 (EIA, 2018a).

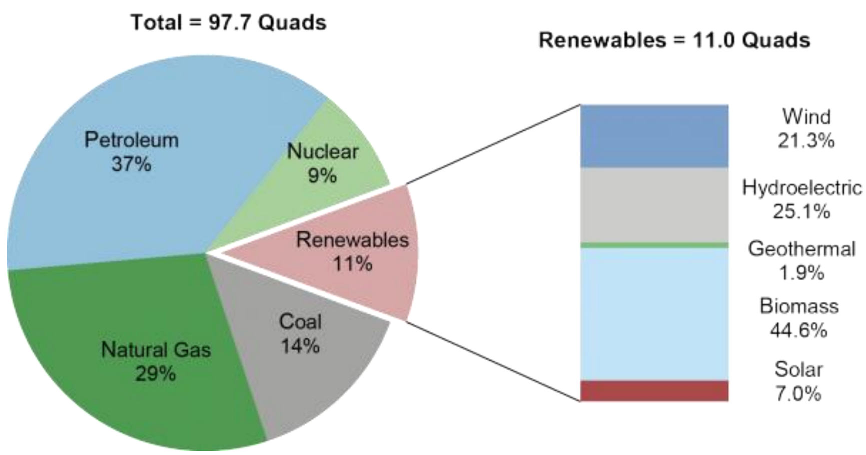


Fig 1. National Energy Use by Source in 2017
(Source: EIA, 2018a)

This energy demand is expected to grow to 120 quadrillion Btu by 2050 under business-as-usual scenario. However, this energy demand does not correlate to an equivalent increase in energy related CO_2 emissions. In 2017, the carbon intensity of US energy consumption fell by 1.1 percent and this can be attributed to the steady increase in the share of natural gas and renewables in the energy mix (EIA, 2017a). With the trend of global energy transition, renewable energy has experienced steady growth and is projected to keep growing. In 2030, renewable energy consumption in the U.S. is projected to reach 15 Quads (Fig. 2). The EIA Annual Energy Outlook (2018b) predicts a sustained growth for share of renewables in the future, with an estimated annual increase of 1.9 percent per year until 2050.

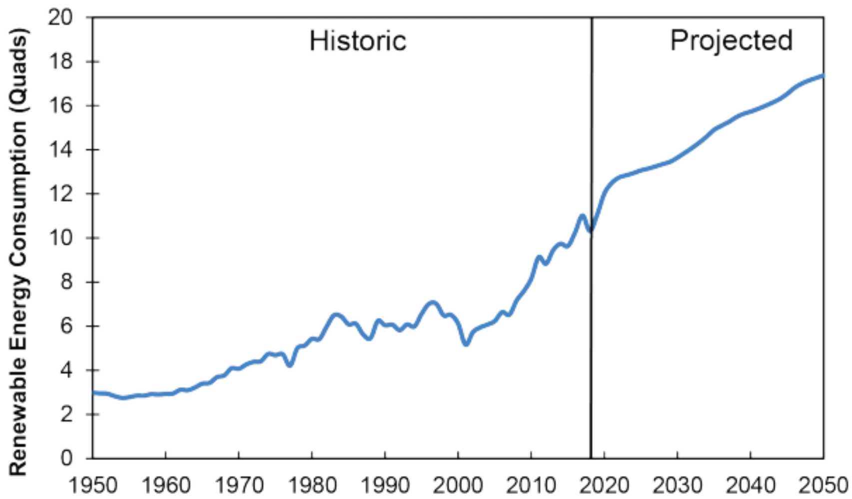


Fig 2. U.S. Renewable Energy Historical and Projected Consumption
(Source: EIA, 2018b)

Electricity accounts for 37.26 quadrillion Btu of the total energy consumption in 2017 (EIA, 2018b). There is a growing need to transition to 100 percent electrical energy generated from renewable energy sources. Various analyses have been conducted to assess the feasibility of a fully-renewable grid (Bazmi & Zahedi, 2011; Baños, et al., 2011; Krajačić, et al., 2011; Mathiesen, et al., 2011). Following this, more than 100 communities in the U.S. have committed to meet 100 percent of the energy demands of communities through renewable energy (Sierra Club, 2019). Some suggest that it will be straightforward to meet future energy demands through wind-water-solar with a relatively small footprint (Jacobson & Delucchi, 2010), while others claim that the current penetration of variable renewable energy sources in most electricity systems is limited to 20% (Zaman, 2018).

Several communities in the U.S. have already set 100% goals for renewable energy generation. For instance, the city of Aspen set a 100% renewable power goal by 2015 and as of 2014 the city reached 86%, mostly through hydropower supplemented with wind (NREL, 2015). The project was inspired by the idea of reducing both operational and community-wide greenhouse gas (GHG) emissions 30% below 2004 levels by 2020 and 80% below 2004 levels by 2050. Another U.S. city, Burlington, the largest city in Vermont with a population of about 42,000, proved that the goal of generating 100% of electricity from renewable sources such as wind, water and biomass is achievable (Policy Institute, 2015). To shift to 100% renewable energy will bring many benefits. It will make healthier communities, boost local economies, create jobs, and saves cities money (Michigan Climate Action Network, 2016). For these reasons and more, over 100 communities have set 100% renewable energy goals, including Traverse City in Michigan (Sierra Club, 2019).

In Michigan, renewables, including wind, biomass, hydroelectric, and solar power, accounted for 8% of state's net electricity generation in 2017 (EIA, 2018c). In January 2019, monthly non-hydroelectric renewables and hydroelectric contributed 736 GWh and 126 GWh respectively, accounting for 8.5% of Michigan's net electricity generation (Fig. 3). There was a slight growth in renewables compared with 2017.

In 2016, electricity generation was 9 million kWh by solar and 4,696 million kWh by wind. Historical electricity generation from wind and solar from 1960 to 2016 is shown in Figure 4. The use of solar was negligible until 2015 and has a great potential to continue increasing. Though the growth of wind energy has slowed down, it contributes the most in the renewable sources, about 75% of total electricity generated by renewables (EIA, 2017b).

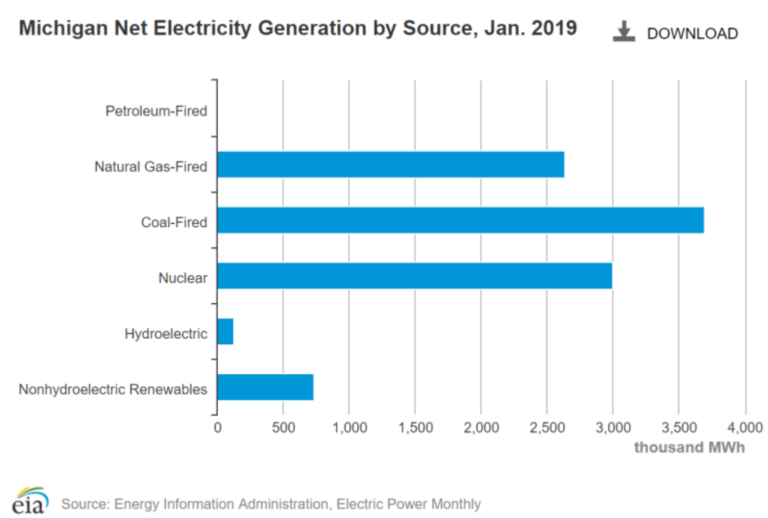


Fig 3. Michigan Net Electricity Generation by Source
(Source: EIA, 2018c)

Year	Solar [f,g]	Wind [f]
	Million Kilowatthours	
1960	NA	NA
1965	NA	NA
1970	NA	NA
1975	NA	NA
1980	NA	NA
1985	0	0
1990	0	0
1995	0	0
1996	0	0
1997	0	0
1998	0	0
1999	0	0
2000	0	0
2001	0	(s)
2002	0	(s)
2003	0	3
2004	0	2
2005	0	2
2006	0	2
2007	0	3
2008	0	141
2009	0	300
2010	0	360
2011	0	456
2012	0	1,132
2013	0	2,800
2014	0	3,868
2015	1	4,797
2016	9	4,696

Fig 4. Historical Michigan Electricity Generation by Wind and Solar
(Source: EIA, 2017b)

Apart from the adoption of renewable energy resources, it is also desirable to meet peak energy demand through the use of energy storage in combination with wind and solar energy (Lisell, 2018). Given that upgrades in energy infrastructure should be adequate to estimate future energy demand, it is necessary to forecast and model energy consumption trends. In addition, the electrification of the private vehicle fleet will have an impact on household and commercial energy consumption. Hence, understanding electric vehicle demand is fundamental to the transition toward electricity generation that encompasses the future needs of the transportation sector.

1.2 Background on Leelanau County

Leelanau County, with a population of 21,657 as of 2017, is located in the northwest Lower Peninsula of Michigan, and is one of 83 counties in the State. It is bordered on 3 sides by Lake Michigan with 100 miles of shoreline, 33 inland lakes, and 5 islands. The county has a total area of 2,532 square miles (6,560 km^2), of which 347 square miles (900 km^2) is land and 2,185 square miles (5,660 km^2) (86%) is water. Leelanau has the second-highest proportion of water area of any county in the United States. A substantial portion of Sleeping Bear Dunes National Lakeshore lies within the county's borders, located on the west side of the county.

Northport Energy, a non-profit organization whose main goal is advocacy for energy efficiency and the use of renewable energy, is devising a plan to transform the Leelanau Peninsula into a community 100 percent powered by efficient and sustainable energy sources (Northern Express, 2018).

Leelanau County is located beside Lake Michigan and is endowed with high wind resources. Figure 5 shows the wind map developed by NREL for Michigan, illustrating that annual average wind speed in Leelanau County is between 5.5 m/s to 7.0 m/s with the maximum wind speed as high as 7.5 m/s in the northeast and very west (U.S. Department of Energy, 2019).

Solar resources in this area are not abundant, ranging from 3.5-4.0 $kWh/m^2/day$ based on NREL estimation as shown in Figure 6 (NREL, 2017). However, given the fact that wind and solar resources are both seasonally variable, it is expected to meet the electricity consumption of the county with a combination of wind facilities operating in winter and solar panels operating in summer.

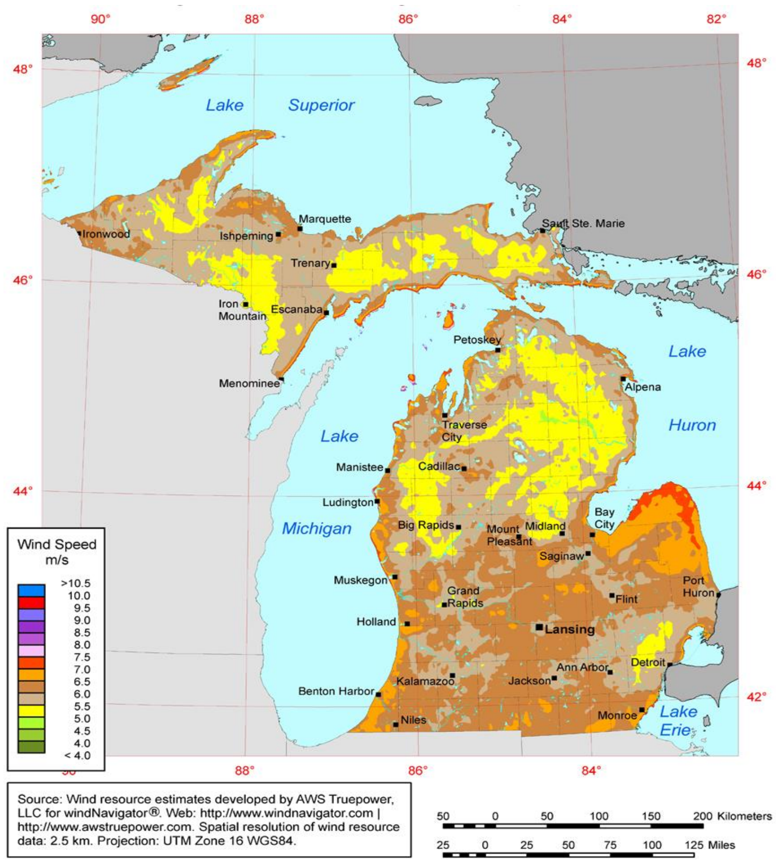


Fig 5. Michigan Annual Average Wind Speed at 80m

(Source: U.S. Department of Energy, 2019)

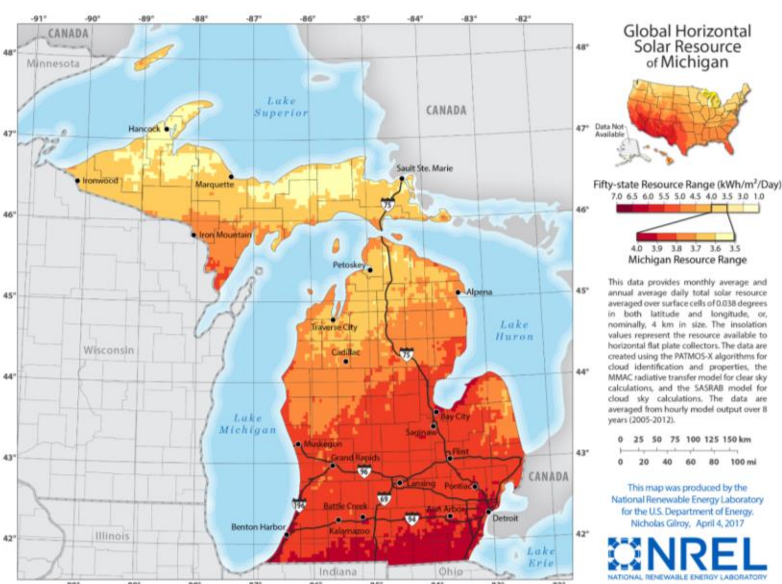


Fig 6. Michigan Annual Average Solar Resources

(Source: NREL, 2017)

Leelanau County's economy is based mainly on agriculture and tourism, and it lacks large, industrial-scale energy users that can impact the baseload demand. However, locations for sites that could host solar and wind turbine installations are severely constrained. Parkland located in the Sleeping Bear Dunes National Lakeshore or township parks are excluded because regulations do not allow solar or wind installations in those places. And offshore wind installations, which have not yet been demonstrated in the Great Lakes, are not considered in this project (Northern Express, 2018).

1.3 Previous Project Summary

A previous Master's Project titled "Northport 100% Renewable Energy Feasibility Study, developing a 100% renewable electricity plan for the Leelanau County, MI", assessed the renewable energy resources available to the Northport community (Cecco et al., 2015). Key takeaways from the previous work include:

- Community members are generally open to the idea of increasing renewable energy in Northport and Leelanau Township.
- The gains from energy-efficiency measures will likely be modest in the overall scheme of moving to 100% renewable energy, but can help to put energy use on a downward trend.
- Leelanau Township has sufficient wind and solar energy to supply the totality of its electricity consumption. The 100% goal could be met by deploying several large-scale systems.
- Three scenarios were developed to achieve 100% renewable energy and their average costs were assessed. In a rapid transfer to renewable scenario, where the goal will be achieved by 2030, the cost per megawatt hour is the lowest, at $146.93.

With the help of this project, Northport is already on its way toward the 100 percent goal, with a previously constructed 120-kW onshore wind turbine that provides 50% of electricity needs for the Northport wastewater treatment plant. There's also the Northport Creek Golf Course, dubbed as the first solar powered golf course in the country (Leelanau, 2015).

Based on the community engagement survey from this project, a practicum titled "Property Assessed Clean Energy (PACE) Renewable Energy Project Plan and Pilot Project." conducted a commercial energy use survey in 2017(Blanchard, 2017). The results suggested that both residential and commercial sectors were supportive of renewable energy. In addition, Blanchard's project assessed and made recommendations for six different facility upgrades for a small business in the township of Northport. An 89-kW solar array would generate the highest cost savings and emissions reductions over a 20-year lifetime, while the combined heat and power system performed best for energy self-generation and wood waste reduction.

Building on these previous studies, this project aims at developing a plan for 100 percent wind and solar electricity grid for Leelanau County in Michigan. Wind energy and solar energy were the renewable sources modeled, as well as the use of battery energy storage to provide balancing reserve power. The energy consumption for the county is forecasted to the year 2040 and is assumed to be correlated with population. The future scenario for the energy sector in the county will be affected by transportation fleet transition towards electric vehicles and the charging demand impact on the electricity grid is assessed.

1.4 Project Objectives

This project will conduct a resource assessment and develop a renewable energy plan for Leelanau County and will also assess how the extensive adoption of electric vehicles in the County will impact the 100% renewable electricity plan. An overview of the objectives is shown in Figure 7. The renewable electricity sources under consideration will be solar photovoltaic and wind energy, with an additional component considering energy storage options.

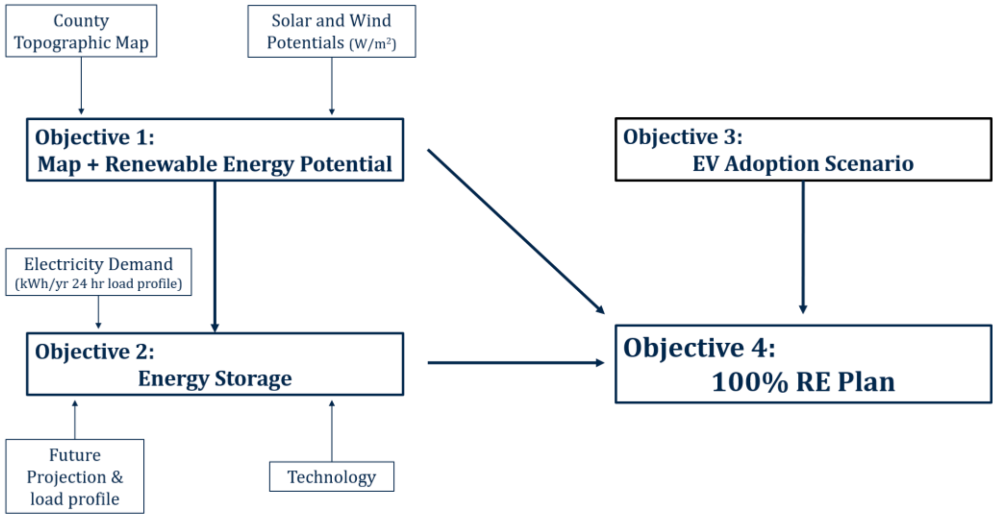


Fig 7. Scheme of Project Objectives

Objective 1: Countywide Resource Potential Assessment

The 2015 project adequately assessed resource potential available within the Northport community and the immediately adjacent areas, but did not assess the potential for the rest of Leelanau County. While resource potential can generally be estimated for the rest of Leelanau County, a full-scale resource and application suitability assessment has not been performed. This objective within the project will provide an assessment of wind and solar energy resources available for electricity generation, and a suitability analysis for the deployment of wind and solar facilities in Leelanau County, conducted through GIS analysis.

Objective 2: Energy Storage Assessment

One aspect that must be considered in a 100% renewables plan is that of energy storage. Due to the variability of renewable resources, energy storage systems help meet peak demands and periods of lower generation from renewables by charging when wind and solar resources meet electricity demand, and discharging when demand exceeds wind and solar resources. This is required to balance of electricity supply and demand. Current grid infrastructure in Michigan has limited capacity to store energy, so an investigation into storage technology will be coupled with consumption data for Leelanau County to produce an initial estimate for sizing grid storage.

Objective 3: Electric Vehicle Demands

Over the next several decades, it is expected that a larger volume of electric vehicles (EVs) will be in operation on America's roadways, as the transportation system shifts away from dependency on fossil fuels. This objective within the project aims to forecast growth in the daily electricity demand requirements from EVs within Leelanau County, which will be incorporated as an electrical load considered under Objective 2.

Objective 4: 100% Renewable Energy Plan

As the final component of the project's contribution, a comprehensive 100% Renewable Energy Plan document will be prepared. Incorporating the objectives listed above, the Plan will provide targets to securing a 100% renewable energy portfolio within the next 10 years. Specific goals will be provided, as well as estimates for expected energy consumption within the county in 2040.

2. Leelanau County 2040 Electricity Demand

2.1 Historical Electricity Consumption

Before assessing the renewable energy potential for the county, it was important to obtain the historical daily and seasonal electricity demand profile and establish the projected electricity demand for the county.

Leelanau County is serviced by Cherryland Electric Cooperative and Consumers Energy. Service areas are shared between these utilities in six counties in northwest Michigan – Benzie, Grand Traverse, Kalkaska, Leelanau, Manistee and Wexford (see Appendix A). Consumers Energy is the main electric supplier, accounting for about 65% of the electricity supply. Since Consumers Energy is a regulated supplier, they are required to reduce electricity generation 1% per year under Public Act 342 as a part of the Energy Waste Reduction program from the Michigan Public Service Commission. Cherryland provides service to townships except Cleveland and Glen Arbor.

Cherryland Electric Cooperative provided us with the electricity consumption data of 5,730 locations served by Cherryland from 2016 to 2018. The annual total electricity consumption was 50.22 GWh in 2016, 50.52 GWh in 2017, and 53.71 GWh in 2018. Average daily consumption increased from 137.59 MWh to 146.75 MWh. Daily consumption over these 3 years is shown in Figure 8. Peak consumption usually took place in July and August with a daily usage between 200 MWh and 250 MWh. The lowest daily consumption of a year was usually in April or May at around 100 MWh. The rest of the year ranged between 100 MWh and 150 MWh with slightly higher consumption during winter (late December and early January).

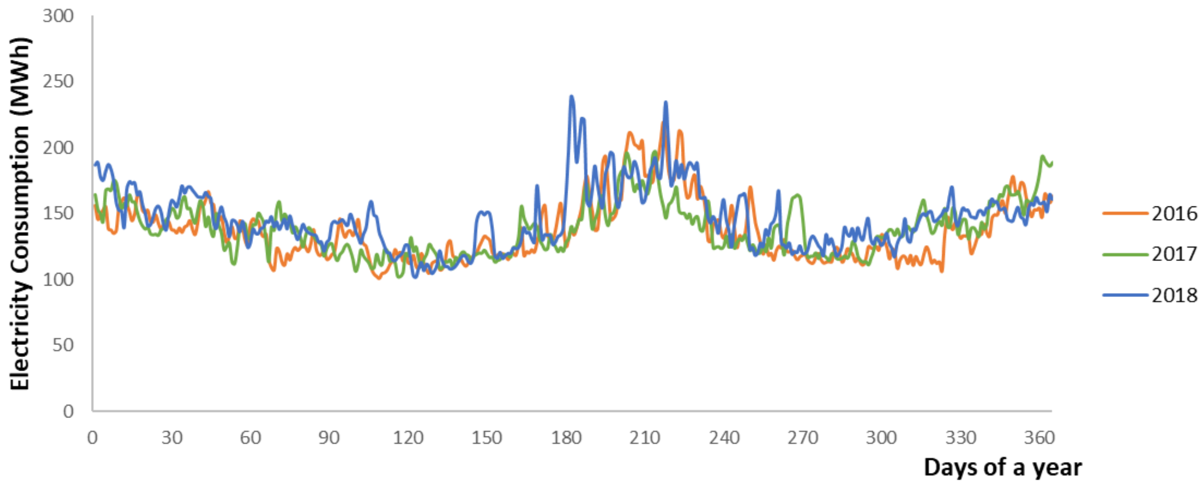


Fig 8. Electricity Daily Consumption from 2016 to 2018 from Cherryland Electric Co-op

Consumers Energy provided monthly electricity consumption data from January 2018 to December 2018. Overall, Consumers Energy provides two thirds of the county's electricity needs as shown in Figure 9. On a monthly level, peak electricity consumption for Consumers Energy happened in December, while that for Cherryland Electric Co-op occurred during summer. This was because Consumers Energy provides electricity to a higher percentage of commercial and industrial buildings than Cherryland Electric Co-op does. Due to the increased requirement of space and water heating, electricity usage was the highest during winter. The relatively high summer electricity consumption occurs due to an influx of tourists and an increase in requirement of air-conditioning. Total consumption in 2018 was 145.75 GWh for the whole county, and the peak monthly demand of 16.56 GWh occurred in January.

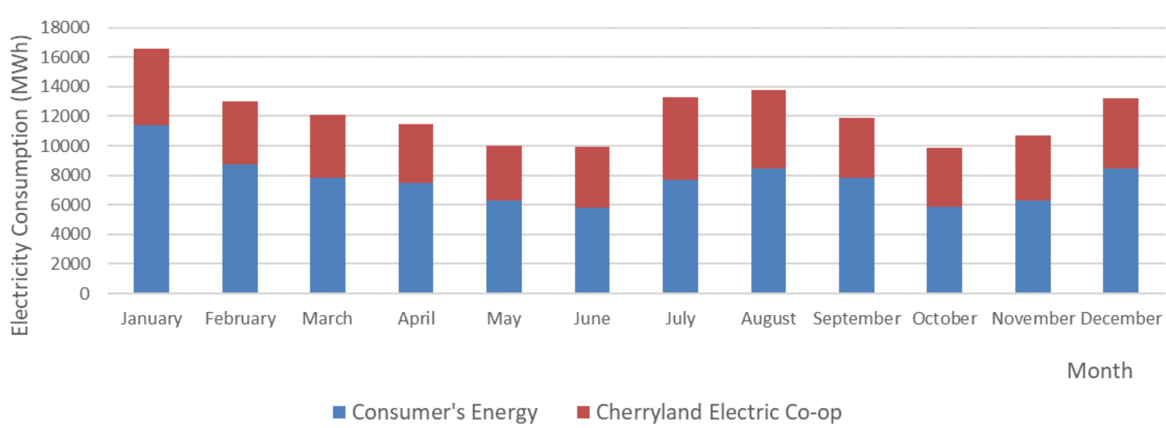


Fig 9. Electricity Consumption in Leelanau County in 2018

Since electricity data from Consumers Energy was monthly data while Cherryland Electric provided hourly data, which was what we need to construct a load profile, we made the assumption that the share of electricity use each supplier took up remained the same for every hour in each month. Table 1 shows the monthly energy use for both suppliers and the share of electricity supplied by Cherryland in 2018. Then we used the share of electricity supplied by Cherryland to allocate the monthly data from Consumers Energy to fit the load profile curve from Cherryland.

Table 1. Electricity Use by Suppliers and the Share from Cherryland Electric Co-op

Electricity Consumption (MWh)	**Consumers Energy**	**Cherryland Electric Co-op**	**Total Electricity Usage**	**Share of Electricity Use from Cherryland Electric Co-op**
January	11373	5191	16564	31%
February	8713	4268	12981	33%
March	7820	4270	12090	35%
April	7466	4032	11498	35%
May	6264	3716	9980	37%
June	5820	4122	9941	41%
July	7667	5602	13269	42%
August	8471	5270	13741	38%
September	7838	4040	11878	34%
October	5864	4031	9894	41%
November	6277	4390	10667	41%
December	8471	4778	13249	36%
Total Electricity Use	92042	53710	145752	37%

Figure 10 and Figure 11 show the seasonal and weekly variation (for the summer peak) of the hourly load profile for the total electricity consumption. The annual peak demand was 33.93MW in 2018, and the base load was 8.09 MW. The average demand was 16.62 MW. The electricity demand kept reducing from January as spring came and reached the lowest demand in April. Then the demand went up during summer and reached the peak demand. In the first week of July in 2018, the electricity consumption was the highest and Cherryland experienced its peak load. The daily peak electricity usage was 549.95 MWh per day.

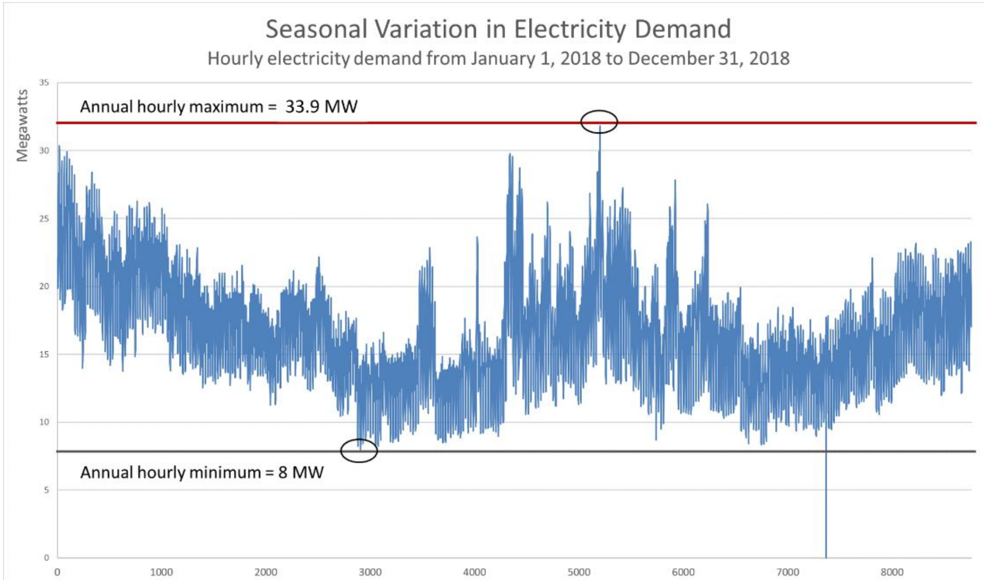


Fig 10. Seasonal Variation in Electricity Demand

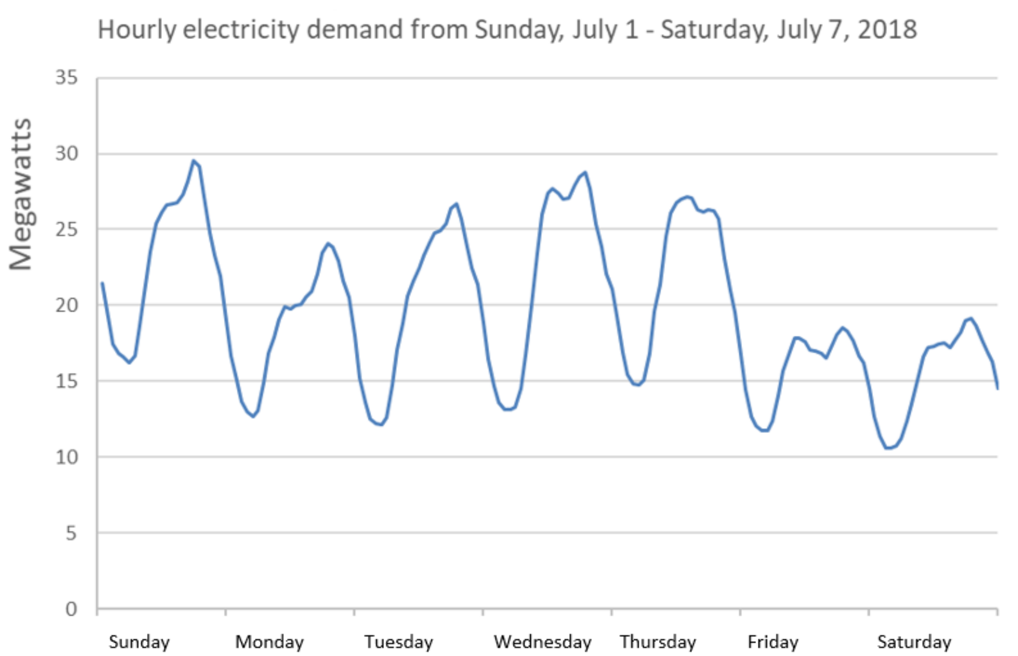


Fig 11. Weekly Variation in Power Demand

2.2 Historical and Projected Population

Electricity consumption in the future was estimated based on the growth of population of the county, and the assumption that electricity demand per capita remains constant (Benchmarks

Northwest, 2012). Networks Northwest developed a county population projection from 2015 to 2040 for Leelanau County in 2012, and concluded that in 2030 the population would be 26,236 and in 2040 it would reach 27,853. However, this projection overestimated the population in 2015 which was 21,624 instead of the forecasted value 22,699, and in 2018 the actual population did not surpass 22,000. Additionally, population estimations from 2010 to 2017 published in the 2017 American Community Survey 5-year estimates by US Census (2017) showed that the population remained at around 21,500 over the past 8 years. When looking at a long time frame, from 1970 to 2018 (U.S. Bureau of the Census, 1982; U.S. Bureau of the Census, 1992; World Population Review, 2019), the population experienced a steady growth from 1950 to 2000, and also remained relatively flat since 2000 (Fig. 12).

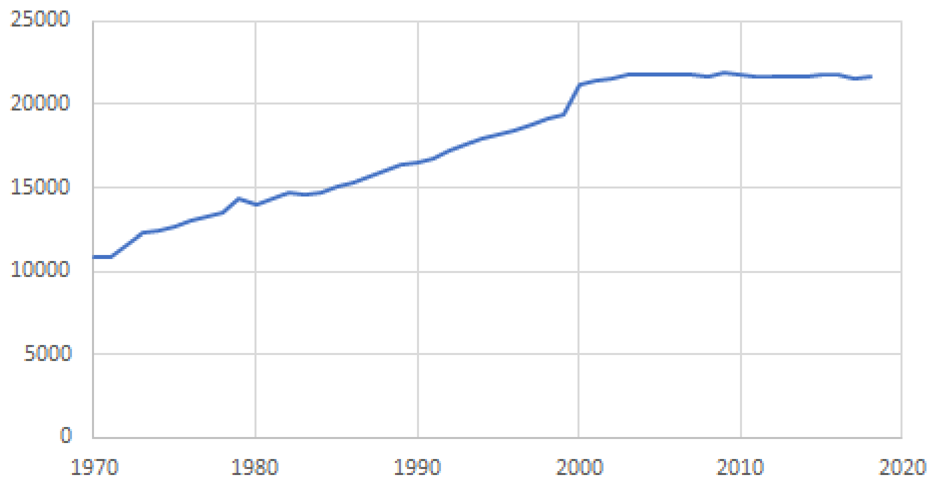


Fig 12. Leelanau County Population from 1970 to 2018
(Source: U.S. Bureau of the Census, 1982; U.S. Bureau of the Census, 1992; World Population Review, 2019)

Therefore, we used time series modeling to forecast the population trend with the population data for 2000 to 2018 (Dhamo Gjika, E. & Puka, L., 2010; Fuqua School of Business, 2019). The population in 2040 is predicted to be 21,644, with a range of 21,414 to 21,873 for the 80% confidence interval and a range of 21,292 to 21,994 for 95% confidence interval.

2.3 Seasonal Variation of Population

The population Figure 12 shows the estimation of permanent population for Leelanau County. However, as a popular place of interest, natural beauty in the county attracts many tourists during summer. A study by Michigan State University Land Policy Institute and Northwest Michigan Council of Governments in 2014 found that total population in June to August was over 33,000, with the highest in August at 35,909. Table 2 shows the seasonal variation in population. Second home population refers to people who only stay in the county in certain seasons or for weekends or other occasional periods throughout the year. Overnight population usually represents tourists. Air conditioning load from permanent residents plus that from tourists made the electricity usage higher during July and August.

Table 2. Leelanau County Seasonal Population Type

Population Type	January	February	March	April	May	June
Permanent Population	21,607	21,607	21,607	21,607	21,607	21,607
Second home population	1,340	1,340	1,831	1,831	1,831	10,751
Overnight	103	160	173	240	695	1,591
Total	23,050	23,107	23,611	23,678	24,133	33,949
%Seasonal	6	6	8	9	10	36

Population Type	July	August	September	October	November	December	Annual Average
Permanent Population	21,607	21,607	21,607	21,607	21,607	21,607	21,607
Second home population	10,751	10,751	2,628	2,628	2,628	1,340	4,137
Overnight	3,359	3,551	1,130	823	347	162	1,028
Total	35,717	35,909	25,365	25,058	24,582	23,109	26,772
%Seasonal	40	40	15	14	12	6	19

(Source: Graebert et al., 2014)

2.4 Projected Electricity Consumption in 2040

Three electricity demand projections were developed for the County with different growth rates between 2018 and 2040. Details of the modeling of the three scenarios are explained below.

Base Case Scenario

The EIA Annual Energy Outlook 2018 projects a constant electricity demand in the Midwest from 2018 to 2040 in the Reference Case and a 0.2 percent per year decrease in electricity demand under the Low Growth scenario (EIA, 2019). However, Leelanau County has a seasonal variation in population, leading to the occurrence of the annual peak in the summer months of June, July and August in addition to the peak in the months of December and January. Benchmarks Northwest, a coalition involving local public and private entities forecast a growth in population in the region (Benchmarks Northwest, 2012). Hence, it is essential to model a higher electricity demand for the County by 2040 accounting for the potential rise in population. A Base Case Scenario was developed by assuming the growth in electricity demand to be proportional to the population growth.

Electric Vehicle Adoption Scenario

Projecting electricity demand for 20 years into the future requires consideration of the impact of electric vehicles. It is essential to consider electric vehicle adoption as one of the factors influencing the electricity demand in 2040. Apart from an increase in electricity demand, large scale adoption of electric vehicles has the potential to influence the overall shape of the demand curve of the County. This impact is influenced by the specific hours of the day that the vehicles are being charged and the energy required to charge them.

Data available from 2010 Census (US Census Bureau, 2010) estimates the number of households in Leelanau County at 9,022 and an average of 2 vehicles per household. The estimated maximum fleet share for electric vehicles is assumed to be 24 percent by 2030 across the U.S. (Becker et al., 2009). Assuming that adoption rate in the U.S. applies to Leelanau County and extrapolating the projections to 2040, we find that the fleet share of electric vehicles would be limited to 40 percent. The average energy demand for one electric vehicle was estimated using data from Kelly et al. (2012) (Fig. 13). Energy demand for the total electric vehicle fleet in the county was estimated by multiplying the demand per vehicle by the estimated number of electric vehicles. This energy demand was superimposed on an hourly basis on the earlier projected electricity demand for the county. The percentage change in hourly electricity demand was calculated.

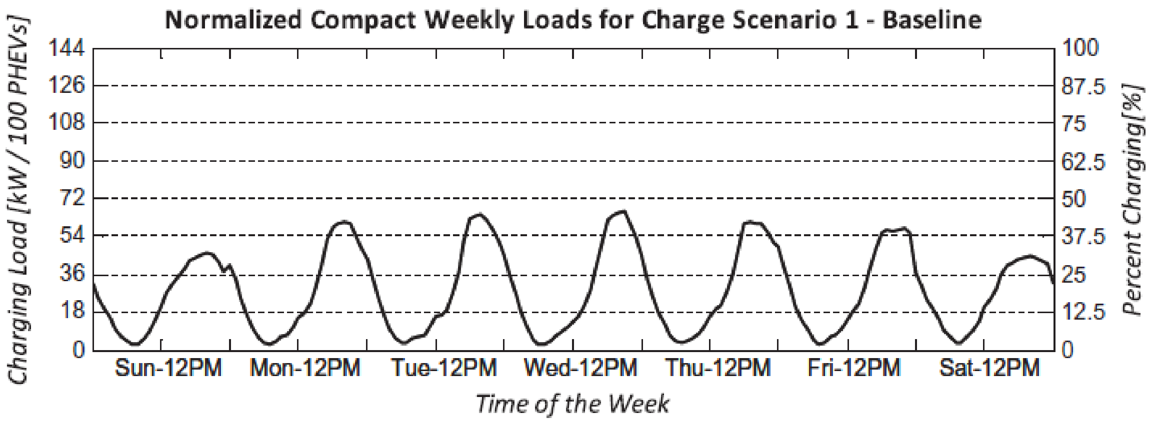


Fig 13. Normalized Compact Weekly Loads for Charge Scenario 1 – Baseline

(Source: Kelly et al., 2012)

Low Demand Growth Scenario

From the Annual Energy Outlook 2019 data (EIA, 2019), a 0.02 percent decrease in electric power demand in the Midwest was observed in the Low Growth Scenario. Based on this data and the available 2018 electricity demand, the lower demand projections were developed for the County. This demand projection is not tied to the county population but the assumption that the demand projection in the county is at the same rate as the entire country. The adoption of electric vehicles was not added to this scenario.

Results

Three scenarios were developed as summarized in Table 3. The Base Case Scenario predicted a 0.24 percent increase in the electric demand per year. This resulted in a projected energy demand of 153.42 GWh in the year 2040. EV Adoption results in a 1.94 GWh increase over the Base Case demand. The Low Demand Growth scenario predicts a demand of 138.75 GWh in 2040.

Table 3. Three Scenarios for Electricity Demand Projection

Scenario	**Base Case**	**EV Adoption**	**Low Demand Growth**
Projected Annual Demand	153.42 GWh	155.36 GWh	138.75 GWh

2.5 Discussion

Given the lack of hourly data from Consumers Energy, the demand curve for 2018 and the resulting base case predictions were assumed to follow the hourly trend of the 2018 electricity consumption data from Cherryland Electric Cooperative. However, there are limitations regarding this assumption. Residential and commercial hourly load profiles are different, and hence the differences in the portion of residential and commercial users in the two suppliers would greatly impact the actual electric load curve. In order to be more accurate, hourly data would be needed from Consumers Energy.

Implementation of demand response strategies at peak demand would result in a decrease in the annual peak demand that the system is required to meet. It would also bridge the gap between daily peak power requirements and power generated from the renewable energy system, thus enabling a reduction in capacity of the energy storage system. Based on the 2017 reporting, Consumers Energy had 47,670 customers in Michigan (47,651 residential and 19 industrial) enrolled in their demand response program with a peak power demand saving of 22.7 MW (EIA, 2018d).

3. Renewable energy potential analysis

After modeling the 2040 electricity demand and load profile for Leelanau County, this section describes the renewable resource assessment, quantifies the energy generation from renewable sources and evaluates the feasibility of achieving the 100% renewable energy goal.

3.1 Methods

For the purposes of investigating county-wide land availability for wind and solar energy resource, the open-source Quantum GIS program, QGIS Desktop 3.4.1 (QGIS Development Team, 2018), was used as the primary tool of base map compilation. The resource assessment and suitability analysis were completed via ArcMap 10.6.1 (Environmental Systems Research Institute (ESRI), 2018). Through these GIS programs, a base map of Leelanau County was generated. Exclusions were applied to this base map after considering land use data and environmental concerns, and the resulting land availability was calculated. Further explanations of land exclusions and the resulting calculated land availability are given in following sections.

Data sources

Datasets for solar and wind resources were obtained from National Solar Radiation Database (NSRDB) produced by the National Renewable Energy Laboratory (Sengupta et al, 2018). TMY stands for "typical meteorological year" and is a widely used type of data available through the NSRDB. TMYs contain one year of hourly data that best represent weather conditions over a multiyear period. Gridded TMY data are derived from the 4-km*4-km gridded NSRDB data, with the 1998–2014 data being used in the currently available TMY (NSRDB, 2015). The dataset contains 69 grid squares that lie in Leelanau County. Data fields extracted from NSRDB are shown in Table 4.

Table 4. NSRDB Dataset Elements

Field	Element	Unit	Description
Grid Information	Location ID	-	Site identifier
	Latitude and Longitude	Degrees (°)	Center of a grid
	Date and Time	-	Date and time of data recorded
Solar Resource Assessment	Global Horizontal Irradiance	1 Wh/m2	Total amount of direct and diffuse solar radiation received on a horizontal surface during the 60-minute period ending at the timestamp
Wind Resource Assessment	Wind Speed	m/s	Wind speed at 50 meters above surface
	Wind Direction	Degrees (°)	Wind direction at the time indicated
	Air Temperature	°C	Air temperature at the time indicated
	Barometric Pressure	Millibar	Air pressure at the time indicated

(Source: NSRDB, 2015; Sengupta et al, 2018)

Land use data for this analysis was obtained via National Land Cover Database produced through a cooperative project conducted by the Multi-Resolution Land Characteristics (MRLC) Consortium (Homer, C., 2004). This dataset included geographical land cover based on fifteen categories: barren land, cultivated crops, deciduous forest, evergreen forest, mixed forest, developed land (high, medium, low intensities), developed open space, emergent herbaceous wetlands, hay and pasture lands, herbaceous land, woody wetlands, shrub and scrubland, and open water. Land use data is a raster file with 30m pixel patches as its mapping unit. Topography for the county was acquired through the U.S. Geological Survey's (USGS) online National Map platform (2017). Datasets for areas concerning critical dunes, wetlands, and state-owned lands within the county were obtained through the State of Michigan GIS Open Data Portal (2018). Road centerlines and village boundaries were obtained from Leelanau County GIS Office (2018). Files for federally owned lands within the county were acquired via the USGS Small-Scale Data Download Portal, which operates in conjunction with the National Map (2014). A dataset for transmission lines was acquired from Homeland Infrastructure Foundation-Level Data (HIFLD) (2018). Datasets regarding airport locations, microwave communication towers, and FEMA coastal flooding hazard areas were obtained through the ESRI Maps & Data online database (Federal Aviation Administration et al., 2018; Federal Communications Commission et al., 2018; Federal Emergency Management Agency et al., 2018). All dataset types and sources are summarized in Table 5.

Table 5. Summary of Data Types and Sources

Variable	Type	Data source
Wind power density / Solar irradiation	Vector (Polygon)	National Renewable Energy Laboratory (Sengupta et al, 2018)
Land use	Raster	National Land Cover Database (Homer, C., 2004)
Slope (Elevation)	Raster	U.S. Geological Survey's (USGS) online National Map (2017)
Wetlands, water body, and dunes	Vector (Polygon)	State of Michigan GIS Open Data Portal (2018)
Villages	Vector (Polygon)	Leelanau County GIS Office (2018)
Roads	Vector (Polyline)	Leelanau County GIS Office (2018)
Federal lands	Vector (Polygon)	USGS Small-Scale Data Download Portal (2014)
Transmission lines	Vector (Polyline)	Homeland Infrastructure Foundation-Level Data (HIFLD) (2018)
Airport & Communication tower	Vector (Point)	ESRI Maps & Data online database (Federal Aviation Administration et al., 2018; Federal Communications Commission et al., 2018)
FEMA coastal flooding hazard areas	Vector (Polygon)	ESRI Maps & Data online database (Federal Emergency Management Agency et al., 2018)

Wind Energy Calculations

Air density was calculated first with pressure and temperature data in the National Solar Radiation Database (NSRDB). The equation showing the relationship between air density, temperature and pressure is:

$$\rho = P/RT$$

where:

ρ = density (kg/m^3)

P = pressure (Pascals)

R = specific gas constant (J/(kg*K) = 287.05 for dry air)

T = temperature (K = C + 273.15)

Once we got air density values, wind power density for each grid was calculated and used as an input for wind energy resource maps. Since the wind speed varies at different time of a day, a summation over time was performed to get the annual and monthly wind power density:

$$WPD = ½ * 1/n * \Sigma(\rho_j * v_j^3)$$

where:

WPD = wind power density (W/m^2)

n = the number of wind speed readings (hour)

ρ = air density (kg/m^3)

v = wind speed at 50m above ground (m/s).

Since wind speed increases with height and NSRDB data are taken at 50 meters off the ground, a correction of wind speed at the wind turbine hub height was needed in order to estimate energy generation. The wind speed at a certain height above ground level h is:

$$v = v_0(h/h_0)^\alpha$$

where:

v = wind speed at wind turbine hub height (m/s)

v_0 = wind speed at 50m above ground (m/s)

h = wind turbine hub height (m)

h_0 = 50m

α = shear exponent (0.28).

The wind shear exponent α reflects how the speed increases with height and depends on types of terrain. Table 6 provides shear exponent values for different surface (Bechrakis & Sparis, 2000). Since Leelanau County can be characterized as a wooded country with small towns, we assumed the shear exponent to be 0.28. A sensitivity analysis on the effect of this assumption on electricity generation per turbine is contained in Appendix C.

Table 6. Typical Surface Shear Exponent Coefficients

Description of Terrain	α
Smooth, hard ground, lake or ocean	0.10
Short grass on untilled ground	0.14
Level country with foot-high grass, occasional tree	0.16
Tall row crops, hedges, a few trees	0.20
Many trees and occasional buildings	0.22-0.24
Wooded country – small towns and suburbs	0.28-0.30
Urban areas, with tall buildings	0.40

(Source: Bechrakis & Sparis, 2000)

Solar Energy Calculations

In the NSRDB, global horizontal irradiance (GHI) for each grid at each hour was given. Therefore, no further data manipulation was needed. An average of GHI (W/m^2) throughout the year was taken and multiplied by 24 hours per day to represent the annual solar resource potential (kWh/m^2/day).

Suitability Analysis

To adequately assess the resource potential, consideration must be given to the two types of protected land cover prominent in Leelanau County: wetlands and critical dunes. Wetlands are specified in Part 303 of the Michigan Natural Resources and Environmental Protection Act (NREPA), 1994 PA 451 that the Michigan Department of Environmental Quality must issue permits in order for anyone to "Construct, operate, or maintain any use or development in a wetland" (State of Michigan, Michigan Legislature, 1994). Additionally, areas of critical dunes are addressed in Part 353 of the same legislation, noting that "a person shall not initiate a use within a critical dune area unless the person obtains a permit from the local unit of government in which the critical dune are located" (State of Michigan, Michigan Legislature, 1994). Thus, to mitigate the potential destruction of protected areas, and to limit the necessity of further permitting and oversight required, these two types of land areas were considered as exclusions and a 1 km set back distance was considered in this investigation.

Several areas within Leelanau County host both federal and state lands. Therefore, to reduce permitting requirements and potential damages to naturally preserved areas, these areas of state and federal lands were excluded from the geospatial analysis.

Although Leelanau County does not have any significant restrictions imposed upon flood zone, to ensure longevity of solar energy initiatives, these areas are excluded within the analysis for solar PV suitability (Villacreses, et al., 2017). However, these areas were not excluded for wind turbine installations because the wind turbines are built with a hub height of over 100 meters which is possible to implement within flood zone areas without significant consequence.

Other constraints regarding human infrastructure were implemented to ensure that the environment and the local population are not negatively affected. Restrictive distance from airports, communication towers, villages and roads were addressed (Baris, et al., 2015; Aydin, et al., 2010).

Constraints and setback distances for geospatial analysis of the deployment of wind turbines and solar PVs are summarized in Table 7 and Table 8.

Table 7. Constraints for Wind Turbine Installations

Variable	Reasons for Selection	Constraints
Water Body and Dunes	‣Ecological sensitive areas ‣Additional permitting and oversight required ‣Part Michigan's NREPA, as amended	>1000m
Federal Lands	‣Additional permitting and oversight required	Excluded
Airport	‣Conflicting land use preoccupied by human infrastructure	>3000m
Communication Tower		>1000m
Villages		>1000m
Roads	‣Avoid areas on the roads	>200m
Wind Power Class	‣Wind potential is essential for wind energy production	Above wind Class I
Transmission Lines	‣Reduce the cost of building new transmission lines	Different values are given to different distances
Land Use	‣Land use is a criterion representing the environmental impacts of the wind farms	Ranked according to suitability level
Slope (Elevation)	‣Slope affects the ease of construction and maintenance	Slope less than 25%

Table 8. Constraints for Solar PV Installations

Variable	Reasons for Selection	Constraints
FEMA coastal flooding hazard areas	‣Long-term viability for large-scale installations ‣Flooding and erosion prone areas ‣Incompatibility of grid infrastructure with inundation events	Excluded
Federal Lands	‣Additional permitting and oversight required	Excluded
Water Body and Dunes	‣Ecological sensitive areas ‣Additional permitting and oversight required ‣Part 303 of Michigan's NREPA, as amended	>1000m
Global Horizontal Irradiance	‣Global horizontal irradiance is essential for solar energy production from solar PV	Graded according to GHI level
Transmission Lines	‣Reduce the cost of building new transmission lines	Different values are given to different distances
Land Use	‣Land use is a criterion representing the environmental impacts of the wind farms	Ranked according to suitability level
Slope (Elevation)	‣Slope affects the ease of construction and maintenance	Slope less than 25%

Table 9. Reclassified Values for Suitable Criteria

Wind power class	Reclassified value
Class I (<200 W/m^2)	0
Class II (200 – 300 W/m2)	3
Class III (300 – 400 W/m^2)	5
Class IV (400 – 500 W/m^2)	7
Class V (500 – 600 W/m^2)	9
Land type	**Reclassified value**
Cultivated crops	9
Barren land, Shrub/Scrub, Hay/Pasture, and Herbaceous	7
Developed low intensity, and Developed open space	5
Developed Medium intensity	3
Evergreen forest, Deciduous forest, Mixed forest, Emergent herbaceous wetlands, Open water, Developed high intensity, and Woody wetlands	1
Slope (%)	**Reclassified value**
0-5	9
5-10	7
10-15	5
15-20	3
20-25	1
>25	0
Distance to transmission line (m)	**Reclassified value**
0-1000	9
1000-2000	8
2000-3000	7
3000-4000	6
4000-5000	5
5000-6000	4
6000-7000	3
7000-8000	2
>8000	1

Additionally, wind power density, land use type, slope and distance to transmission lines were ranked according to suitability as described in Table 9.

Since solar resources in Leelanau County vary in a small range, global horizontal irradiance was classified into 5 categories using natural breaks method in ArcGIS. This classification method best groups similar values and maximizes the differences between classes (ESRI, 2007). And then the highest GHI class was given value 9, while the lowest GHI class was given value 1.

Wind power class is a critical criterion of feasibility because it determines the amount of electricity a wind turbine can generate if placed in this area. Since Class I wind power is generally not available for electricity generation, it was assigned a value 0 and was excluded. The higher the wind power class is, a greater value was given.

Of the 15 land cover categories within the NLCD pertinent to Leelanau County, 7 were isolated as extremely low suitability in the geospatial analysis and were given a value 1. Forests do not provide adequate space for either wind turbine or PV installations. To minimize additional permitting and siting requirements from the state and federal governments, the categories of emergent herbaceous wetlands, woody wetlands, and open water were also identified as low suitability areas. Areas concerning high development intensities imply existing commercial or residential infrastructure, and therefore cannot be easily modified to meet the requirements of large renewable energy installations. Medium to low intensity developed lands and developed open space were more suitable as compared to categories described above, and were given a value of 3 for medium development intensities and 5 for the other two. The categories within the NLCD that were considered high suitability are: cultivated crops, hay fields and pasture lands, herbaceous lands, shrub and scrub lands, and barren lands. Among these categories, cultivated crop land was considered as the most suitable land use type and was given a value of 9, while the rest were given a value of 7.

Areas with the gentlest slopes are most suitable because steep slopes can lead to extra infrastructural investments. Therefore, slopes greater than 25% were given a value of 0 which means these areas were identified unsuitable. Slopes ranging from 0% to 25% were classified into 5 categories and were graded from 9 to 1 with the increase of the slope.

Renewable energy facilities supply electricity to nearby communities or to an electricity grid to transmit electricity through transmission lines. Short distance to existing transmission lines can reduce the cost of building new transmission lines. Therefore, distance to transmission lines was scaled in a decreasingly linear way, so that a closer distance would mean a more optimal score.

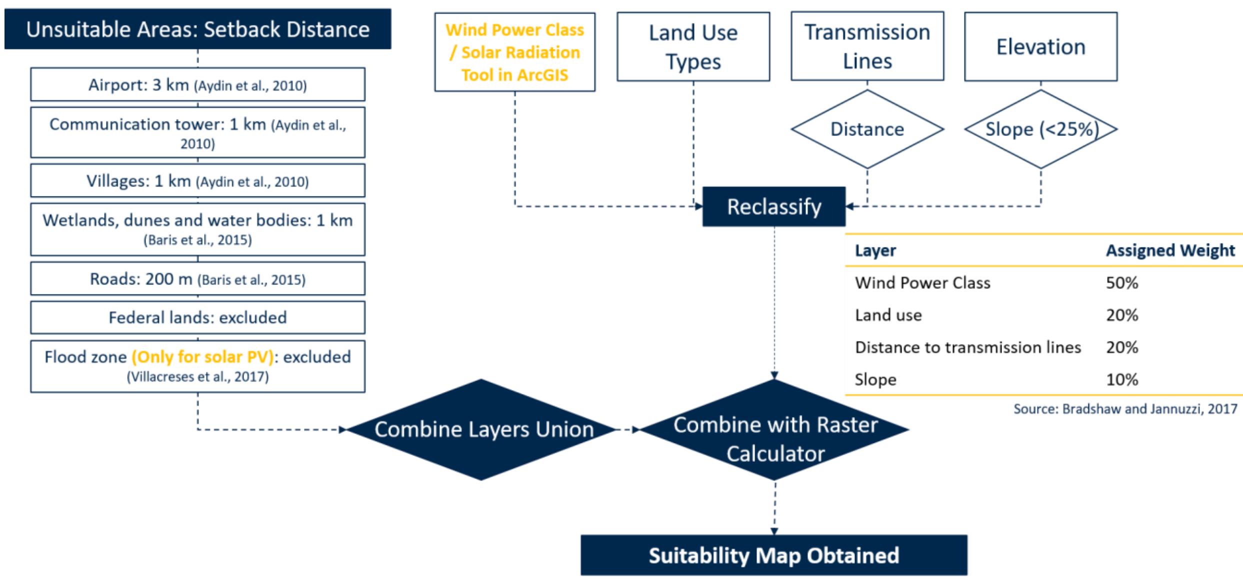


Fig 14. Flow Chart for Suitability Analysis Processes

A flow chart representing the overall GIS analysis processes and references is shown in Figure 14.

First, each layer was projected to NAD 1983 State Plane Michigan Central 2112 coordinate system. All vector files were buffered according to the constraints described above. Following this, vectors were converted to raster of the same pixel size as the land use raster. This step was to ensure resolution was consistent for all raster when performing raster calculation. The elevation raster layer was converted to a slope raster layer using the slope tool in ArcGIS. Using the ArcMap area solar radiation tool and NSRDB data, the global radiation raster was generated.

Then each raster layer was reclassified. Within each layer, areas that should be excluded were given a cell value of zero while the rest of the areas were given a cell value of one. Other criteria were reclassified accordingly as presented in Table 9. Notably, in order to exclude wind power Class I, wind power class layer was reclassified twice, one with a value of zero for Class I and a value of 1 for all higher classes, the other one with different values based on wind power class.

Once the reclassified raster was created for each criterion, weights were applied to these layers. Certain components hold a higher value than the others and applying weights to these layers allowed us to designate greater value to these components. These weights are based on the existing literature which used multi-criteria decision analysis to determine the weights (Bradshaw, 2017; Díaz-Cuevas, et al., 2018; Sliz-Szkliniarz & Vogt, 2011). However, decision-making processes cannot always be entirely objective. It would be better to make the planning decision that involve key community stakeholders including Leelanau County residents, planners and investors. The weights for this project were assigned as presented in Table 10.

Table 10. Assigned Weight for Siting Criteria

Layer	**Weight (%)**
Wind/Solar	50
Land use	20
Transmission Line Distance	20
Slope	10

At last, the raster calculator tool in ArcGIS was used to create the overall suitability layers for wind and solar for the entire County. The formulas used for each grid square in the raster calculation were:

Wind Energy Suitability Index *= Airport (0/1) * Communication Tower (0/1) * Villages (0/1) * Federal lands (0/1) * Wetlands, water body, and dunes (0/1) * Roads (0/1) * Wind class (0/1) * (50% * Wind power density + 20% * Land use + 20% * Transmission lines + 10% * Elevation)*

Solar Energy Suitability Index *= Federal lands (0/1) * Wetlands, water body, and dunes (0/1) * Floodzone (0/1) * (50% * Global Horizontal Irradiance + 20% * Land use + 20% * Transmission lines + 10% * Elevation)*

In doing so, cells that are not suitable for the deployment of wind turbines or solar PVs were assigned a value of zero, and the rest of the cells have values varying according to their suitability.

Land Requirement for Wind Turbine and Solar Panel Installations

Denholm et al. (2009) analyzed the land area reportedly associated with U.S. wind projects based on official documents and found the average value for the total project area was about 34 ± 22 hectares/MW and a permanent direct impacted area of 0.3 ± 0.3 hectares/MW. In our project, 3.4 MW wind turbines were considered and the average land requirement of 0.0204 km^2 per turbine (0.6 hectares/MW * 3.4MW) was used. For the land-use requirement of solar, a minimum of 0.0308 km^2 (7.6 acres) land area was required for each megawatt (Ong et al. 2013).

3.2 Wind Energy Resources

Wind power density in Leelanau County varies seasonally and spatially as shown in the annual averages in Figure 15 and monthly averages in Figure 16. With lakes and wetlands excluded, 47% of the County land area (318.2 km^2 out of 677 km^2) only has wind power Class I which is not sufficient for commercial generation of electricity. 35% of the County land areas are Class II, which may be suitable for rural applications, and 18% are Class III, which are suitable for most utility-scale wind turbine applications.

A large percentage of Class II and Class III wind resources are located near big lakes and coastal areas, especially in the west part of Leelanau County around Glen Lake. Unfortunately, wind turbines cannot be built in much of these areas due to incompatibility with these land use types.

From October to February, there is Class II and Class III wind power in more than half of the County area. In December and January, some areas have a Class V or above, which is an excellent wind resource. However, from May to August, the monthly wind power density is lower than 200W/m^2 across the county and this is generally not suitable for electricity generation.

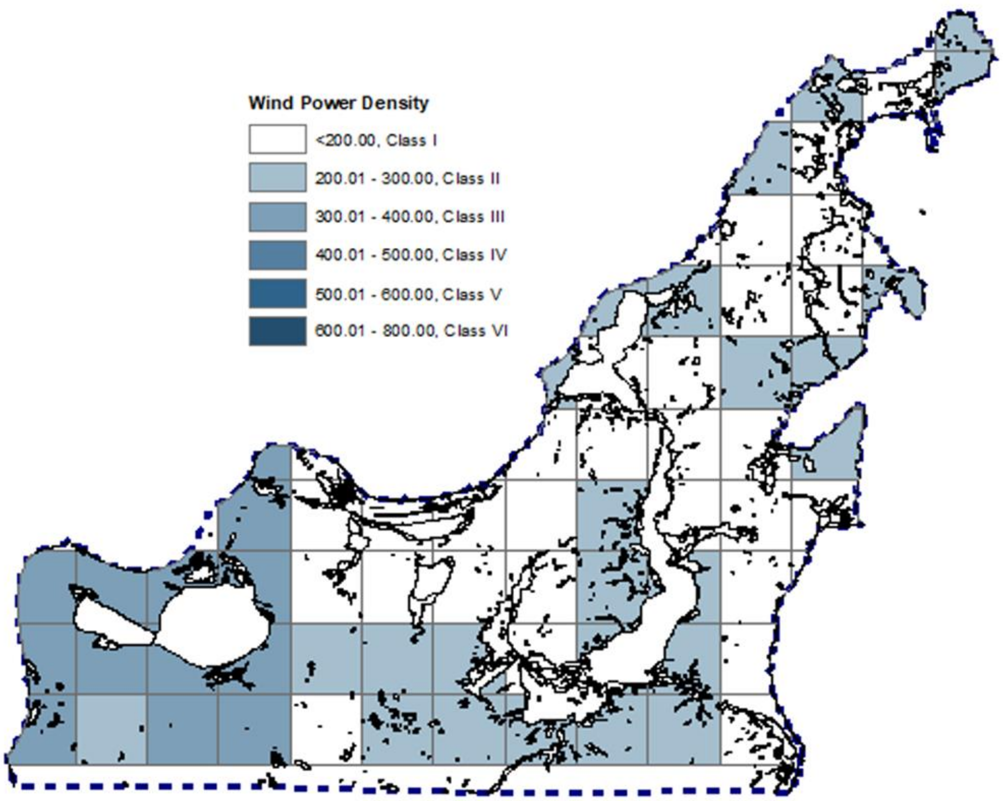


Fig 15. Annual Wind Energy Resources

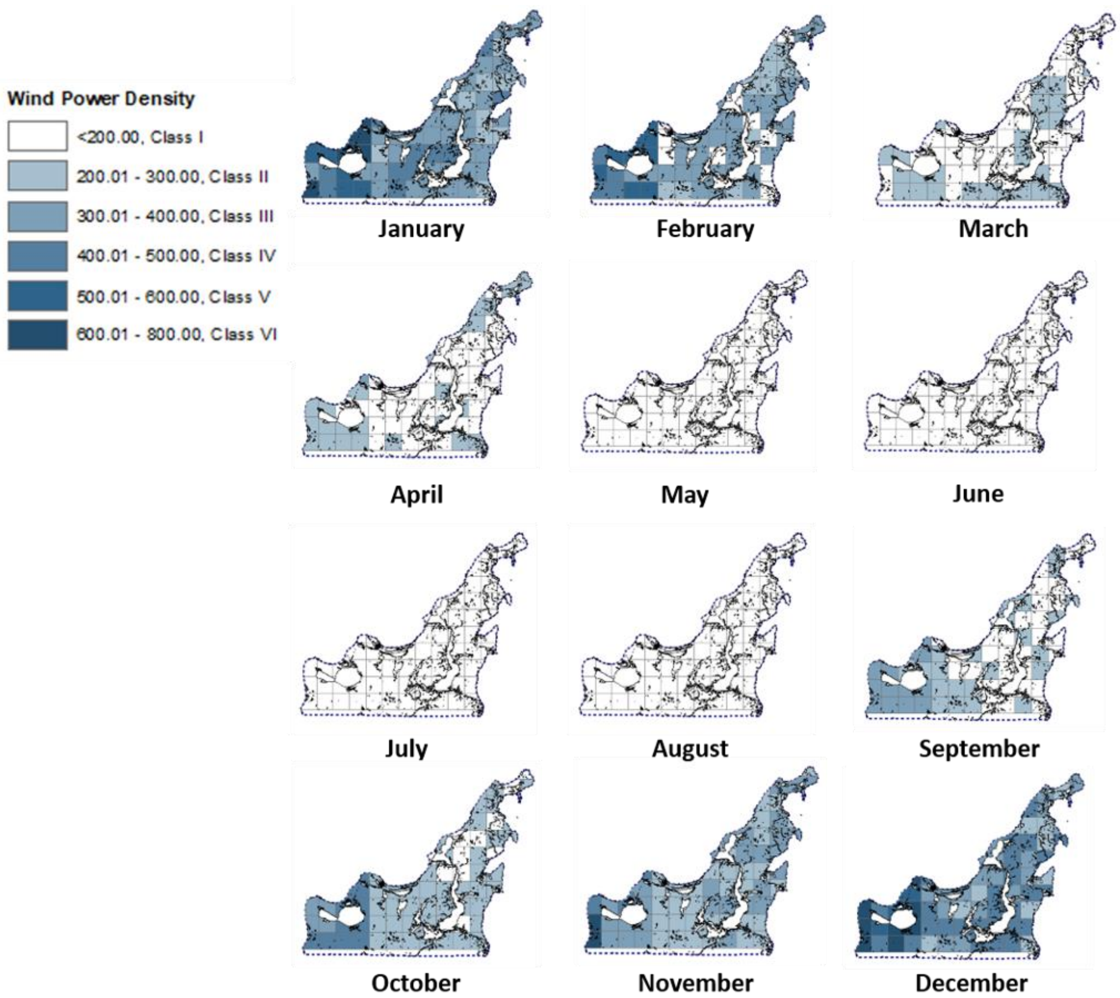


Fig 16. Seasonal Variation of Wind Energy Resources

3.3 Solar Energy Resources

Figure 17 illustrates solar energy resources across the County, and some areas in the west part of Leelanau County appear to have a slightly better solar resource. However, the range of variation is very narrow, from 3.75 to 4.0 kWh/m^2 per day across the county.

Similar to wind, the solar resource is highly seasonally variable as shown in Figure 18. From April to September, the solar resource is excellent, with a potential from 4 kWh/m^2 to 7 kWh/m^2 per day. However, in winter, the solar resource is not adequate for commercial electricity production.

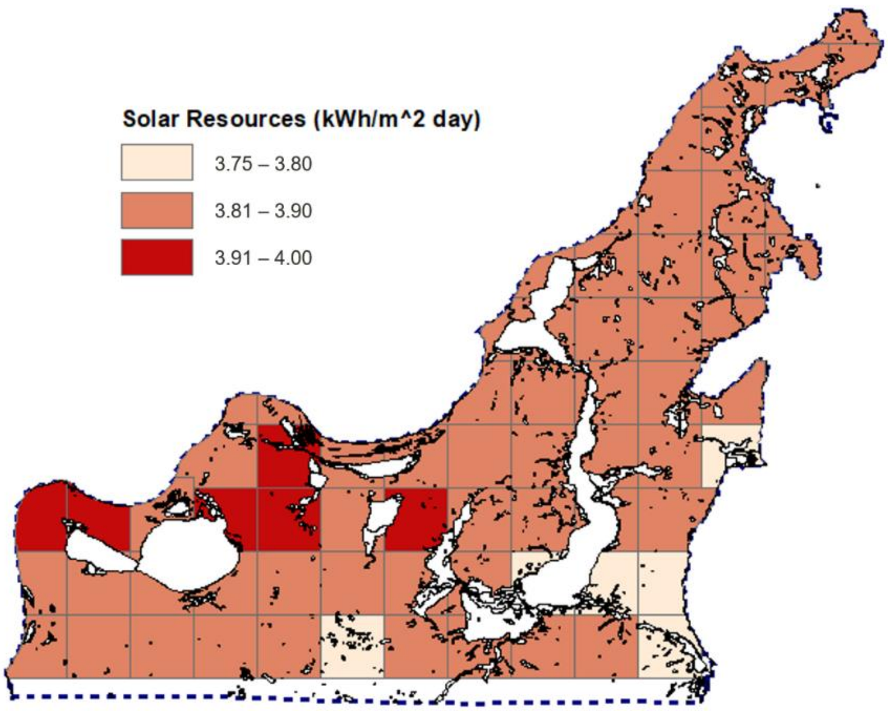


Fig 17. Annual Solar Energy Resources

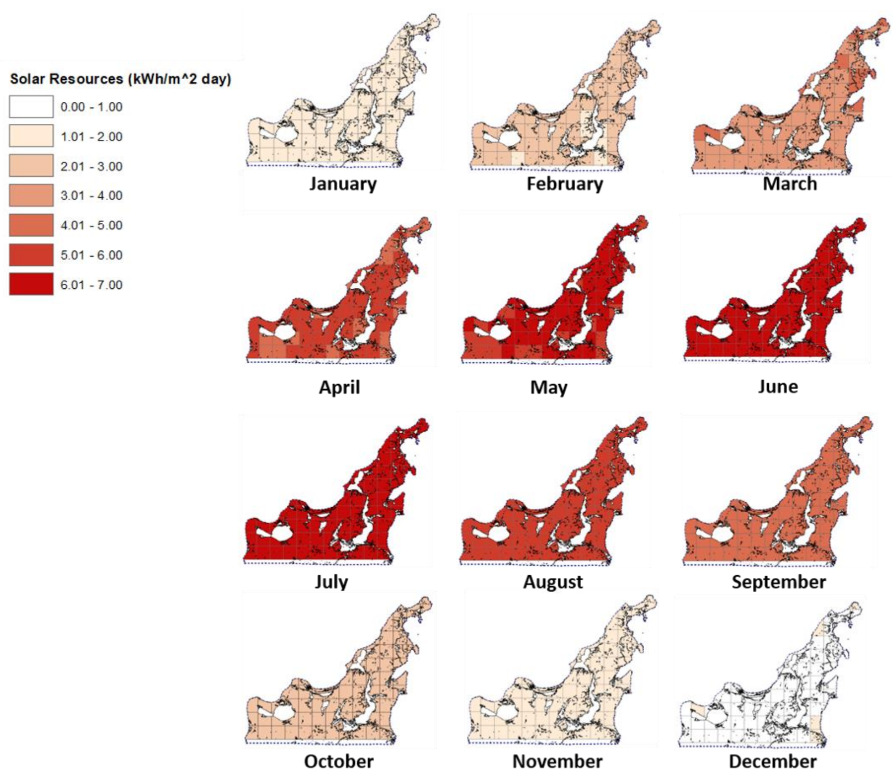


Fig 18. Seasonal Variation of Solar Energy Resources

Given the fact that the wind energy resource is excellent in winter and poor in summer, while solar energy resource is abundant in summer and insufficient in winter, a 100% renewable energy plan should emphasize harvesting the wind resource to meet electricity demand in winter and the solar resource to meet demand in summer.

3.4 Suitable Areas for Wind Turbine and Solar PV Installations

Figure 19 shows the total area suitable for wind turbines, which is 95.41 km^2 (23,576 acres), about 14.1% of land area in Leelanau Peninsula not including water body. Possible areas for wind turbines are shown as follows. All areas that do not meet the constraints shown in Figure 19 were excluded and are shown in black. Low suitability is indicated by green while red represents areas with high suitability for wind turbine installations. The east side of the county is generally more suitable for wind turbine facilities. One of the main reasons is that this area is close to transmission lines and a large portion of the land in this area is in compatible land cover types: cultivated crop, shrub, pasture, or herbaceous land.

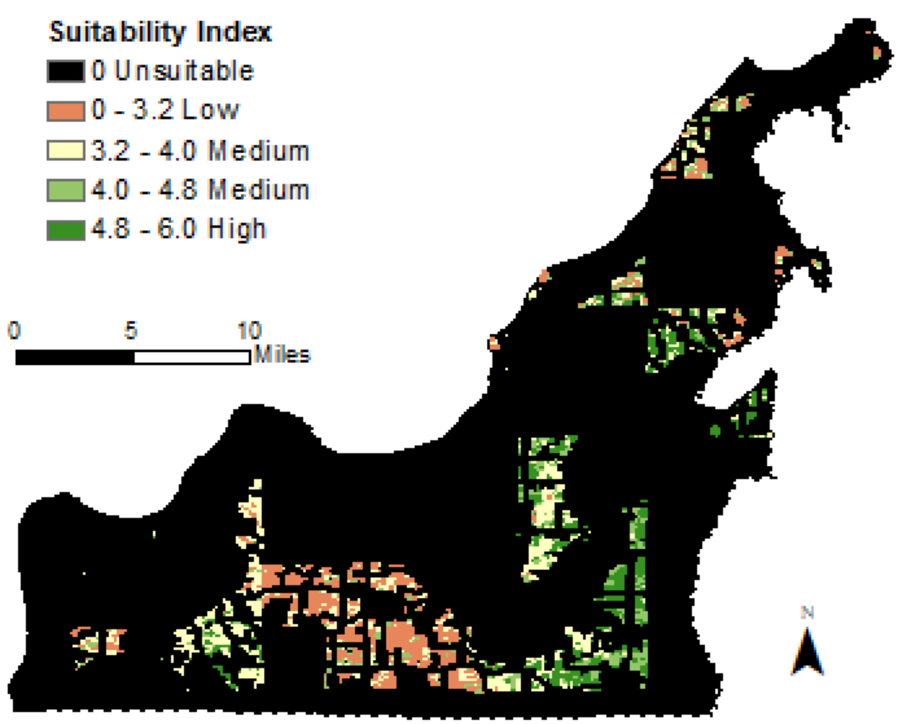


Fig 19. Suitable Areas for Wind Power Facilities

However, land areas that would be suitable for wind turbine installations were divided into pockets. Pockets smaller than $0.0204km^2$ (5.04 acres) were excluded for turbine deployment since a 3.4MW wind turbine would require that much land.

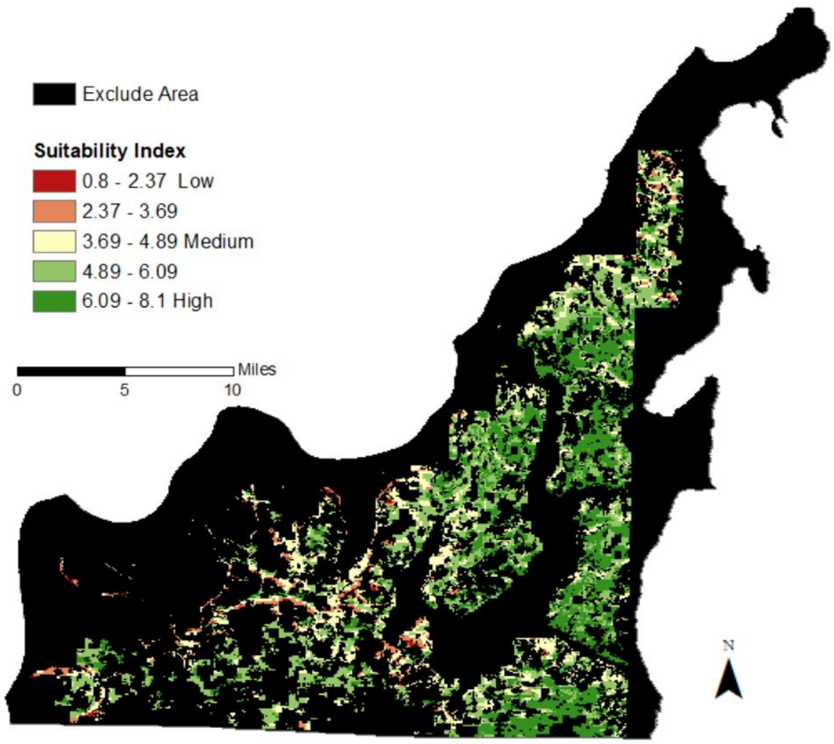


Fig 20. Suitable Areas for Solar Panel Installations

The total land area suitable for solar PV is $213.41km^2$, which is 52,735 acres, 31.5% of the land area in the county. The suitability of the deployment of solar PVs is relatively uniform across the county as shown in Figure 20, with a medium to high suitability.

4. Energy Storage Assessment

One aspect of renewable energy generation that must be considered in a 100% renewables plan is that of energy storage. Due to the variability of renewable resources, energy storage can help meet peak demands and periods of lower generation from renewables. Current grid infrastructure does not have the capacity to store surplus energy generation, so an investigation into storage technology will be coupled with consumption data for Leelanau County to produce an initial estimate for sizing grid storage.

4.1 Energy Storage Technologies

Accounting for the high penetration of variable-renewable energy in the grid, it is necessary to add energy storage in order to accommodate uncontrolled variability and to maximize the utilization of renewable energy generation through solar photovoltaic systems and wind turbines. The need for energy storage can be justified by the simple observation in this project that a wind farm consisting of 17 wind turbines, 3.4 MW each, can generate enough energy over the span of a year to meet the annual energy demand of the county. However, in order to utilize this energy at the hours of the year when the solar and wind energy generation is less than the demand requires the addition of energy storage.

In the US electricity grid, energy storage systems currently account for 2.5 percent of the electricity delivered (Center for Sustainable Systems, 2018). This project analyzed the use of battery-based electrical energy storage systems. This involves the integration of lead acid, lithium-ion, or vanadium-flow batteries to bridge the gap between generation and electricity demand. Other opportunities lie in utilization of thermal energy storage and demand side management to fit the demand curve to the Variable Renewable Energy (VRE) generation. Figure 21 summarizes the battery choices available for deployment of grid-scale energy storage. Battery-based electrical energy storage benefits from features like modularity, controllability for VRE generation, high round-trip efficiency, flexible power and energy characteristics to meet grid functions, long cycle life and low maintenance requirements. Table 11 shows the parameters for comparison between different energy storage technologies on a grid scale storage installation.

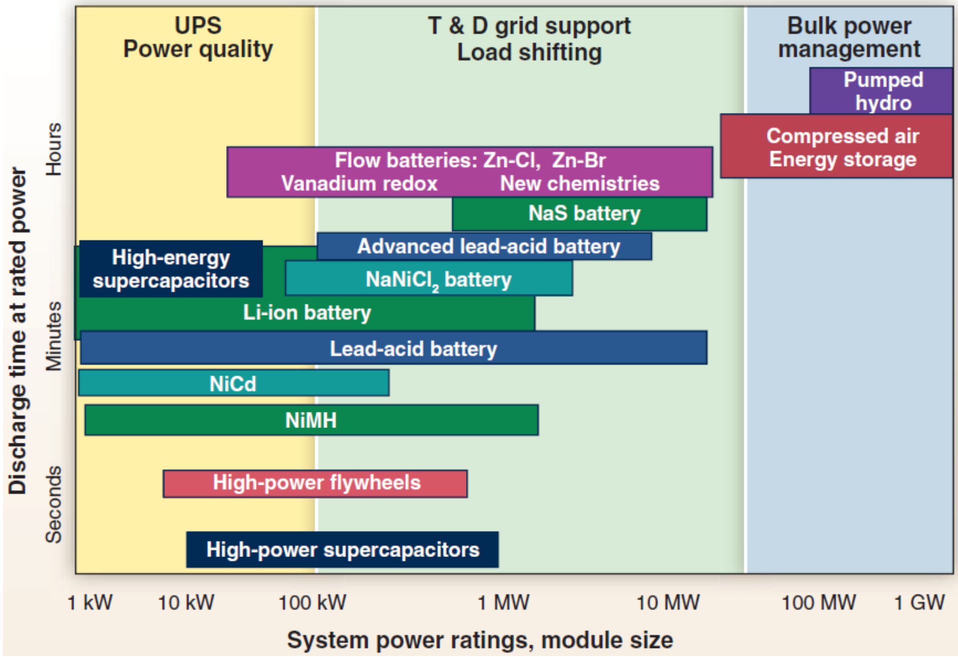


Fig 21. Current Battery Technologies and Their Properties

(Source: Dunn et al., 2011)

In the absence of energy storage technologies, renewable energy generation has to be built with enough capacity to meet the electricity demand in a micro-grid at every point in time. This can be exceptionally challenging in situations where the available renewable energy resources are not sufficient to meet the demand at certain points in the year. This also leads to the high probability that most of this built capacity sits idle for most of the year. Energy storage performs the important function of matching supply and demand over a time period without having to curtail the generation from VRE resources. Energy Storage Systems also can ensure that the demand at any point in time is met at the lowest possible generation cost.

For the purposes of this project, lithium ion batteries were considered. Vehicle-to-grid technology can be utilized as a way to reduce the battery storage capacity required. However, due to lack of knowledge of the availability of the vehicle batteries at off-peak hours and the battery capacity degradation concerns among EV battery manufacturers, the adoption of EVs has only been modelled as an increase in demand and Vehicle-to-Grid (V2G) storage potential has not been modelled.

Table 11. Parameters for different energy storage systems

	High round-trip efficiency (%)	High service life (year)	Low capital cost ($/MW)	Low capital cost ($/MWh)
pumped-hydro storage (PHES) [5], [6], [8], [34], [35], [37]	85	60	441,000	5,000
adiabatic compressed-air energy storage (ACAES) [5], [6], [8], [34]	95	60	700,000	40,000
diabatic compressed-air energy storage (DCAES) [5], [6], [8], [34]	60	60	400,000	2,000
lead-acid (PbA) battery [6], [7], [8], [34], [35]	90	15	222,000	200,000
vanadium redox flow battery (VRFB) [6], [8], [34], [35]	95	15	398,000	150,000
Li-ion battery [6], [34], [39]	98	20	400,000	600,000
sodium-sulfur batteries (NaS) [5], [6], [8], [34], [35], [39]	90	15	350,000	350,000
polysulfide bromide battery (PSB) [8], [35]	85	15	330,000	120,000
zinc–bromine battery (ZBB) [5], [8], [35]	75	10	178,000	150,000

(Source: Arbabzadeh, 2018)

Redox-flow Batteries

Redox-flow batteries have the advantage that the power and energy are decoupled, resulting in design flexibility for stationary energy storage applications. The energy capacity of the battery is influenced by the capacity of the reservoir and concentration of the electrolyte and the power rating can be varied by changing the connections among the cells. The technology faces application concerns due to the lack of preceding large-scale deployment. The requirement of a flow management system and membrane performance are other potential concerns. The system needs research to find better membranes. Based on the data from Table 11, it also can be seen that higher service life and higher roundtrip efficiency favor the use of lithium-ion battery systems as grid scale energy storage.

4.2 Methods

The required capacity of energy storage was calculated in order to ensure that the battery system can meet the maximum cumulative difference between the County electricity demand and available VRE generation over a span of multiple hours. The battery system is assumed to lose 5 percent of the energy stored as standby loss (Battery Education, 2006). The maximum energy capacity of the battery storage system can be decided with a consideration for annual demand met and the total capacities of the wind farms and solar photovoltaic installations. The maximum power rating of the battery is the maximum power entering or leaving the battery at any hour. The energy capacity of the battery was varied between 100 MWh and 600 MWh. The energy capacities of major lithium-ion (Tesla, 2017; PG&E, 2018) and Vanadium flow (Uni Energy) battery storage stations were used to set the above limits. The footprint area required for the installation of the energy storage system is not accounted for in this land area constraints.

4.3 Results

At 100 MWh, the maximum power rating of the battery was found to be 54.4 GW. The system is capable of meeting 80 percent of the demand with 27.5 MW of installed solar and 30.6 MW (9 * 3.4 MW) capacity of wind turbines. A 600 MWh battery system allows 92 percent of the demand to be met and reduces the electricity sold to the grid from 94.13 GWh to 10.84 GWh in the first year.

4.4 Discussion

The land footprint constraint might be a limiting factor for the deployment of the energy storage system. A comparison of grid-scale energy storage systems on the basis of land area requirement and cost per MWh can be considered to choose the energy storage technology to be utilized. The availability of second-use EV batteries can result in a reduction in cost of the battery storage system involved. The cost of battery storage is discussed in the following chapter.

5. 100% Renewable Energy Plan

5.1 Methods

Electricity demand was assumed to be correlated with the population of the county for the purposes of forecasting demand 20 years into the future. Based on the population projections for 2040, the electricity demand projections for 2040 were made using the 2018 total county electricity usage data provided by Cherryland Electric Cooperative and Consumers Energy.

Based on the resource potential assessment for the county, the total generation potential using all available undeveloped land was projected. Resource potential data combined with the land suitability analysis for installation were used as a criterion to divide the available land between solar photovoltaic installation and wind farms. The land area requirement for wind farms was obtained from Denholm et al. (2009) and the average area requirement of 0.0204 km^2 per turbine was used. Technical data for the Vestas 3.4 MW wind turbines (Bauer, L) were used to predict the annual generation potential from each wind turbine.

A model was developed to compare the power demand projections in 2040 to the potential power generation from VRE resources and a battery system. The model was designed such that the surplus generation - between the projected electric demand and total renewable generation - is stored into the battery storage. As the batteries accumulate this energy over multiple hours, it can be utilized later to meet the electricity demands in the hours when the generation is less than demand. It is also important to deduct the energy lost as the losses from the batteries. Hence, the size of the battery storage system required is the maximum value between the energy required to be provided by the batteries and the energy flowing into the batteries. Then the percentage of annual hours that the total renewable energy (solar photovoltaics + wind generation + energy from batteries) is able to meet the demand is calculated. The percentage of land covered with solar photovoltaics, energy capacity of the battery and the number of wind turbines is varied and the values of percentage of hours on renewable energy surplus generation sold to the grid and energy bought from the grid over a year are noted. These calculations can be reiterated multiple times to evaluate the performance of different combinations of renewable generation and storage, and identify the best performing combinations.

Algorithm

In order to assess the fraction of demand met from renewable energy sources developed in the County, the system was modelled to compare the electricity generation from solar photovoltaic and wind turbine farms deployed on the available land with demand as shown in Figure 22. The value of total renewable generation was calculated as the sum of generation from solar photovoltaic installation and wind farms. If the power generated at hour t is higher than the demand at hour t, the surplus is fed to the battery storage. The battery energy capacity is presented as an input for the model and can be varied between 100 MWh and 600 MWh (based on the battery capacity limits indicated in Chapter 4). The battery power rating is determined by the maximum flow of power in/out of the battery.

The excess generation is stored in the battery until the energy capacity of the battery system is reached. Beyond this point, any excess generation is sold to the grid. At the same time, if at hour t, the generation and the battery cannot meet the demand, the electric power is bought from the grid. These calculations are performed for t=0 to t=8760 (span of a year). At the end of a year, the cumulative energy sold and bought from the grid is found. The fraction of 8760 hours when the demand can be met using renewable generation and storage is calculated.

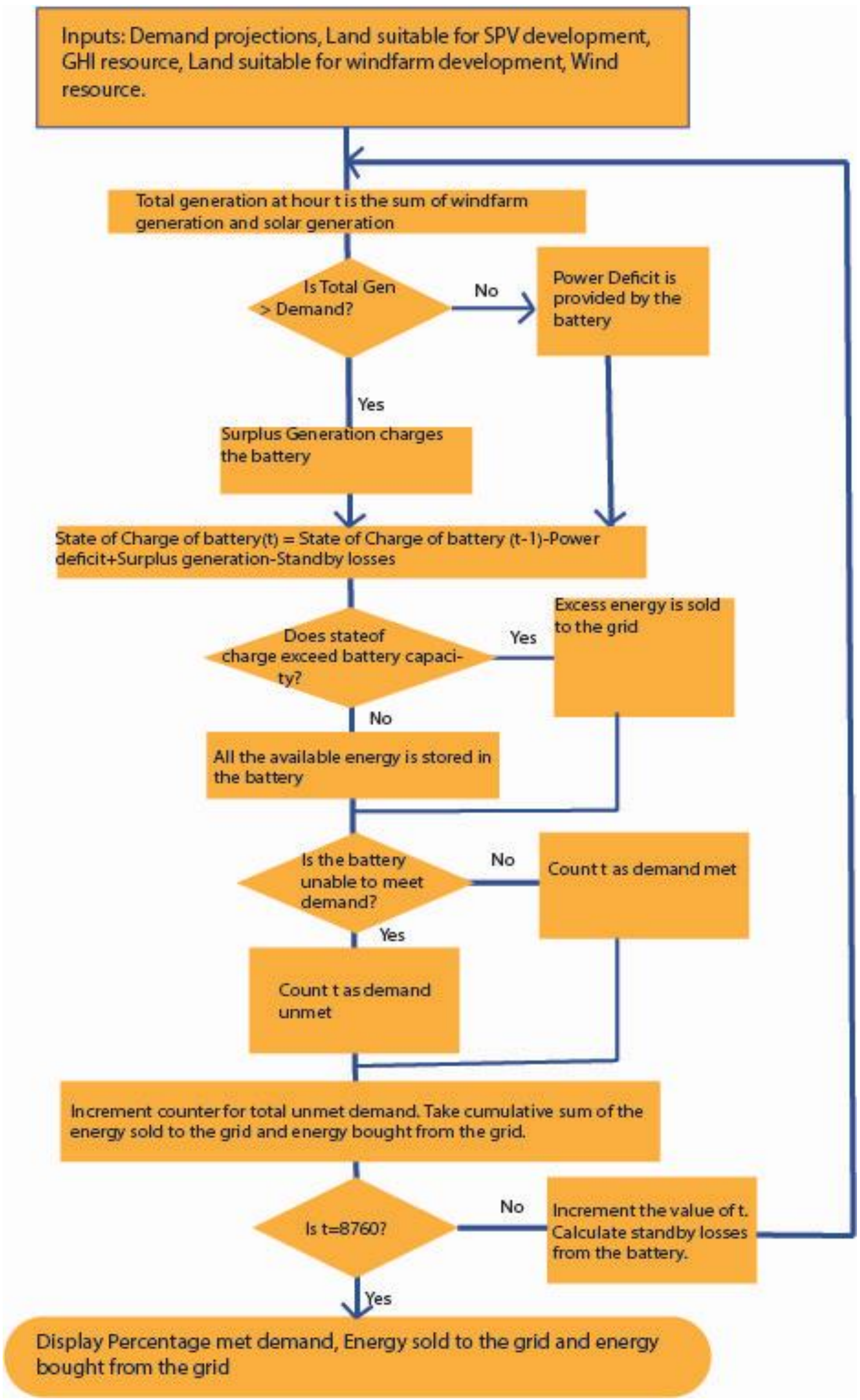


Fig 22. Algorithm Logic of Energy Storage Model

5.2 Economic Considerations

Along with the capability to meet the demand, it is necessary to evaluate a system for its cost of installation, operation and maintenance. Table 12 lists the economic assumptions for solar photovoltaics, wind turbines and lithium-ion battery storage system. Overall project life is assumed to be 25 years. The electricity drawn from the grid is expected to decrease as the capacity of renewable generation deployed in the county increases. There is revenue generated from the sales of electricity from the deployed renewables. All installations are finished by the year 2030 and only operations and maintenance costs are paid for.

Table 12. Assumptions for Economic Calculations for Solar Photovoltaics, Wind Turbines and Lithium-ion Battery Storage

Variable	**Value**	**Units**	**Source/ Justification**
Installed Cost of SPV	1,060,000	$/MW	(Fu et al 2018)
Installed Cost of WT	15,900,000	$/MW	(Stehly et al, 2017)
Installed Energy Cost of Battery	316	$/kWh	(Lazard, 2018)
Installed Power Cost of Battery	105.5	$/kW	(Lazard, 2018)
O&M Cost of SPV	13,000	$/MW-yr	(Fu et al, 2018)
O&M Cost of WT	52,000	$/MW-yr	(Stehly et al, 2017)
O&M Cost of Battery	3.03	$/kWh-yr	(Lazard, 2018) (=0.96% yearly of installed cost)

5.3 Results

The algorithm was run for multiple combinations of installed solar capacity, installed wind capacity and energy capacity of the battery system. Six combinations with demand met fraction greater than 80 percent were chosen as representative results (Table 13). The installed capacities of solar photovoltaics, wind farms and battery storage can be varied independent of each other, allowing for better flexibility in visualizing the variation in generation and economic considerations. The individual combinations are listed as follows.

Table 13. Capacity of Solar Photovoltaics, Wind Turbines, Battery Storage and Demand Met, Energy Sold to the Grid and Bought from the Grid under 6 combinations

#	Solar PV (MW)	Wind Turbines (MW (# of turbines))	Battery (MWh)	Demand Met (%)	SaletoGrid (TWh/yr)	BoughtfromGrid (GWh/yr)
1	15.96	30.6 (9)	200	89	0.063	16.18
2	159.62	51.0 (15)	100	81	1.132	7.72
3	159.62	34.0 (10)	100	94	1.056	11.56
4	159.62	51.0 (15)	600	100	0.938	0
5	159.62	51.0 (15)	384	100	1.018	0
6	159.62	30.6 (9)	600	100	0.749	0

Based on the above rates, the capital expenditure for installing the system was estimated as follows:

Capital Expenditure = (Installed Cost of Solar PV per MW) * (Nameplate Capacity of Solar PV) + (Installed Cost of Wind Turbines per MW) * (Nameplate Capacity of Wind Turbines) + (Installed Cost of Battery per MWh) * (Nameplate Energy Capacity of Battery)+ (Installed Cost of Battery per MW) * (Nameplate Power Rating of Battery)

The yearly Operations and Maintenance expenditure was estimated as follows:

Operating Expenditure/yr = (Operating Cost of Solar PV per MW) * (Nameplate Capacity of Solar PV) + (Operating Cost of Wind Turbines per MW) * (Nameplate Capacity of Wind Turbines) + (Operating Cost of Battery per MWh) * (Nameplate Capacity of Battery)

The energy bought from the grid serves as another cost for the system. However, the system is able to displace a fraction of the electricity demand of the County every year. This avoided cost would count as revenue from the system. Similarly, excess generation sold to the grid generates revenue.

Net Revenue/yr = Rate of electricity ($/kWh) * (Energy sold to the grid per year-Energy bought from the grid per year)

Under six different system configurations, the capital expenditure, the operating costs over the lifetime of the project (25 years) and the revenue generated are estimated and shown in Table 14. Figure 23 shows the variations of the capital expenditure, operating expenditure (25 years) and net revenue (25 years) for the six combinations.

Table 14. Capacity of solar PV, wind turbines, battery along with capital cost, operating costs and revenue calculations for 6 combinations

#	Solar PV (MW)	Wind Turbines (MW (# of turbines))	Battery (MWh)	Total Generation (GWh/yr)	Capital Cost (million USD)	Operating Cost (million USD)	Net Revenue (million USD)
1	15.96	30.6 (9)	200	257.63	129.51	66.10	163.43
2	159.62	51.0 (15)	100	1317.37	282.94	185.61	3936.06
3	159.62	34.0 (10)	100	1236.27	255.91	163.51	3656.67
4	159.62	51.0 (15)	600	1317.37	443.09	223.48	3282.99
5	159.62	51.0 (15)	384	1317.37	374.35	207.12	3563.30
6	159.62	30.6 (9)	600	1219.89	410.96	196.96	2622.20

It can be seen that the yearly generation from the system is many times higher than the annual energy demand. As a result, there is enough surplus generation to generate revenue higher than the total cost of the system. At the same time, the surplus generation is not lost due to curtailment. In the absence of a connection to the grid, this opportunity will be forfeited. However, these calculations do not account for the inability to sell electricity to grid during the congestion periods. It would be necessary to upgrade the grid infrastructure in the region in order to utilize and sale more of the excess renewable energy. Simultaneously, this would affect the fraction of the demand met by the system through renewable energy. Increasing the capacity of the battery storage can help address both of these issues at the same time. It can be observed by comparing combinations 2-4 that decreasing the size of the battery storage without changing the installed capacity of solar PV and wind turbines decreases the fraction of demand met by the system. However, comparing combinations 4 and 5 illustrates that increasing the battery storage capacity also reduces the amount of energy that needs to be sold to the grid.

Levelized Cost of Electricity (LCOE) is an essential metric to represent the cost of producing electricity taking into account the capital and operating costs of generating electricity over the entire lifetime of the project.

$$\boldsymbol{Levelized\ Cost\ of\ Electricity} = \frac{(CRF * Capital\ Cost + Annual\ Operating\ Cost)\ (\$)}{Total\ Annual\ Generation\ (kWh)}$$

where:

$$Capital\ Recovery\ Factor\ (CRF) = \frac{d(1+d)^n}{(1+d)^n - 1}$$

d = discount rate.

For the three scenarios resulting in 100 percent renewable electricity generation, the estimation of LCOE can be done using the capital costs, total operating costs and the total generation from the system. Hence, the values of LCOE has been estimated for combinations 4-6 and are summarized in Table 15.

Table 15. LCOE estimates for 3 combinations

#	Solar PV (MW)	Wind Turbines (MW (# of turbines))	Battery (MWh)	Total Generation (Gwh/yr)	LCOE ($/kWh)
4	159.62	51.0 (15)	600	1317.37	0.224
5	159.62	51.0 (15)	384	1317.37	0.194
6	159.62	30.6 (9)	600	1219.89	0.205

5.4 Discussion

The reliability of the projections is restricted by the fact that population-based projections do not account for the changes in electricity demand due to energy efficiency measures on the demand side. With a potential reduction in demand from energy efficiency of 0.5% per year estimated from the earlier study (Cecco et al., 2016), the possibility that the installed Solar-Wind-Battery system will meet a higher percentage of the demand cannot be eliminated. However, a conservative estimate is necessary to ensure that the highest possible demand can be met. The seasonality of the county population is not accounted for in the model because the electricity projections are assumed to proportional to the highest annual county population and the 2018 electricity data is assumed to vary with respect to the seasonal changes in population.

For solar photovoltaic installations, any potential for rooftop installations has not been accounted for as only undeveloped land around the county was utilized to estimate potential solar energy generation. Based on EIA data for net capacity of small-scale solar installation (EIA, 2017c) in the United States for 2014-2017 (Fig. 24), the installed capacity of residential solar photovoltaics will keep growing. This can also be seen from the projections made in Annual Energy Outlook (2019), where the net summer capacity of solar photovoltaics in the Midwest is predicted to grow at 6.3 percent per year between 2017 and 2050.

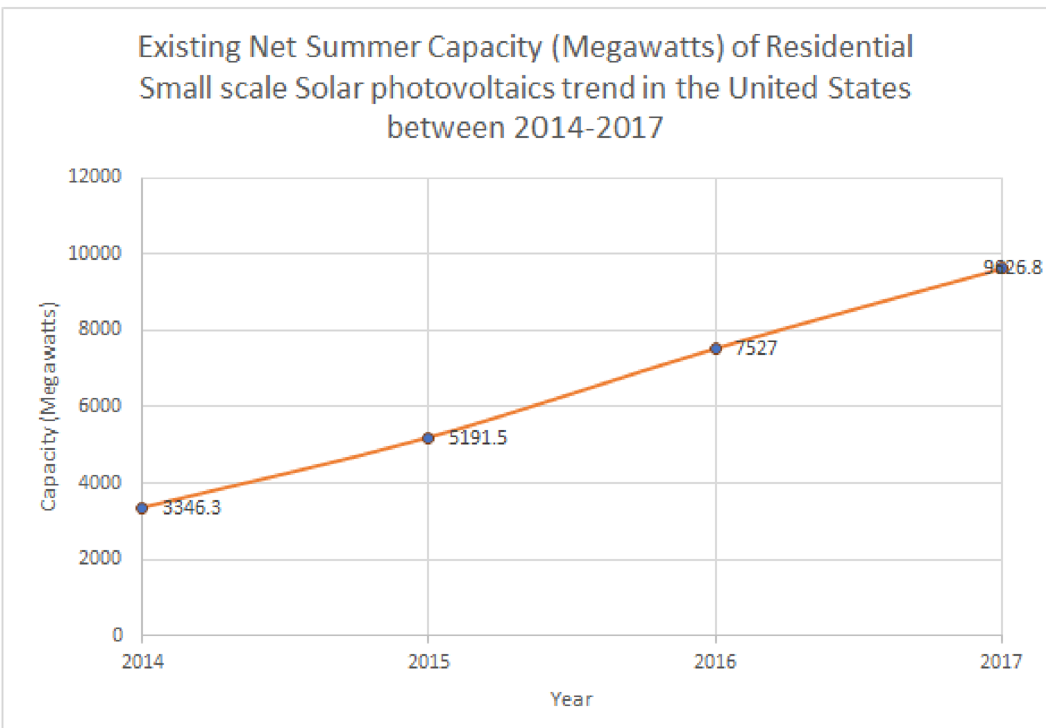


Fig 23. Net Existing Solar Rooftop Capacity

(Source: EIA, 2017)

As a part of the Integrated Resource Plan put forth by Consumers Energy for consideration by the Michigan Public Service Commission, the utility plans to retire over 4 GW of its fossil fuels-based generation capacity by 2039 (Consumers Energy, 2018). This retired capacity is set to be replaced by sustainable energy solutions in the form of energy efficiency and demand response measures and generation through solar and wind power. The total installed capacity is set to be 8 GW by 2040. The utility plans to tap into the low-risk, high-yield opportunities like energy efficiency and demand response, followed by building capacity in grid-scale solar photovoltaics, wind and eventually adding large-scale battery storage. While this plan is not specific to the county, it can be used as proxy for the development of renewable electricity capacity for the county.

Overall, a combination of wind and solar energy has the potential to meet the 100 percent goal of powering the county with renewable energy source. 52% of land areas in Leelanau Peninsula have a Class II or above wind class, which is suitable for wind turbine installations. Solar resource potential available in the County ranges between 3.5 – 4.0 kWh/m^2 per day. The most significant feature of wind and solar resources is their seasonality. There is more reliance on wind energy during winter and solar energy during summer.

Suitability analysis for wind and solar facilities showed that 95.41 km^2 (23,576 acres, 14.1%) and 213.41km^2 (52,735 acres, 31.5%) of land areas are suitable for wind turbine and solar PV installations respectively. The criteria and weights applied in this project were derived from other studies. To develop a more holistic decision regarding site selection, pairwise comparisons and interviews among different stakeholders in Leelanau County would be needed.

Fraction of demand met, surplus energy generation, energy bought from the grid, capital and operating expenditures, and net revenue to the community from selling renewable electricity were identified as key parameters to evaluate multiple renewable electricity deployment options. Six combinations of representative results were evaluated which can meet 88.9-100 percent of the annual electricity consumption. For these combinations, the capital expenditure was found to range between $0.56-1.17 billion and operating costs for 25 years lies between $60-163 million. At the same time, the system has excess capacity of 0.063-1.13 TWh/yr, which can be sold back to the grid to generate revenue. A net annual revenue of $6-157 million dollars is possible.

It becomes difficult to keep track of the values of these parameters individually when making decisions. The parameters can be weighted in order to create a scoring system or a decision support tool for the renewable electricity options. Potential demand reduction due to onsite generation in the form of small-scale photovoltaics and wind turbines has not been incorporated in this project and could be analyzed in future research.

References

Aydin, N.Y., Kentel, E., & Duzgun, S. (2010) GIS-based environmental assessment of wind energy systems for spatial planning: a case study from Western Turkey. Renew Sustain Energy Rev 14:364-373. https ://doi.org/10.1016/j.rser.2009.07.023

Arbabzadeh, M. (2018). Green Principles, Parametric Analysis, and Optimization for Guiding Environmental and Economic Performance of Grid-scale Energy Storage Systems.

Baños, R., Manzano-Agugliaro, F., Montoya, F., Gil, C., Alcayde, A., & Gómez, J. (2011). Optimization methods applied to renewable and sustainable energy: A review. Renewable and Sustainable Energy Reviews, 15(4), 1753-1766. doi:10.1016/j.rser.2010.12.008

Baris, K.B., Bahadir, S., Ulucan, A., & Umur, M. (2015) A GIS-based multiple criteria decision analysis approach for wind power plant site selection. Util Policies 3:86-96. https://doi.org/10.1016/j.jup.2015.06.001

Battery Education (2006) Battery Degradation and Power Loss. Retrieved from http://www.batteryeducation.com/2006/04/battery_degrada.html

Bauer, L. (n.d.). Start. Retrieved from https://en.wind-turbine-models.com/turbines/1282-vestas-v136-3.45

Bazmi, A. A., & Zahedi, G. (2011). Sustainable energy systems: Role of optimization modeling techniques in power generation and supply—A review. Renewable and Sustainable Energy Reviews, 15(8), 3480-3500. doi:10.1016/j.rser.2011.05.003

Bechrakis, D., & Sparis, P. (2000). Simulation of the Wind Speed at Different Heights Using Artificial Neural Networks. Wind Engineering, 24(2), 127-136. doi:10.1260/0309524001495503

Benchmarks Northwest (2012). County Population Projections. Retrieved from http://www.benchmarksnorthwest.org/userfiles/uploads/PopProj2015to2040-Leelanau-26089.pdf

Blanchard, R. (2017). Property Assessed Clean Energy (PACE) Renewable Energy Program Plan and Pilot Project

Bradshaw, A. (2017). A Multicriteria GIS-Based Approach to Wind Energy Siting in Brazil. International Association for Energy Economics (IAEE).

Cecco, L., Chen, Y., Good, J., Lai, K.H., Loshakova, E., & Weinberg, E. (2015). Northport 100% Renewable Energy Feasibility Study.

Center for Sustainable Systems, University of Michigan. 2018. "U.S. Grid Energy Storage Factsheet." Pub. No. CSS15-17.

Consumers Energy (2018). 2018 Integrated Resource Plan. Retrieved from https://www.consumersenergy.com/-/media/CE/Documents/sustainability/integrated-resource-plan-summary.ashx?la=en&hash=9F602E19FE385367FA25C66B6779532142CBD374

Data Access and Dissemination Systems (DADS) (2010). American FactFinder - Results. Retrieved from https://factfinder.census.gov/bkmk/table/1.0/en/ACS/17_5YR/DP05/0100000US

Denholm, P., Hand, M., Jackson, M., & Ong, S. (2009). Land Use Requirements of Modern Wind Power Plants in the United States. doi:10.2172/964608

Dhamo Gjika, Eralda & Puka, Llukan. (2010). Using the R-package to forecast time series: ARIMA models and Application.

Díaz-Cuevas, P., Biberacher, M., Domínguez-Bravo, J., & Schardinger, I. (2018). Developing a wind energy potential map on a regional scale using GIS and multi-criteria decision methods: The case of Cadiz (south of Spain). Clean Technologies and Environmental Policy, 20(6), 1167-1183. doi:10.1007/s10098-018-1539-x

Dunn, B., Kamath, H., & Tarascon, J. M. (2011). Electrical energy storage for the grid: a battery of choices. Science, 334(6058), 928-935.

Environmental Systems Research Institute (ESRI). (2018). ArcGIS Release 10.6. Redlands, CA.

Environmental Systems Research Institute (ESRI). (2007). Retrieved from http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?topicname=natural_breaks_(jenks)

Federal Aviation Administration, National Transportation Atlas, & Esri. (2018). [USA Airports]. ArcGIS Online. Geospatial dataset.

Federal Communications Commission, & Rayer, J. (jrayer_geoplatform). (2018). [Microwave Service Towers]. ArcGIS Online. Geospatial dataset.

Federal Emergency Management Agency, Atkins, Strategic Alliance for Risk Reduction, & Morgan, J. (Jesse.Morgan_FEMA). [Leelanau County, Michigan – Coastal Flood Analysis]. ArcGIS Online. Geospatial dataset.

Fu, R., Margolis, R. M., & Feldman, D. J. (2018). US Solar Photovoltaic System Cost Benchmark: Q1 2018 (No. NREL/TP-6A20-72399).

National Renewable Energy Lab. (NREL), Golden, CO (United States).

Fuqua School of Business (2019). ARIMA models for time series forecasting. Retrieved from https://people.duke.edu/~rnau/411arim.htm

Graebert, M.B., Wyckoff, M., Bretz, L. (2014) Northwest Michigan Seasonal Population Analysis.

Homer, C., C. Huang, L. Yang, B. Wylie and M. Coan, 2004. Development of a 2001 national land cover database for the United States. Photogrammetric Engineering and Remote Sensing Vol.70, No.7, pp 829-840

Jacobson, M. Z., & Delucchi, M. A. (2011). Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy, 39(3), 1154-1169. doi:10.1016/j.enpol.2010.11.040

Kelly, J. C., Macdonald, J. S., & Keoleian, G. A. (2012). Time-dependent plug-in hybrid electric vehicle charging based on national driving patterns and demographics. Applied Energy, 94, 395-405. doi:10.1016/j.apenergy.2012.02.001

Krajačić, G., Duić, N., Zmijarević, Z., Mathiesen, B. V., Vučinić, A. A., & Carvalho, M. D. (2011). Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO2 emissions reduction. Applied Thermal Engineering, 31(13), 2073-2083. doi:10.1016/j.applthermaleng.2011.03.014

Lazard (2018). Lazard's Levelized Cost of Storage Analysis. Retrieved from https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf

Leelanau County Dept. of Equalization, & Herman, R. (2018). [Leelanau County Geographic Boundary]. Geospatial dataset.

Leelanau County Population. (2019). Retrieved 2019-04-27, from http://worldpopulationreview.com/michigan-counties/leelanau-county/

Leelanau.com. (2015). Northport & University of Michigan working on 100% Renewable Energy. Retrieved from https://leelanau.com/northport-university-of-michigan-working-on-100-renewable-energy

Lisell, L. (2018). When Does Energy Storage Make Sense? It Depends. Retrieved from https://www.nrel.gov/state-local-tribal/blog/posts/when-does-energy-storage-make-sense-it-depends.html

Mathiesen, B. V., Lund, H., & Karlsson, K. (2011). 100% Renewable energy systems, climate mitigation and economic growth. Applied Energy, 88(2), 488-501. doi:10.1016/j.apenergy.2010.03.001

Michigan Climate Action Network (2016). Michigan 100% Cities. Retrieved from https://www.miclimateaction.org/michigan_100_cities

Michigan Department of Environmental Quality (2018). State of Michigan GIS Open Data Portal. Geospatial dataset.

MPSC Electricity - Service Area Map. (n.d.). Retrieved from https://www.michigan.gov/mpsc/0,4639,7-159-16377-41337--,00.html

National Renewable Energy Lab (2017). Solar Maps.

National Solar Radiation Database (NSRDB). (2015). Retrieved from https://nsrdb.nrel.gov/tmy

Northern Express (2018). An Audacious Goal for Leelanau County. Retrieved from https://www.northernexpress.com/news/feature/an-audacious-goal-for-leelanau-county

Oak Ridge National Laboratory (2018). Homeland Infrastructure Foundation-Level Data (HIFLD) Electric Power Transmission Lines.

Ong, S., Campbell, C., Denholm, P, Margolis, R., Heath, G. (2013) Land-Use Requirements for Solar Power Plants in the United States. Retrieved from https://www.nrel.gov/docs/fy13osti/56290.pdf

PG&E Proposes Four New Cost-effective Energy Storage Projects to CPUC | PG&E. (n.d.). Retrieved from https://www.pge.com/en/about/newsroom/newsdetails/index.page?title=20180629_pge_proposes_four_new_cost-effective_energy_storage_projects_to_cpuc

Policy Institute (2015). Burlington, VT - 100% Renewable Public Power.

QGIS Development Team. (2018). QGIS Desktop (Version 3.4.1) [Computer software]. Chicago: Open Source Geospatial Foundation.

REACHING 100% RENEWABLE ENERGY City of Aspen and the National Renewable Energy Laboratory develop and implement a strategy to cost-effectively reach a groundbreaking goal. (2015). Retrieved from http://www.nrel.gov/docs/fy15osti/62490.pdf

Sengupta, M., Xie, Y., Lopez, A., Habte, A., Maclaurin, G., & Shelby, J. (2018) The National Solar Radiation Data Base (NSRDB), Renewable and Sustainable Energy Reviews, 89, 51-60. doi.org/10.1016/j.rser.2018.03.003.

Sierra Club (2019). 100% Commitments in Cities, Counties, & States. Retrieved from https://www.sierraclub.org/ready-for-100/commitments

Sliz-Szkliniarz, B., & Vogt, J. (2011). GIS-based approach for the evaluation of wind energy potential: A case study for the Kujawsko–Pomorskie Voivodeship. Renewable and Sustainable Energy Reviews, 15(3), 1696-1707. doi:10.1016/j.rser.2010.11.045

State of Michigan, Michigan Legislature. (1994). Natural Resources and Environmental Protection Act. Lansing, MI.

Stehly,T., Heimiller, D., Scott, G., (2017) 2016 Cost of Wind Energy Review. No. NREL/TP-6A20-70363. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Tesla Powerpack to Enable Large Scale Sustainable Energy to South Australia. (2017, July 07). Retrieved from https://www.tesla.com/fr_FR/blog/tesla-powerpack-enable-large-scale-sustainable-energy-south-australia

Uni Energy Technologies Strategic Partner to Deliver World's Largest Battery. (n.d.). Retrieved from http://www.uetechnologies.com/news/72-unienergy-technologies-strategic-partner-to-deliver-world-s-largest-battery

U.S. Bureau of the Census (1982) Preliminary Estimates of the Intercensal Population of Counties 1970-1979.

U.S. Bureau of the Census (1992) Preliminary Estimates of the Intercensal Population of Counties 1980-1989.

US Census Bureau (2010). QuickFacts – Leelanau County, Michigan. Internet Website: http://www.census.gov/quickfacts/fact/table/leelanaucountymichigan/NES010216 (accessed 3 May 2019).

U.S. Department of Energy (2019). Michigan 80-Meter Wind Resource Map.

U.S. Energy Information Administration (EIA) (2017a). U.S. Energy-Related Carbon Dioxide Emissions.

U.S. Energy Information Administration (2017b). State Energy Data 2016: Consumption.

U.S. Energy Information Agency (2017c). EIA adds small-scale solar photovoltaic forecasts to its monthly Short-Term Energy Outlook. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=31992

U.S. Energy Information Administration (2018a). Monthly Energy Review April 2018.

U.S. Energy Information Administration (2018b). Annual Energy Outlook 2018.

U.S. Energy Information Administration (2018c). Independent Statistics and Analysis. Retrieved from https://www.eia.gov/state/?sid=MI

U.S. Energy Information Administration (2018d). Annual Electric Power Industry Report. Retrieved from https://www.eia.gov/electricity/data/eia861/

U.S. Energy Information Administration (2019). Annual Energy Outlook 2019. Retrieved from https://www.eia.gov/outlooks/aeo/data/browser/#/?id=2-AEO2019&cases=ref2019~highmacro~lowmacro~highprice~lowprice~highrt~lowrt~aeo2018no&sourcekey=0

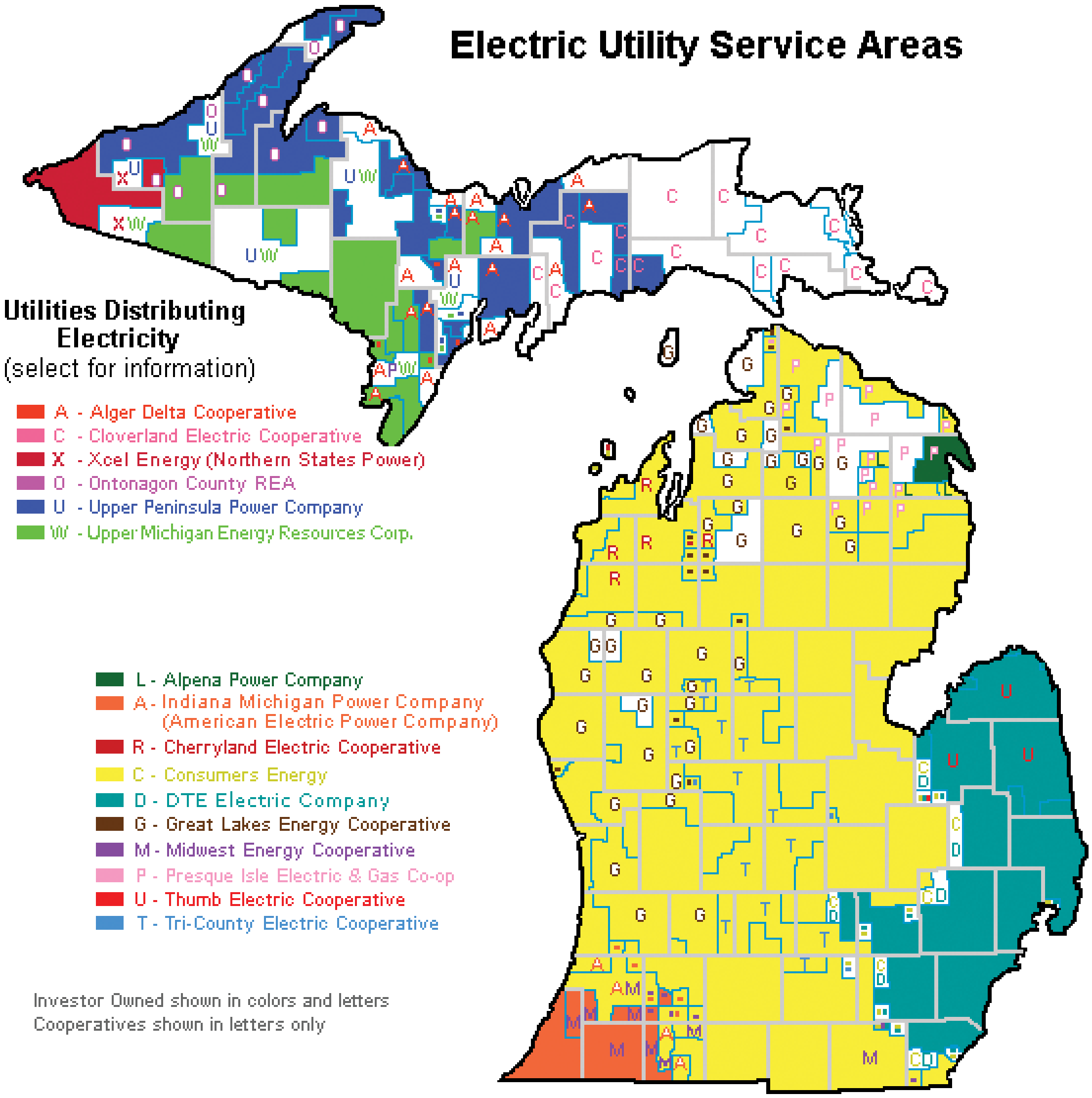
U.S. Geological Survey (2017). National Geospatial Technical Operations Center (NGTOC).

U.S. Geological Survey (2014). The National Map Small-Scale Data Download Portal. Geospatial dataset.

Villacreses, G., Gaona, G., Martínez-Gómez, J., & Jijón, D. J. (2017). Wind farms suitability location using geographical information system (GIS), based on multi-criteria decision making (MCDM) methods: The case of continental Ecuador. Renewable Energy,109, 275-286. doi:10.1016/j.renene.2017.03.041

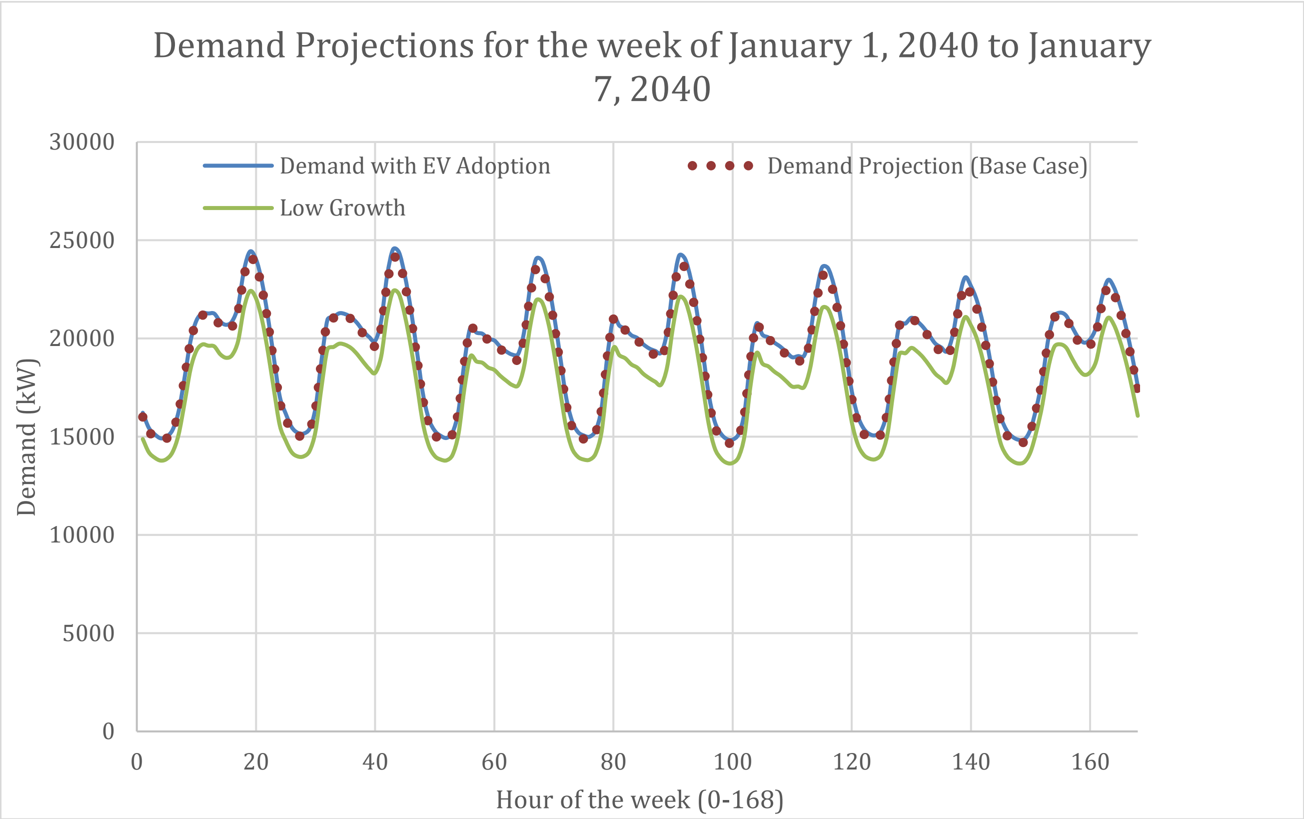
Zaman, A. (2018) 100% Variable Renewable Energy Power Systems: Survey of Possibilities.

Appendix A: Service Area Map for Electric Utilities in Michigan



Source: MPSC Electricity - Service Area Map. (n.d.). Retrieved from https://www.michigan.gov/mpsc/0,4639,7-159-16377-41337--,00.html

Appendix B: Demand Projections under the three scenarios for the week of January 1, 2040 to January 7, 2040

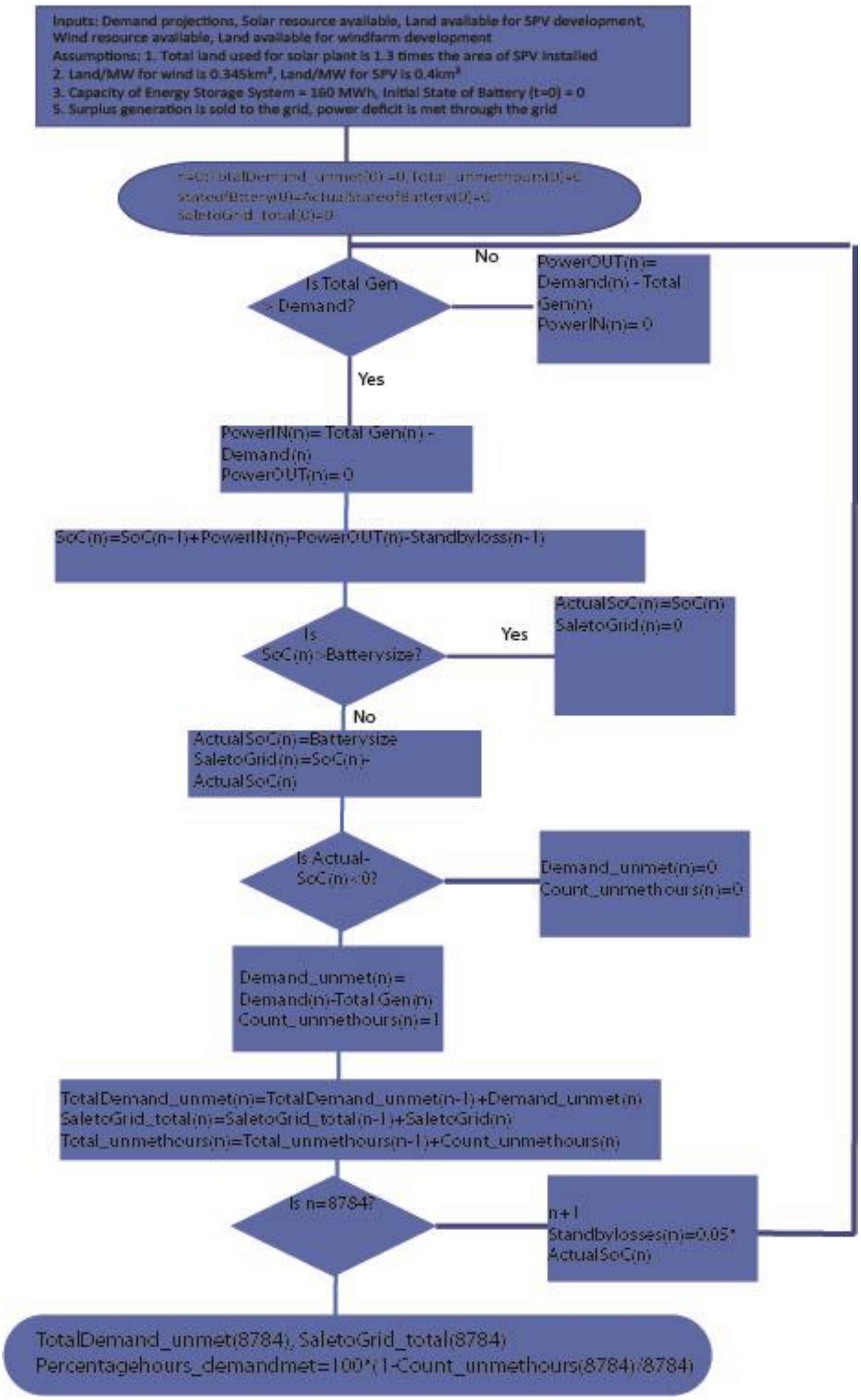


Appendix C: Sensitivity of Wind Turbine Generation to Wind shear ratio

For the original analysis, a wind shear coefficient of 0.28 was used for the entire County. Based on Table 6, a sensitivity analysis was performed to identify the variation in windfarm generation with the wind shear coefficient. The value of α was varied from 0.14 to 0.30 and the difference in generation from 15 turbines was observed. The reference value of 0.28 has been highlighted below.

α	Generation from Wind Turbines (GWh/yr)
0.14	178.38
0.15	183.82
0.16	189.42
0.17	195.19
0.18	201.14
0.19	207.27
0.20	213.59
0.21	220.09
0.22	226.80
0.23	233.71
0.24	240.84
0.25	248.17
0.26	255.74
0.27	263.53
0.28 (Reference)	271.56
0.29	279.84
0.30	288.37

Appendix D: Algorithm with Equations



$$\boldsymbol{Solar\ Generation_t} = 0.17 * Solar\ irradiance\ per\ hour\ (in\ kW)$$

$$\boldsymbol{Generation\ from\ one\ wind\ turbine\ per\ hour\ (in\ kW)} = \frac{1}{2} * C_p * Air\ pressure * Windspeed^3 * \eta_{turbine} * \eta_{generator}$$

$$\boldsymbol{BatteryIN\ (in\ kW)} = Total\ Generation\ per\ hour\ (in\ kW) - Demand\ per\ hour\ (in\ kW),\ if\ Total\ Generation\ per\ hour\ (in\ kW) > Demand\ per\ hour\ (in\ kW)$$

$$\boldsymbol{BatteryOUT\ (in\ kW)} = Demand\ per\ hour\ (in\ kW) - Total\ Generation\ per\ hour\ (inkW),\ if\ Total\ Generation\ per\ hour\ (in\ kW) < Demand\ per\ hour\ (in\ kW)$$

$$\boldsymbol{Cumulative\ BatteryIN_n} = Cumulative\ BatteryIN_{n-1} + BatteryIN_n,\ if\ BatteryIN_{n-1} > 0\ and\ BatteryIN_n > 0$$

$$\boldsymbol{Cumulative\ BatteryOUT_n} = Cumulative\ BatteryOUT_{n-1} + BatteryOUT_n,\ if\ BatteryOUT_{n-1} > 0\ and\ BatteryOUT_n > 0$$

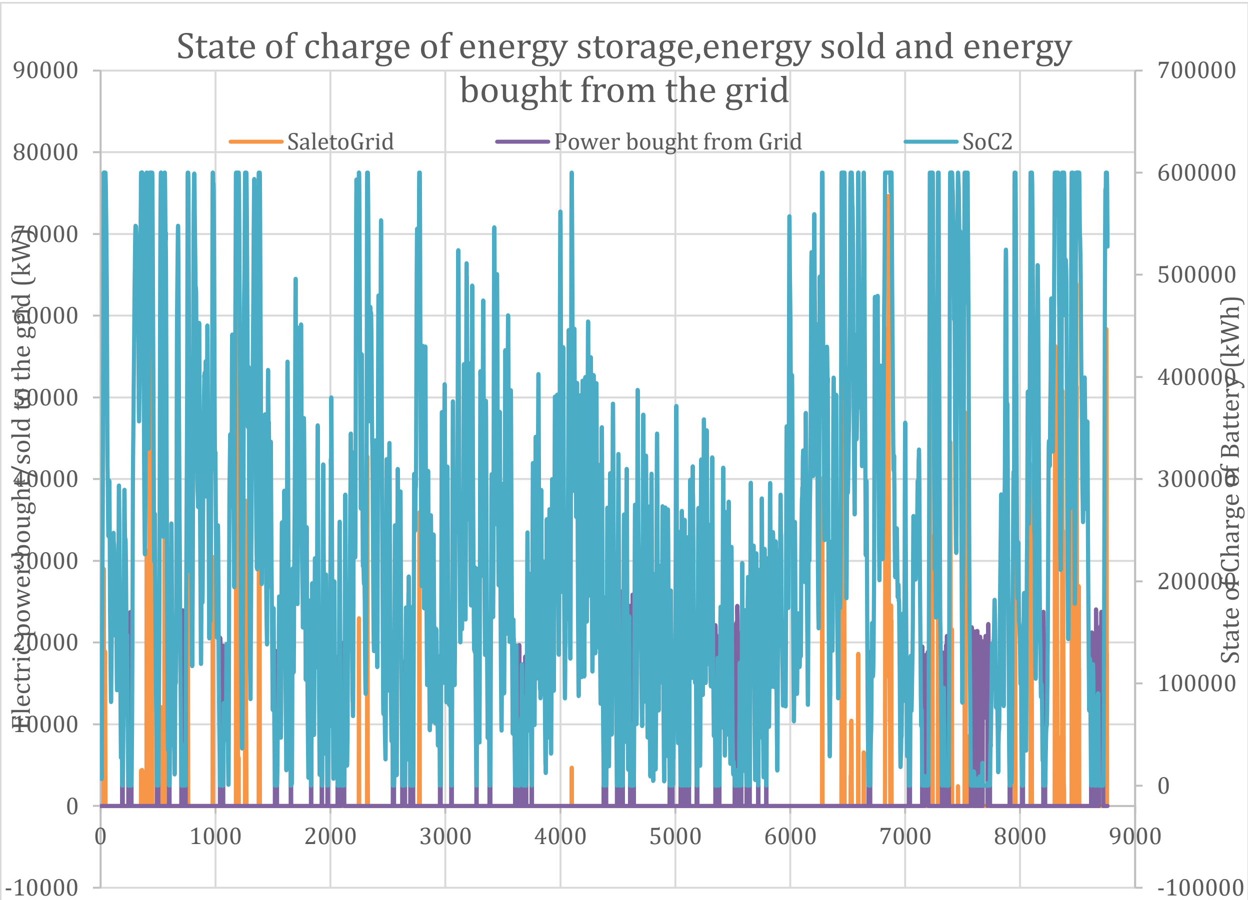
$$\boldsymbol{StateofBattery(inkW)_n} = State\ of\ Battery\ (in\ kW)_{n-1} + BatteryIN\ (in\ kW)_n - BatteryOUT\ (in\ kW)_n - Standby\ losses\ (in\ kW)_{n-1}, if\ \leq\ Battery\ size$$

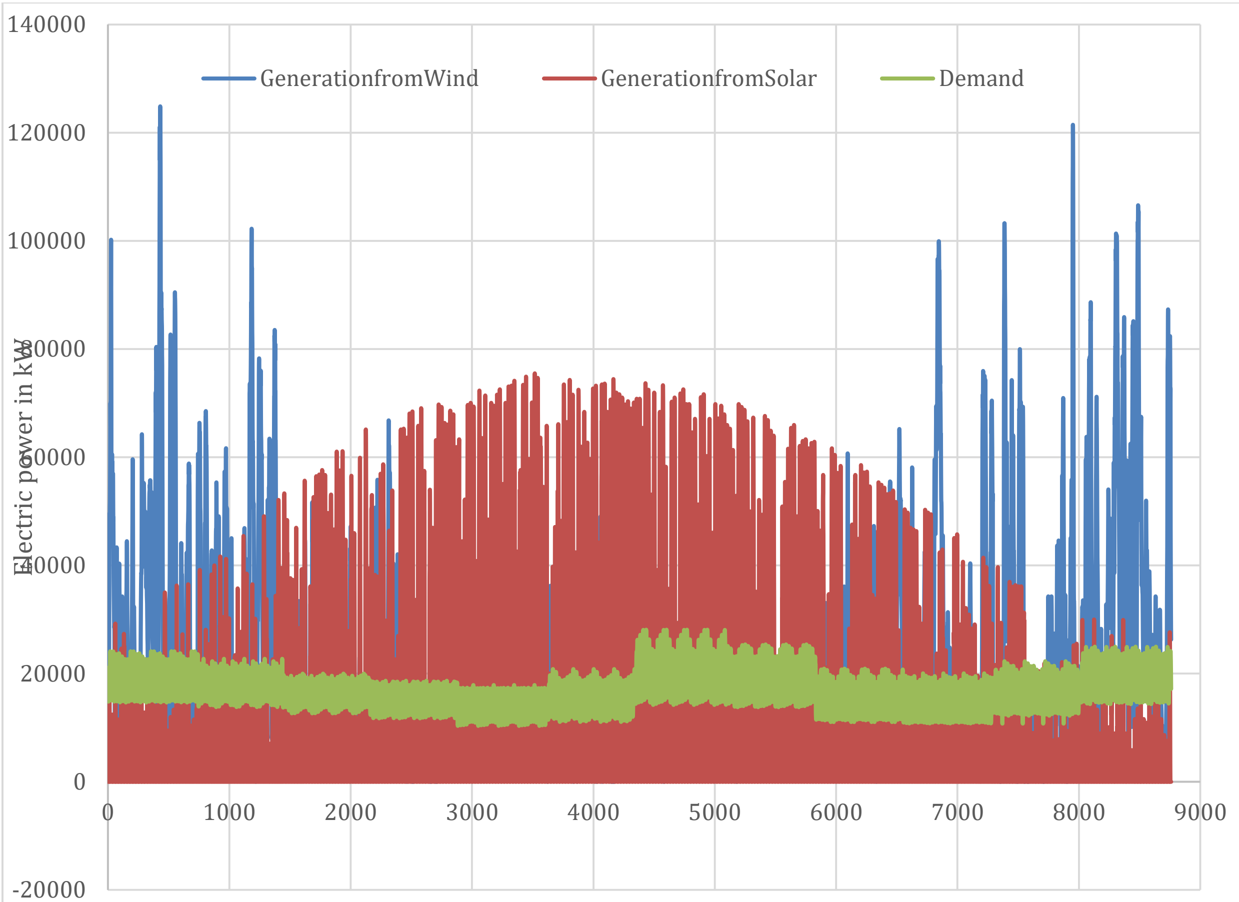
$$\boldsymbol{Surplus\ to\ the\ grid\ (in\ kW)} = Cumulative\ BatteryIN_n - StateofBattery\ (in\ kW)_n$$

$$\boldsymbol{Unmet\ Demand\ (in\ kW)} = \sum [State\ of\ Battery\ (in\ kW)_n - BatteryOUT(in\ kW)]$$

$$\boldsymbol{Percentage\ hours} = 1 - \frac{Count\ of\ State\ of\ Battery\ (in\ kW)_n < 0}{8784}$$

Appendix E: Graphs depicting Battery State of Charge, Renewable Electricity Generation, Electricity Transactions





140000
120000
100000
80000
60000
40000
20000
0
-20000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
GenerationfromWind
GenerationfromSolar
Demand
Electric power in kW