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Distributed Energy Resources : An Assessment of New Jersey's Clean Energy Future

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Abstract

The demand for renewable energy in New Jersey will continue to grow as economic opportunities and community support drive development. The effective integration of Distributed Energy Resources (DERs) will transform energy production, storage, and use. To achieve sustainable energy production, the current reliance on fossil fuels must be reduced and replaced with less carbon-intensive energy sources that optimize the electric grid. DERs help pioneer the path to a clean energy transition where the implementation of new renewable energy projects will diversify New Jersey's energy portfolio and provide a more resilient, equitable, and independent energy source. This thesis investigates different perspectives of small wind and solar energy options that are supported by state and governmental initiatives in New Jersey and shows a quantitative review to support these programs. The research combines various scopes, resources, and methods to analyze current perspectives involved in the wind and solar industry with capacities under 10 MW (megawatt). The first assessment will consist of analyzing stakeholder values on sustainable community solar placement characteristics consisting of environmental and social-economic factors, and governmental support. The second assessment involves the aggregation of onshore wind turbine life cycle data and costs in combination with various life extension and disposal strategies to verify small-wind as a carbon-friendly and cost-effective energy source.

In Chapter 1, we review the current conditions and motivation to transition to a clean energy resource, such as the current reliance on fossil fuels and the associated negative impact on local economies and ecosystems. Additionally, we explain how DERs can play a core role in facilitating energy goals better than large-scale utility projects through providing an opportunity to optimize the electric grid, the ability to account for flexible load demands, and increased targeted consumer economic benefits (such as reduced rates). The impact of implementing DERs is strategic and will

be critical in supporting the energy transition process. A fundamental principle for sustainable energy development is the optimization of the grid. In Chapter 2, environmental, social, and technical land use characteristics are utilized to determine strategic community solar placement. In this objective we analyzed 9 completed survey responses from solar providers and environmental organizations to gain clarity on their beliefs toward the community solar program, its impact on communities and the environment, challenges, and the future of the industry. The information that was collected through the survey was categorized into a Saaty Rating Scale using an Analytical Hierarchy Process (AHP) to determine the relative importance of each variable. This data was then represented spatially using an intuitive mapping analysis tool, ArcGIS Pro, to visualize optimal shared solar locations. In Chapter 3, we utilize a Life Cycle Cost Assessment (LCCA) that estimates the environmental and economic impacts of a 1.5 MW onshore wind turbine using Life Cycle Assessment (LCA) and Life Cycle Cost (LCC). This objective involves scenario analysis of various disposal and life extension options. The assessment can inform policymakers who want to achieve economically viable clean energy alternatives. In Chapter 4, we review policies and implications of this study and how DERs can play a role in promoting sustainable energy practices that are eco-conscious and provide benefits to low to moderate income populations. These methods assist in providing a comprehensive understanding of small-scale wind and solar that can support environmental-focused policies and future decision-making.

Keywords: GIS suitability analysis; Analytical Hierarchy Process; community solar; onshore wind; life cycle cost assessment

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Chapter 1: Introduction

1.1 The Problem

Human activity has increased greenhouse gas (GHG) emissions with a great magnitude of carbon dioxide, methane, and nitrous oxide (Intergovernmental Panel on Climate Change, 2007). Carbon dioxide, methane, and nitrous oxide are the main environmental contributors for the production and consumption of electricity used in housing and industry. Although climate change is a naturally occurring event, the current rate and magnitude in which this process is occurring has not been presented in over 800,000 years (National Oceanic and Atmospheric Administration, 2021). Represented in *Figure 1*, the average for atmospheric carbon dioxide was at 412.5 ppm (parts per million) whereas previous peak carbon dioxide readings were at 300 ppm about 350,000 years ago (National Oceanic and Atmospheric Administration, 2021). Atmospheric carbon dioxide concentration is used as a proxy to aid in reconstructing past climate conditions. Although fluxes in atmospheric carbon dioxide have cyclically occurred, human influence has propelled the rate at which unprecedented volumes of long-lived GHG remain within the atmosphere and retain energy. This anthropogenic impact on the environment is resulting in global climate change that natural climate variations cannot elucidate (Rosenzweig et al., 2008). Characteristics of this phenomenon include an increase in worldwide air and ocean temperatures, increased snowmelt, and global sea-level rise (Intergovernmental Panel on Climate Change, 2007). Anthropogenic climate change has disproportionate impacts on different social, economic, and ecological systems (Gibson, 2006; O’Brien et al., 2009). Climate change results from land use changes that have altered natural ecosystems and impacted the environment's quality, biodiversity, ecosystem services (Polasky et al., 2011). Economic impacts include energy shortages, damages to infrastructure, disruption within supply chains, and increased losses to industry (NJ Board of Public Utilities 2020b). Additionally, there are social impacts such as degrading human health through extreme weather events, disease, and food system disruptions (Patz et al., 2005; Panwar et al., 2010; Intergovernmental Panel on Climate Change, 2007). Consequently, it has become critical to reduce GHG emissions and mitigate the impacts by investing in a clean energy future.

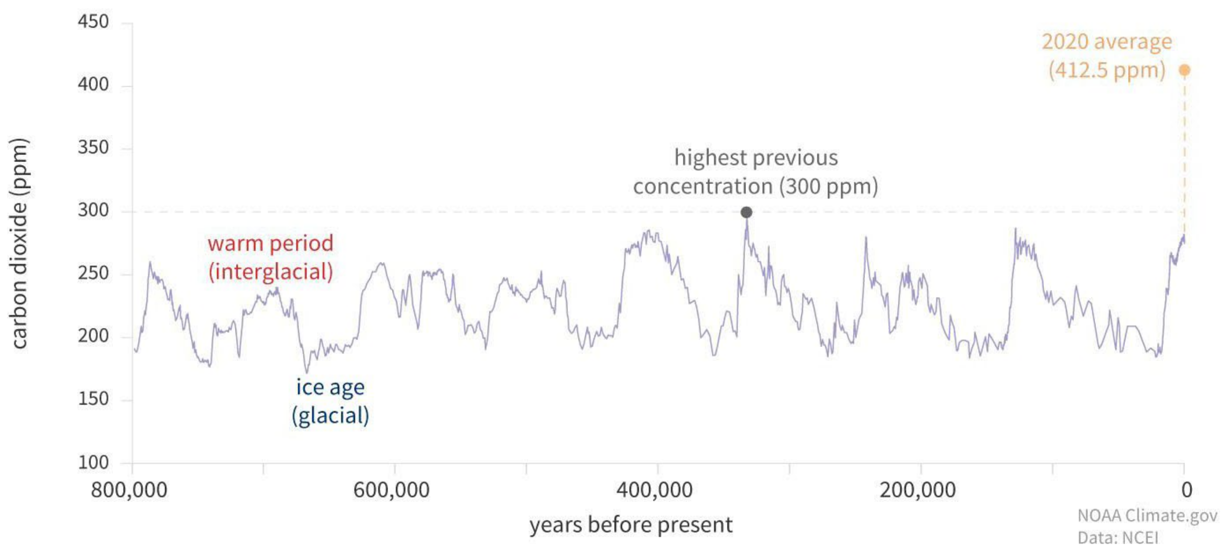


Figure 1: Atmospheric carbon dioxide concentrations (CO_2) in parts per million (ppm). Source: National Oceanic and Atmospheric Administration, 2021.

GHG emissions have continued to increase alongside urbanization, industrial production, and population. Anthropogenic climate change has resulted in ramifications along the social, economic, and environmental spectrums accompanied by changes in land use functions such as extensive deforestation and urbanization (Rosenzweig et al., 2008; Intergovernmental Panel on Climate Change, 2007; Panwar et al., 2010). Coal, oil, and natural gas are primary energy sources that feed intensifying GHG through, most prominently, transportation and electricity production. Contemporary energy sourcing relies upon an 80:20 fossil fuels to renewable energy mix, producing large amounts of emissions while causing other issues such as degrading the environment, aggravating climate change, creating economic dependency, resource depletion, and diminishing health via air pollution and contamination (Gomaa et al., 2019). *Figure 2* depicts electricity generation as a core contributor to the United States' GHG emissions along with transportation, industry, agriculture, commercial, residential, and US territories (US Environmental Protection Agency, 2019). Nearly 30% of the total emission production of all domestic GHG is produced by electricity generation (US Environmental Protection Agency, 2019). Alternatives to prevailing consumer energy resources will reduce ecological, economic, and social impacts consistent with current climate change trends. This reduction in environmental effects within end-use energy consumption can be made possible by providing alternative energy resources such as wind and solar power (Gomaa et al., 2019).

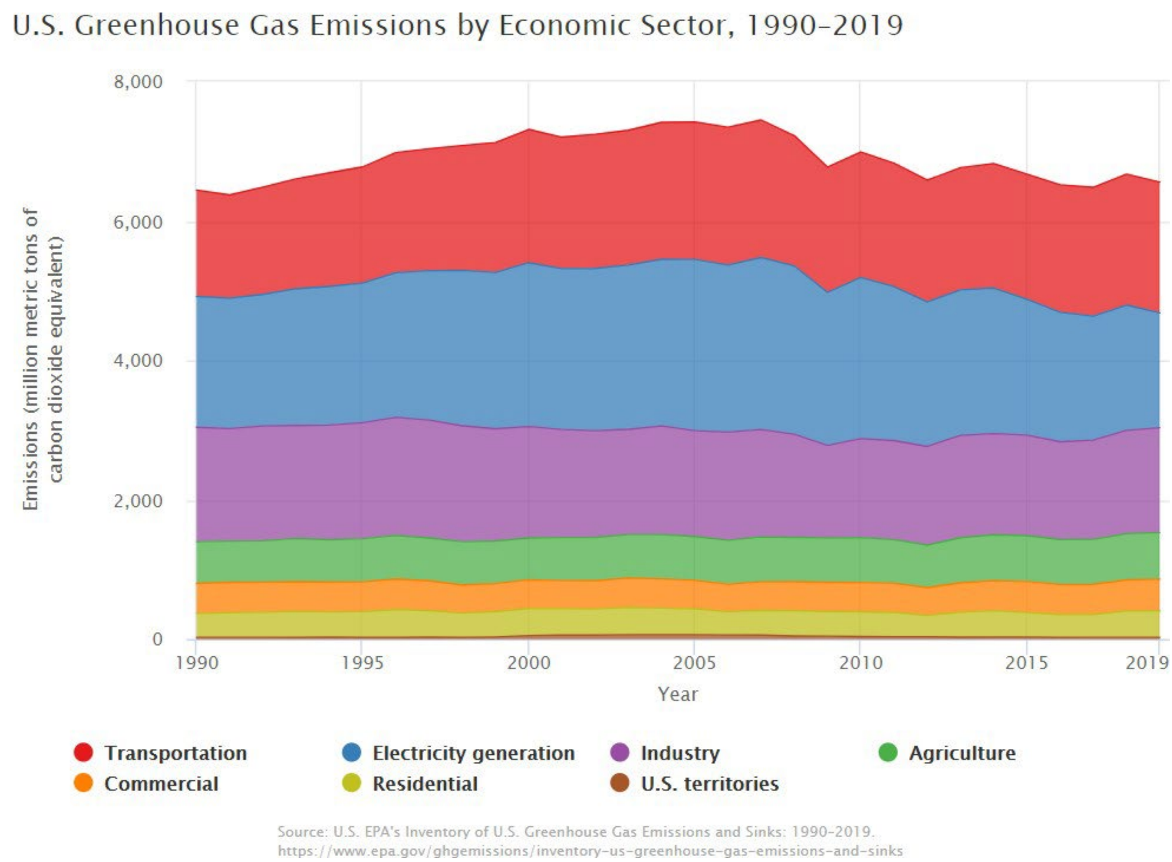


Figure 2: US Greenhouse Gas Emissions (Source: US Environmental Protection Agency, 2019).

In the past, the fossil fuel industry's competitive pricing and reliable supply chain were the most significant hurdles in the transition to renewable energy generation (NJ Board of Public Utilities, 2020b). The National Renewable Energy Laboratory (NREL) reports on the life cycle emissions for various nonrenewable and renewable energy generation methods by their carbon dioxide equivalent (CO_2 eq). This unit is an aggregate of multiple greenhouse or climate forcing gasses into a base measure of global warming potential where one ton of GHGs is comparable to one ton of CO_2. NREL's Life Cycle of Greenhouse Gas Emissions from electricity generation finds traditional fossil fuels to produce substantial emissions, specifically coal 1001 g CO_2 eq (grams of CO_2 equivalent), oil 840 g CO_2 eq, and natural gas 486 g CO_2 eq comparable to renewable methods such as solar photovoltaic (PV) 43 g CO_2 eq, geothermal 37 g CO_2 eq, and wind 13 g CO_2 eq (National Renewable Energy Laboratory, 2021). A previous NREL report, Life Cycle Assessment Harmonization, states that when comparing life cycle assessments of renewables to fossil fuel counterparts, renewable energy technology produces 400 to 1,000 g CO_2 eq/kWh less than fossil fuels (National Renewable Energy Laboratory, 2013).

Although renewables can effectively reduce emission rates, renewables have been slowly adopted into the current electricity generation mix. Some renewable energy options have lacked scalability and efficiency in the past and made development an uneconomical energy production alternative. However, the costs of renewable energy sources, such as wind and solar energy generation, have decreased due to technological advancements, subsidies, and facility requirements (Chang et al., 2017). These advancements have made renewable energy generation feasible to increase the scale of its production. Wind and solar are reliable energy alternatives (US Department of Energy, 2021), and expanding their energy production can fulfill the crucial requirements for reaching economy-of-scale, a regularly sought-after determinant for scoping attainable economic investments. Increasing the amount of renewable energy generation will have a greater impact on emission reduction than nonrenewable counterparts (US Energy Information Administration, 2015).

Renewable energy development has looked primarily toward wind and solar energy generation as a source for clean energy generation to moderate climate change impacts (Panwar et al., 2010). Life cycle emission data on different electricity generation sources has found that wind energy produces the least number of emissions on average. The solar PV life cycle emissions are far less than nonrenewable counterparts, although having one of the highest emissions for a renewable resource (US Energy Information Administration, 2015; National Renewable Energy Laboratory, 2021). NJ offers ample physical, political, and economic resources for the growth of renewables to reduce overall emissions.

1.2 An Opportunity for Change

Demand for energy production has increased with population growth, access to electricity-fueled resources, and thusly been coupled with environmental degradation. Simultaneously there has been a substantial decline in some renewable energy generation costs for solar and wind. Distributed Energy Resources (DERs) are small-scale electricity generation that provides an impactful prospect for local-scale energy production that offer community support ease environmental stressors and reshape the electricity industry (NJ Board of Public Utilities, 2020b; NJ Board of Public Utilities, 2019; Chowdhury et al., 2021). DERs are decentralized and allow for independence within electricity generation normally consisting of capacities under 10 MW (US Department of Energy, 2021; US Department of Energy, 2020b). DERs function through the utilization of smart-grid design which is enabled by virtual demand-response resources and net-metering. This method focuses on reducing transmission congestion through real-time information necessary to better coordinate with utilities, therefore, improving demand response capabilities (US Department of Energy, 2020b). Large-scale renewable energy utility projects cannot encompass the achievements of small-scale wind and solar. These achievements include flexibility to reach load demands, optimization of the grid, and increased consumer economic impacts (Chowdhury et al., 2021; NJ Board of Public Utilities, 2019). Incentivizing small wind and solar projects may provide a unique opportunity to help appease energy requirements during the transition into a carbon-neutral future.

Solar and wind technologies are currently available at competitive prices. They can be pivotal in reducing state emissions while helping meet electricity demand (NJ Board of Public Utilities, 2019). Crucial precursors to small-scale wind and solar carbon neutrality are energy efficiency systems and other improvements in distribution and transmission. The integration of energy-efficient technologies and advancements to the utility company supply chain for the electrification of the grid will keep energy demand for end-users at attainable levels. Energy efficiency is crucial to note during New Jersey’s transition to a clean energy future (NJ Board of Public Utilities, 2019; NJ Board of Public Utilities, 2020b). This obstacle can be avoided via substantial growth in energy efficiencies, preventing future electricity demand from further development, even with additional electrification of devices (NJ Board of Public Utilities, 2019).

To optimize the grid, communities would benefit from added electricity security that distributed energy provides while increasing DER production (Chowdhury et al., 2021). The addition of consistent small electricity generation will permit the transmission infrastructure to be better utilized and reduce peak plants by avoiding demand-pricing mechanisms and reducing blackouts (since this utilizes living demand readings and provides energy storage) (US Department of Energy, 2020b; Chowdhury et al., 2021). Sustainability principles and policies not only drive the availability of DERs, but economic development continues to expand these interests. Large-scale projects are not capable of providing community support where there are energy interruptions without local turbines and local solar (NJ Board of Public Utilities, 2019; NJ Board of Public Utilities, 2020b).

Emission reduction policies are paramount in New Jersey’s transition to a clean energy future. Policy-driven, New Jersey’s Global Warming Response Act and target goal of 80% below 2006 levels by 2050 targets energy production efforts. Several mechanisms including government policy

(Clean Energy Act, Global Warming Response Act, Offshore Wind Economic Development Act, Solar Act) and incentives (Solar Renewable Energy Program, Community Solar Energy Pilot Program), often via tax credits or subsidies, are being implemented to achieve the state’s ambitious climate goals (NJ Department of Environmental Protection, 2021). The Energy Master Plan specifically outlines critical strategies for reaching 100% carbon neutrality by 2050 by addressing current-day energy system problems within New Jersey, including electricity generation, transportation building, and their associated pollutants and greenhouse gases (NJ Board of Public Utilities, 2019). The New Jersey Board of Public Utilities (NJBPU) composed a list of 5 workgroups that are necessary to achieve state energy goals: Clean and Renewable Energy, Sustainable and Resilient Infrastructure, Reducing Energy Consumption, Clean and Reliable Transportation, and Building a Modern Grid. The core takings from Strategy 2, Accelerate Deployment of Renewable Energy and Distributed Energy Resources, will be applied as the primary focus for this study. This strategy replaces fossil fuels with renewable energy sources within the electric generation sector (NJ Board of Public Utilities, 2019). Moreover, it comprises wind and solar energy generation and storage, containing costs and opening the electrical distribution companies’ circuits to distributed energy.

Many states such as Texas, New York, California, and Iowa are implementing a competitive approach to incentivize clean energy generation at a much larger scale (US Department of Energy, 2021). The incentive techniques include developing a clean energy standard, lower costs, loans/financing, and other market-based compensation forms (NJ Board of Public Utilities, 2019). The effort for these incentives is supported by industry trends, in which wind and solar continuously outweigh almost any other resource addition annually in the US (*Figure 3*). 4

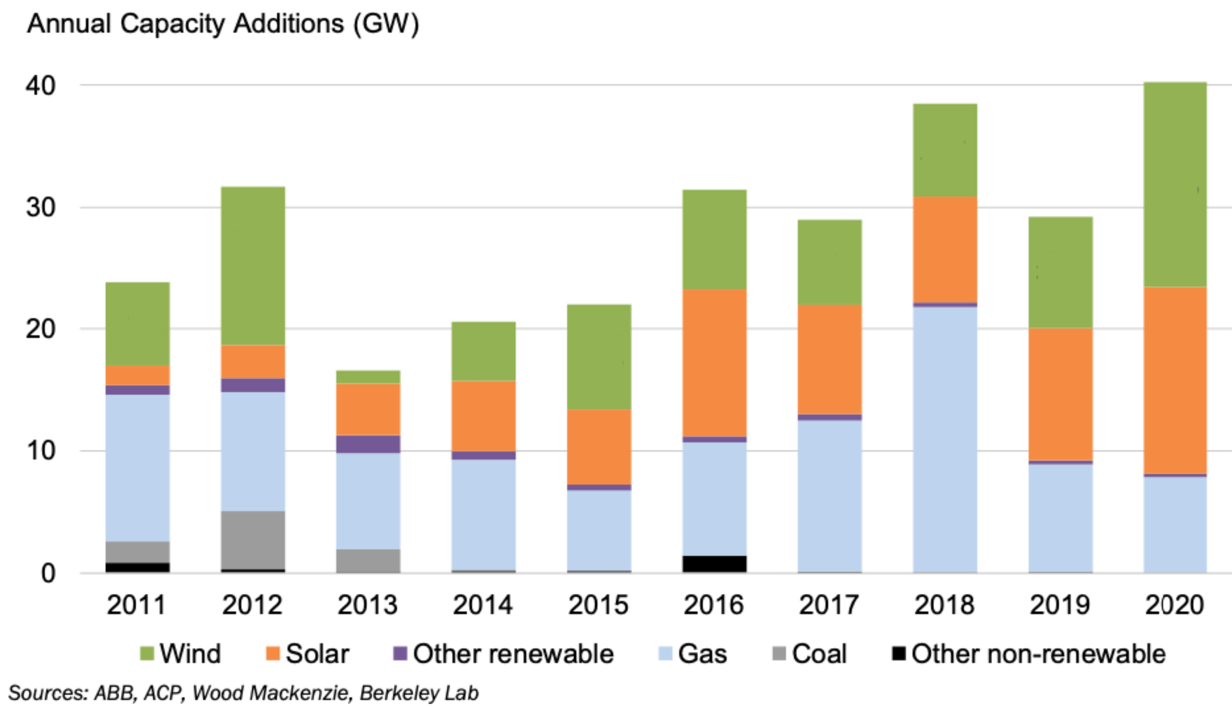


Figure 3: United States Annual Capacity Additions (GW) (US Department of Energy, 2021).

The proliferation of renewable energy includes primarily solar and wind energy generation (NJ Board of Public Utilities, 2020b; NJ Board of Public Utilities, 2019; Chowdhury et al., 2021; US Department of Energy, 2021). The primary basis for the market growth in recent years is due to state officials incentivizing diversifying their energy portfolio (in most cases meaning to increase renewable energy production) along with other tax credits (such as the production tax credit) (US Department of Energy, 2021). Beside other environmental and socioeconomic benefits, foremost the diversification of NJ's energy generation mix will provide energy independence and security (US Environmental Protection Agency, 2016). To properly validate wind energy generation, the environmental impact of wind in New Jersey is necessary.

Clean energy initiatives in New Jersey are aimed at a community level based on perspective and local attribution, leading to the expansion of programs and initiatives such as the Community Solar Energy Pilot Program and the Energy Master Plan and much larger projects such as the

Onshore Wind Development plan (NJ Board of Public Utilities, 2019). These essential attributes will push community solar and other DERs aside from environmental and economic benefits. DERs can also provide a form of environmental justice, providing equitable energy and equitable costs (NJ Department of Environmental Protection, 2020; NJ Board of Public Utilities, 2020b). Although extensive investments are still needed to implement distributed wind and solar power farms, face-value costs can still be significantly lower than larger farms and fossil fuel power plants (Chowdhury et al., 2021). It is crucial to support government intervention to include low- to moderate- income groups in DERs opportunities. This will prevent various socio-economic, health, and environmental burdens that they have been restricted to in the past. Current NJ policies support and exclusively require the inclusion of disadvantaged groups to promote a more equitable energy production (NJ Board of Public Utilities, 2020a; NJ Board of Public Utilities, 2019).

1.3 Study Area

The study area is New Jersey, which is a coastal region located in the northeastern part of the United States. Given the state's small size and dense population, New Jersey does not have enough homegrown energy for the state's current demand (*Table 1*) (Energy Information Administration, 2019). The state's primary energy mix relies almost exclusively on nuclear and natural gas generation. To reduce New Jersey's energy mix emissions, investing in renewable energy sources must be supported, implemented, and facilitated. By diversifying the energy mix to incorporate more renewable energy, we can shift from a reliance on natural gas and other carbon-dense fuel sources to lower carbon emissions. Emissions reduction is a minimum requirement in new state laws and regulations policies under Regional Greenhouse Gas Initiative (RGGI) and the Climate Change Response Act (NJ Department of Environmental Protection, 2020; NJ Board of Public Utilities, 2020b).

Additionally, there are health concerns related to the state's current carbon-free fuel source. New Jersey's primary carbon-neutral resource, nuclear energy, has additional external outfalls incentivizing energy generation through other methods (US Energy Information Administration, 2020a). Although nuclear power plants do not produce direct carbon emissions, the resource acquisition and manufacturing of uranium ore require a large amount of energy. The storage and decommissioning of a nuclear plant require a large influx of energy (US Energy Information Administration, 2020a). Lastly, nuclear energy production produces radioactive waste (e.g., uranium mill tailings, spent reactor fuel, etc.) that can damage human and ecosystem health. Overall, there is significant public concern regarding the inability for disposal, long-term onsite storage and usability of land in perpetuity, and potential discharges over time which coincide with high costs (US Energy Information Administration 2020a). This corresponds with the EMP least cost scenario, the state electricity capacity for nuclear energy stays stagnant where solar, wind, and storage is expected to grow (NJ Board of Public Utilities, 2019). Transitioning away from nonrenewable energy sources provide a case for development for an energy mix consisting of primarily renewable energy resources (NJ Board of Public Utilities, 2019).

New Jersey's renewable energy generation mix consists of predominantly solar and wind resources. Additionally, although the state's environmental and climate resources do not amount to those, such as solar in California or wind in Texas, New Jersey still has a good combination of environmental properties (US Department of Energy, 2021). Resources including wind and favorable political climate that promotes this underutilized resource are now driving policy forward. The environmental and socio-economic benefits of sustainability-based energy production outweigh the costs and time to transition to a clean energy future.

In-state electricity generation is essential to meeting the state's emission goals that do not have the widespread externalized impacts that nuclear energy entails, as presented in *Table 1* (Energy Information Administration, 2019). The need to source in-state energy incentivizes optimizing site selection through multi-criteria decision analysis (NJ Board of Public Utilities, 2019). In 2018, there was a necessary update to New Jersey's renewable energy portfolio standard to reflect the state's energy needs more accurately. This change requires the generation of 21% of the electricity sold statewide to be renewable by 2021, 35% by 2025, and 50% by 2030 (NJ Board of Public Utilities, 2019). These goals act in correspondence with the Energy Master Plan (EMP) Pathway to 2050 signed into law in 2019.

Table 1: New Jersey 2019 Energy Consumption and Production Estimates (Source: Energy Information Administration, State Energy Data System, 2019).

Category	New Jersey 2019 Energy Consumption Estimates Trillion Btu	New Jersey 2019 Energy Production Estimates Trillion Btu
Coal	13.8	0
Natural Gas	789.3	0
Motor Gasoline excl. Ethanol	434.7	0
Distillate Fuel Oil	167.7	0
Other Petroleum	93.5	0
Nuclear Electric Power	278.1	278.1
Hydroelectric Power	0.2	0
Biomass	52.4	16.8
Other Renewables	32.4	32.6

1.4 Research Objectives

This research consists of two objectives that encompass New Jersey's growing efforts to mitigate the impacts of climate change. Both state and non-governmental agencies have come together to reduce the state's greenhouse gas emissions to mitigate the impact of climate change. These state initiatives guide the renewable energy sector to expand its market to support a clean energy future. Distributed Energy Resources provide an opportunity to help transition the state to achieve carbon reduction goals. DERs will help reshape the current electricity industry while providing socio-economic and environmental benefits (NJ Board of Public Utilities, 2020b; NJ Board of Public Utilities, 2019; Chowdhury et al., 2020). The first objective utilizes new initiatives associated with the EMP, such as the Community Solar Energy Pilot Program and Re-Powering America's Land Initiative. Each effort aims to enable communities to repurpose locations with a wide range of development potential for renewable generation, promote local economies, and provide environmental social justice. However, limited funds and resources are available. Optimal site selection is critical for successful repowering strategies. We propose a solar suitability study based in New Jersey constructed around current policies and initiatives that act in the state's interests for an equity energy future. The crux of this model is on repurposing degraded or underutilized land and building upon previous suitability studies. The model will account for locations with a high potential to utilize solar energy while accounting for other social and environmental characteristics. Analytical Hierarchy Process (AHP) will be the technique used in this Multi-Criteria Decision Analysis (MCDA) to interpret environmental, social, and economic factors that should impact community solar site locations. Lastly, ArcGIS Pro will be utilized to provide a geospatial analysis of suitable locations through a Weighted-Overlay method informed by the AHP survey results.

The second objective investigates how onshore wind energy provides an additional opportunity for distributed energy generation in New Jersey. A Life Cycle Cost Assessment (LCCA) analysis provides an in-depth perspective on the sustainability of onshore wind development in New Jersey. This assessment goes beyond traditional emissions valuations including environmental impact metrics, resource scarcity estimates, human health impacts, and costs associated with the development and operation of onshore wind. The LCCA provides constructive information to apprise policymakers to make the best decision related to statewide renewable energy generation growth. This analysis consists of a life cycle assessment (LCA), which is a method to investigate environmental emission impacts, and life cycle costing (LCC), an economic analysis. This analysis will attempt to support the future improvement of products and services involved in wind energy generation, build upon stakeholder decision-making, and support future market claims that adopt new technologies as they become cost-competitive. This research addresses two related objectives that will answer the following research questions:

1) Determine Community Solar suitability by combining Analytical Hierarchy Process statistical analysis and Geographic Information Systems (GIS) spatial analysis.
2) Assess the environmental and economic impacts of onshore wind using SimaPro Life Cycle Cost Assessment (LCCA).

Chapter 2: An Analytical Hierarchy Process (AHP)-Based Spatial Analysis of Community Solar in New Jersey

Abstract:

Climate change is a growing concern in New Jersey. Both state and non-governmental agencies have come together to reduce the state's GHG emissions to mitigate the impacts of climate change. State initiatives such as those found in the Energy Master Plan (EMP) guide the renewable energy sector to expand its market to support a clean energy future. However, limited resources (i.e., open

space, funds) are available, and thus optimal site selection is needed to improve efficiency. We propose an Analytical Hierarchy Process (AHP)-based spatial analysis of solar suitability study in New Jersey constructed around the Community Solar Energy Pilot Program and informed stakeholder opinion on different environmental, socioeconomic, and technical criteria. This model utilizes a GIS weighted-overlay method to repurpose degraded or underutilized land, building upon previous suitability studies. The model will account for locations with a high potential to utilize solar energy while accounting for other social and environmental characteristics to inform the AHP through stakeholder survey data. This process is known as a Multi-Criteria Decision Analysis (MCDA) that interprets the prioritization of environmental, social, and economic factors that impact the community solar site selection. We hope to inform the New Jersey Board of Public Utilities (BPU) site selection process by providing spatial analysis of community solar capability. This study found that stakeholders find residential and commercial properties the most influential on-site selection, and that Public Service Electric and Gas (PSE&G) has the most significant number of suitable community solar locations.

2.1 Introduction

Hazards from climate change have provided a sufficient incentive to transition to renewable energy generations, especially in communities most affected by climate change and air pollution (Singh et al., 2003). Most of the renewable energy development in New Jersey has been in the solar sector, with a statewide goal of 5.1% solar energy generation, as part of the GHG emission reductions efforts (NJ Board of Public Utilities, 2019). Solar energy has made large strides in efficiency and affordability due to technological advances (Chang et al., 2017). Likewise, the advances in photovoltaic technology have proportionally increased the popularity of solar arrays. The technology has made solar more scalable and is more easily integrated with battery storage and microgrids. The versatility of solar arrays makes solar a solid contributor for future generation portfolios.

New Jersey has a long history of launching various environmental legislations and initiatives. One state incentive that is influential in guiding clean, cost-effective energy generation is the New Jersey Clean Energy Program (NJCEP). This program offers various financial incentives, services, and programs to support local governments, residents, and businesses (NJ Board of Public Utilities, 2020a). The state’s past programs include the Electric Discount and Competition Act (EDECA) (1999), which implemented the Renewable Portfolio Standard (RSP) and Societal Benefits Charge. This standard has catalyzed market development for renewable energy (NJ Board of Public Utilities, 2019). New Jersey also joined the Regional Greenhouse Gas Initiative in 2018. RGGI is the first mandatory cap-and-trade program to limit carbon dioxide emissions initiatives in the US (NJ Department of Environmental Protection, 2020). The Global Warming Response Act states a requirement to reduce greenhouse gas emissions to 80% below the 2006 level by 2050. It requires that emissions be moderated and tracked regularly to gauge progress toward the statewide emission reduction goals (NJ Board of Public Utilities, 2020b). The EMP outlines strategies to reach emission goals and implement this paradigm shift in the energy sector (NJ Board of Public Utilities, 2019). The Solar Act enables the state to govern generation, interconnection, and financing needs for renewable energy (NJ Board of Public Utilities, n.d.).

Additionally, the Solar Act requires that all solar projects in New Jersey be part of the Solar Renewable Energy Certificates (SREC) Registration Program. SRECs are then provided to the owner account for a minimum of 1 megawatt-hour (MWh) of solar electricity generation. Once received, the owner can claim green power benefits from their solar project (US Environmental Protection Agency, 2016). The Clean Energy Act improved and added new renewable energy initiatives relating to Renewable Portfolio Standards (RPSs), offshore wind development, and energy efficiency and storage to expand renewable energy programs (NJ Board of Public Utilities, 2019). The combined state initiatives helped progress green initiatives through research, rebates, subsidies, and mandates.

Diversifying the energy sector has associated energy security, environmental and socioeconomic benefits. The Community Solar Energy Pilot Program plays a prominent role in New Jersey's distributed energy resource due to its restriction to sites no larger than 5 MW direct current (MWdc) (NJ Board of Public Utilities, 2020c). The small size of plants has prompted great popularity in residential communities and is appropriate for the urban landscape. State efforts to reduce emissions have been successful, as displayed in *Figure 4*, where New Jersey's CO_2 emissions rate was 492 pound/MWh. This rate is significantly lower than the Pennsylvania, Jersey, Maryland Power Pool (PJM) average of 948lb/MWh (NJ Board of Public Utilities, 2020c). This change is associated with small-scale energy projects that have been approved and developed in past years. New Jersey has begun to reduce its dependency on fossil fuels through diversifying the in-state energy generation mix. This industry change has significantly impacted the market for renewables, especially solar, in lowering energy costs. Solar electricity is an excellent opportunity to offer reduced rates to communities (NJ Department of Environmental Protection, 2017). However, LMI populations are less likely to install on-site solar due to various limitations that these communities experience. These limitations include the lack of availability for financing, property ownership, and other budget pressures (US Environmental Protection Agency, 2016). Solar programs will help give LMI communities access to opportunities ordinarily unavailable to those of lower socioeconomic statuses (Lukanov and Krieger, 2019). Community solar sources are a more accessible and sustainable energy source to residents limited by their roofing conditions, shading, angle, renter, or financial restraints. The pilot program prioritizes local energy generation in an attempt to directly influence the Low- to Moderate- Income (LMI) communities, support environmental justice, and promote a more equitable future (NJ Board of Public Utilities, 2019). LMI communities are given the highest priority in Community Solar Energy Pilot Program's scoresheet (NJ Board of Public Utilities, 2020c).

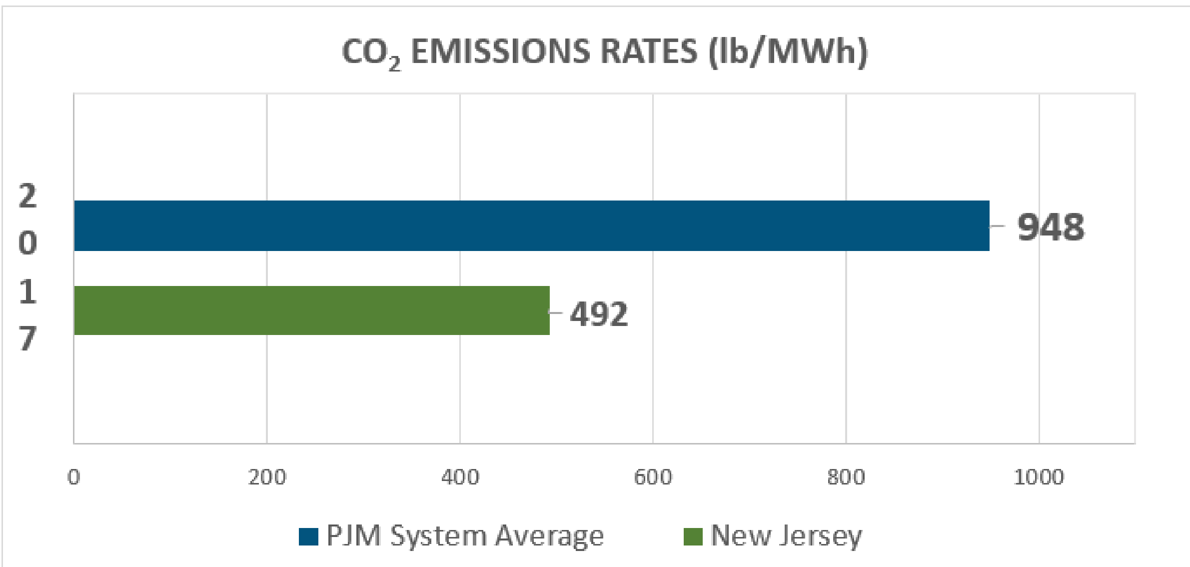


Figure 4: CO_2 Emissions Rate Comparison Electricity Sector (Source: NJ Department of Environmental Protection, 2021)

Much of the Community Solar Energy Pilot Program's scope and goals align with US EPA's RE-Powering America's Land Initiative core aspects. This program enables communities to repurpose sites with low development potential, including landfills and contaminated sites. There are three main criteria for a potential RE-Powering: (1) low-cost land with no competing uses, (2) providing a land reuse benefit (e.g., decontamination), and (3) being located around an LMI community (US Environmental Protection Agency, 2016). The community solar program's primary goal is to incentivize and support local clean energy generation. The program can provide effective developmental programs in LMI communities to help affordable and equitable access to renewable energy (NJ Board of Public Utilities, 2019). However, the initiative has been highly underutilized due to low awareness relating to this initiative, concerns about site preparation, additional complexities and costs associated with the re-use of contaminated land (US Environmental Protection Agency, 2016). With additional financial incentives for re-powering sites and governmental support, land repurposing is typically not chosen from community solar locations.

Problem Statement

Energy optimization within renewable energy production ends at allocating resources, not just the product (NJ Board of Public Utilities, 2019). Determining the proper location to place a solar farm is essential in achieving maximum efficiency. As shown in *Figure 5*, New Jersey has a consistent gradient of solar radiation. However, the state has a significantly lower solar potential than other states like New Mexico, Arizona, and California (National Renewable Energy Laboratory, 2019). This limited resource makes placement critical in ensuring the success of consistent energy generation. Although fixed location is essential for creating a cost-effective and consistent solar energy generation industry, community solar is meant to benefit the community directly, specifically LMI communities (NJ Board of Public Utilities, 2019). Multiple attributes, including sensitive ecological zones, governmental regulations, land attributes, and historically significant locations, determine the area's suitability. New Jersey's limited open spaces, natural lands, and ecosystems are protected, further restricting the placement of solar farms (NJ Department of Environmental Protection, 2017). Solar farms must fulfill size limitations to ensure that they are small enough to fit within communities yet large enough to achieve economies of scale (Chang et al., 2017).

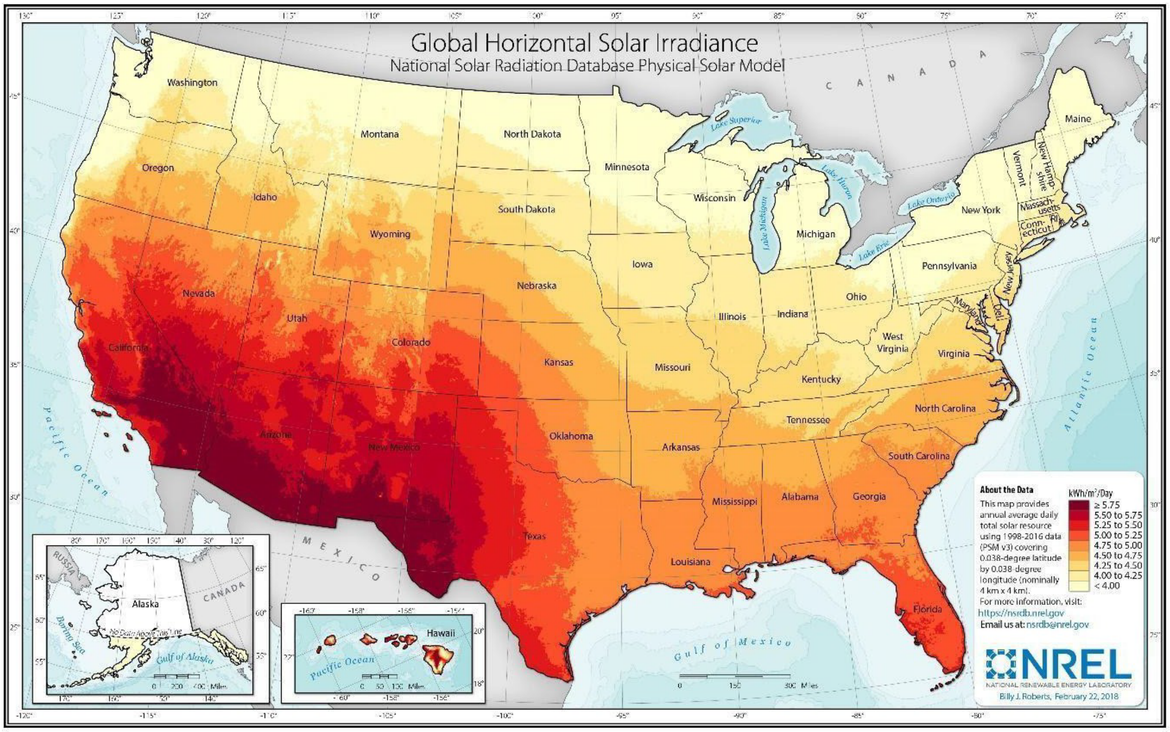
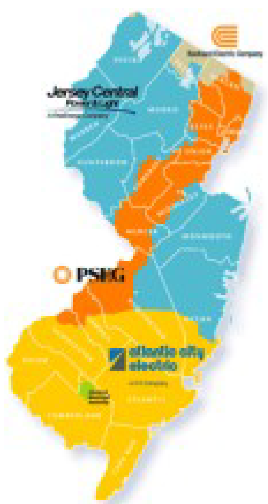


Figure 5: US Global Horizontal Irradiance (National Renewable Energy Laboratory, 2018).

Study Area

New Jersey has many locations that can effectively house community solar sites without wasting the state's precious land resource. This project aims to utilize spatial analysis to investigate solar photovoltaic energy potential in New Jersey. There are four core electric distribution companies that are responsible for the distribution of wholesale energy and retail sales to consumers: Atlantic City Electric (ACE), Jersey Central Power and Light (JCP&L), Public Service Electric and Gas (PSE&G), and Rockland Electric Company (RECO). The Board of Public Utilities (NJBPU) has approved funding for 45 projects to participate in the first year of the Community Solar Energy Pilot Program. Out of these 45 projects, ACE has 3, JCP&L has 16, PSE&G has 26 and RECO has 0 approved projects (NJ Board of Public Utilities, 2020a; Chang et al., 2017). *Figure 6* presents the geography of each Electric Distribution Company (EDC) and its number of customers. These projects can be located on landfills, brownfields, rooftops, parking canopies and will be required to serve LMI households (NJ Board of Public Utilities, 2020). EDC logistics are essential to determine locations where environmental and societal benefits are maximized.



Utility	Customers	Counties
PSE&G	2,200,000	13
Jersey Central Power & Light	1,100,000	13
Atlantic City Electric	547,000	8
Rockland Electric Company	72,354	3

Figure 6: Core NJ Electronic Distribution Companies and customers (Chang et al., 2017).

Community Solar Constraints and Framework

The development of solar power plants has increased recently to meet the US's growing energy demand. The high cost of solar farms incentivizes thorough pre-investment studies to determine the best site locations (Yousefi et al., 2018). The Community Solar Energy Pilot Program provides the framework that enables communities to repurpose sites with low development potential for renewable energy generation. This program is an opportunity to reduce capital costs for solar farms and further develop the market for blighted land (US Environmental Protection Agency, 2016). Incentives such as the Clean Energy Standard will provide substantial and competitive investments and lower costs for distributed energy resources (NJ Board of Public Utilizes, 2019). We propose a solar suitability analysis in New Jersey, focusing on repurposing degraded land or multi-purposeful surfaces with high potential for solar energy generation. An AHP survey results combined with GIS software determines suitable sites for solar PV development. This combination of methods improves efficiency and accelerates the decision-making process. This analysis is made possible by conducting a multi-criteria sensitivity analysis that combines multiple layers by creating different conceptual models (Yousefi et al., 2018).

New Jersey’s Community Solar Energy Pilot program is a three-year program released in 2019 to significantly increase interest in utilizing NJ’s solar resources inclusively and provide the footings for a future permanent program (NJ Board of Public Utilities, 2020a). Project requirements can be found in the application scoresheet. Project constraints include project limitation of 5 MWdc (and at least a total 75 MW generation each year of the program), sales restrictions to EDC boundaries, 51% LMI customers, various product offerings (such as guaranteed savings, provide local jobs/training) and land restrictions from forested and agricultural land and other siting location preferences, including underutilized land like brownfields and landfills (NJ Board of Public Utilities, 2020). Open land, flood zones, and farmland are excluded from the program due to initiatives for preserving open green space and farmland preservation found in the Green Acres, Farmland, Blue Acres, and Historic Preservation Bond Act (NJ Board of Public Utilities, 2020c). This act is meant to provide and preserve interconnected systems of open space and enhance the natural environment for public use rather than energy generation or other forms of development.

Figure 7 presents the framework for how community solar functions. This orientation enables ratepayers to subscribe to a community solar project similar to their typical utility billing plan. Community members participate in community solar through ownership (buying a set number of panels for which the owner receives an electricity credit) or through subscriptions (purchasing a portion of the electricity from a solar farm). This information is managed through a bill-credit system called virtual net metering (VNM). Electricity generated from the solar farm is sent directly to the electrical grid. Afterward, participants receive credit based on their stake in the program (US Environmental Protection Agency, 2016).

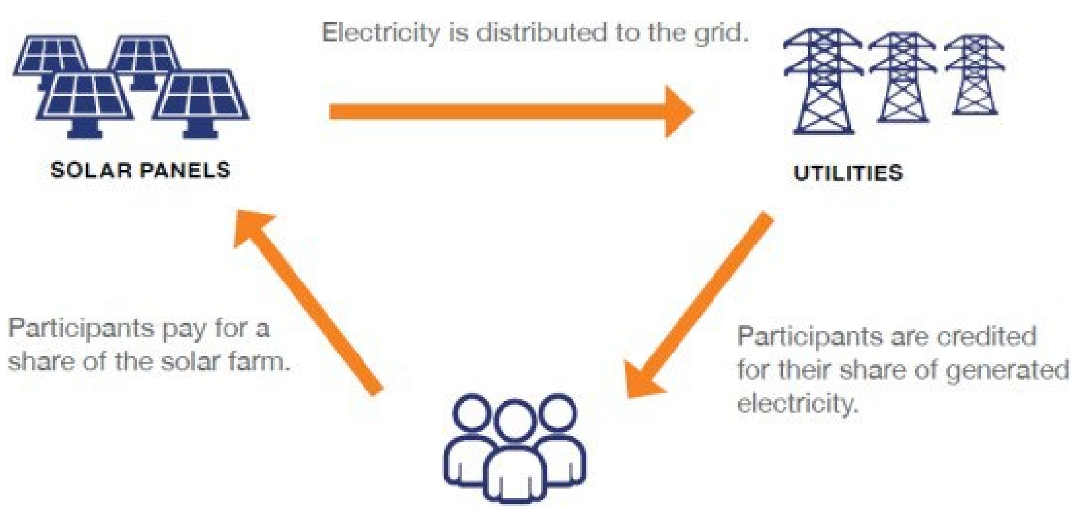


Figure 7: Simplified Interactions for Community Solar (US Environmental Protection Agency, 2016).

The acceleration of distributed energy resources calls for interconnected community solar generation to reduce overall emissions (NJ Board of Public Utilities, 2019). Increasing local energy independence while reducing emissions will result in additional environmental and economic benefits. In this study, AHP provides the means for ranking the selected community solar criteria and incorporating the results in a GIS environment to identify suitable solar locations spatially. This analysis is derived from the Community Solar Energy Pilot Program, which aims to provide New Jersey residents with affordable and equitable energy generation that will benefit communities, the environment, and provide economic growth through better community planning (NJ Board of Public Utilities, 2019). Community Solar is a tool that is woven into many of the EMP roadmap strategies to achieve 80% emission reduction by 2050 as mandated by the Global Warming Response Act (GWRA). Community solar provides holistic benefits that extend to other external systems unattainable for other energy practices. External benefits include improving public and environmental health, creating quality jobs, alleviating grid congestion, and reducing energy rates (NJ Board of Public Utilities, 2020a).

2.2 Method

Analytical Hierarchy Process

Analytical Hierarchy Process is derived from ratio scales created from a pairwise comparison of different criteria that determine each criterion's relative importance. This mathematical method is often used to support MCDM where there is no clear best choice. This method utilizes expert opinions and aggregates the information into objective scoring. AHP helps with complex decision-making and removing biases (Rios and Duarte, 2021). There are four main steps required for AHP: (1) Define the problem and collect essential information; (2) construct a hierarchy of objectives; (3) create a set of pairwise comparison matrices; and (4) use the results of the comparisons to weigh the priorities for each element (Smith et al., 2019). *Figure 8* demonstrates the AHP Framework for determining the most critical property attribute for community solar development. The goal is to determine which property has the most importance for community solar site selection. Through literature and policy review, a set of environmental and economic factors were selected as core determinants (NJ Board of Public Utilities, 2019; NJ Board of Public Utilities, 2020b; Lukanov et al.,2019; Khemiri et al., 2018; Guaita-Pradas et al., 2019; Jones et al., 2015; US Environmental Protection Agency, 2015b; Al-Ruzouq et al., 2018). The criteria were then broken up into sub-criterion, including the five layers this assessment will be analyzing: Global Horizontal Irradiance (GHI); brownfields, landfills, and barren land; areas in need of redevelopment; LMI communities; and residential and commercial property rooftops. For this research, we will determine the specific weights between the different sub-criteria. Past research has focused on comparing environmental and economic factors, but both criteria are essential, as demonstrated through New Jersey policy and legislation. Determining the weight of the specific attributes can help us better implement incentives and predict future market trends relating to this attribute.

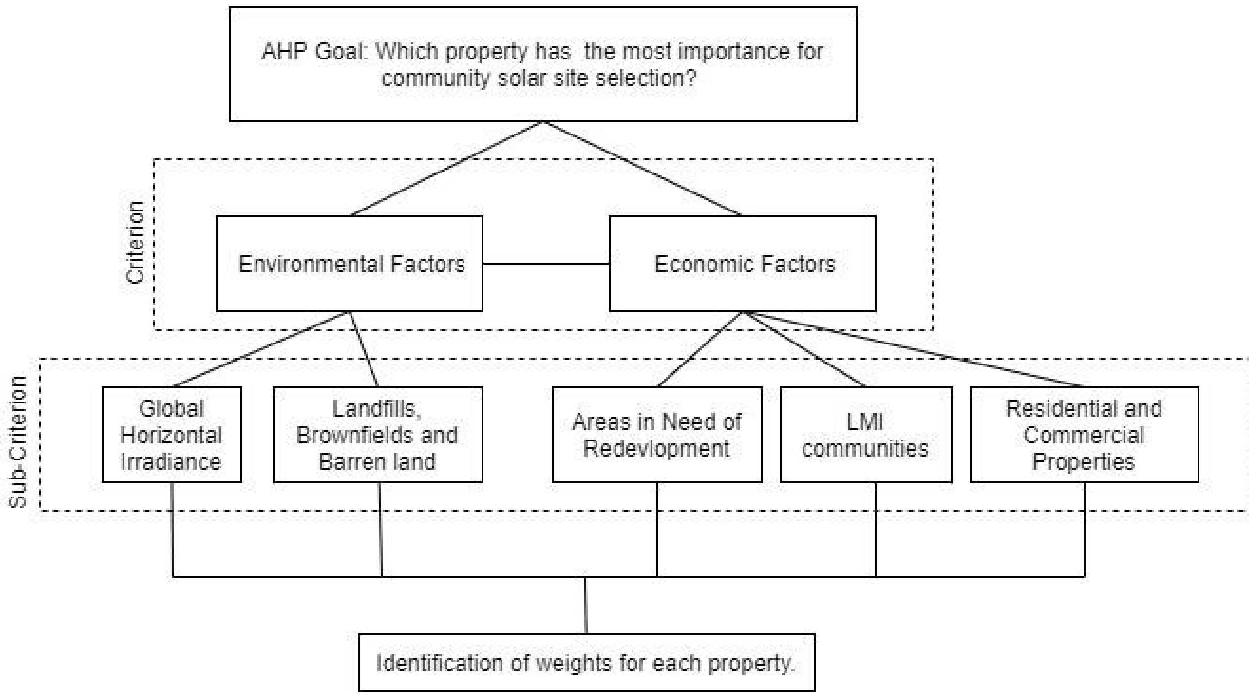


Figure 8: AHP Framework (Adapted from Smith et al., 2019).

AHP Calculations:

There are two main calculations involved *CI*, the Comparison Inconsistency, and the *CR*, the Consistency Ratio. The CI is used to estimate the extent of consistency for a comparison matrix. The calculation is dependent on *n*, the number of participants, and the equation is represented as the Comparison Inconsistency (*CI*) equation below. *CR* is represented below and shows where the *RI* represents the random index generated from a random matrix from the number of participants (*n*). A general rule for acceptable limits is the $CR \leq 0.1$ or 10% (Alonso and Lamata 2006; Smith et al., 2019). If the analysis were successful, the *CR* would be within these limits. This number is impacted by *n*, meaning that receiving more responses will improve the score. An essential additional value is for absolute errors, which calculate the error/variance within the calculation. The lower the number, the less variability within the results.

Comparison Inconsistency (CI) equation:

$$\boldsymbol{CI = \frac{\lambda max - n}{n - 1}}$$

Consistency Ratio (CR) equation:

$$\boldsymbol{CR = \frac{CI}{RI}}$$

AHP uses the Eigenvalue Method (EM), which helps determine the priority of each vector in decision-making. The data collected from the surveys were transcribed into an AHP Excel template version 15.09.2018 (Goepel, 2013). This spreadsheet includes a summary sheet that consolidates the results of the pairwise comparisons, matrices, and a dominant Eigenvalue power method sheet. The default for this analysis is 0.1, which represents 90% certainty in the data. Moreover, we analyzed each respondent within their selected stakeholder group: Environmental Organization (participants in sustainability-based non-profits, environmental justice, and other environmental founded groups that are considered stakeholders of solar programs) or Solar Provider (participants in solar energy companies, solar energy providers, and other solar companies that are considered stakeholders in solar programs).

The AHP method uses linear algebra to assess the results of each pairwise comparison (Coyle, 2004). Through this, each criterion receives its importance weight, in which the higher the weight, the more critical it is to the decision. *Table 2* presents the Saaty Rating Scale, which describes the pairwise comparisons factors used to construct the matrices' calculations. Each participant is asked to select the ranking of each value. These values are then applied and attributed to the final CR. This hierarchy structure is created using a numerical scale that ranges from 1 to 9 (*Table 2*). An intensity score of 1 describes a criterion having equal importance for the attribute and means each element contributes equally to the objective. An intensity score of 9 describes a criterion of having extreme importance for the attribute and with evidence favoring one element over another. Intensities found between 1 and 9 are considered a gradient between the two extremes.

Table 2: AHP Criteria Importance Weights and Reasoning.

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly factor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	These values can be used to express intermediate values

Study's AHP Criteria:

1) Global Horizontal Irradiance (GHI)

Solar energy resource is a general determinant for an appropriate solar site location. The region in which arrays are placed must have adequate sunlight to produce a substantial amount of energy. Global Horizontal Irradiance (GHI) is often also called the Global Horizontal Radiation and is simplified to mean the sum of direct and diffuse radiation. The number of solar resources a location has can dictate the possible energy generation. Solar energy is currently one of the most promising renewable energy generation methods that can assist in replacing fossil fuels in the energy sector (Guaita-Pradas et al., 2019). There are additional factors that play into the suitability of locations with high GHI, such as landcover, evaluation, and slope. However, it has been found that solar radiation is the main decisive factor for communities with high gradients of solar radiation (Guaita-Pradas et al., 2019).

2) Low- to Moderate-Income Communities (LMI)

Low to Moderate Income Communities have historically excluded from rooftop solar programs that provide access to local renewable energy production (Lukanov and Krieger, 2019). However, the community solar program allows this group access to clean energy, additional workforce, and protection from price shock (a commonly occur disadvantage of nonrenewable energy generation) (NJ Board of Public Utilities, 2019). Low-Income populations are determined by household members whose income would qualify as "very low income" under the Section 8 Housing Assistance Payments program. Generally, these Section 8 limits are based on 50% of the area median. Similarly, moderate-income relies on Section 8 "lower-income" limits, generally tied to 80% of the area median. A minimum of 51% of project capacity is allocated to Low- to Moderate- Income subscribers (LMI) and typically provides a 10-15% rate reduction (NJ Board of Public Utilities, 2019; Sustainable New Jersey, 2021).

3) Brownfields, Landfills, and Barren Land

Solar development of these locations would provide environmental and social benefits at a lower land cost. Brownfields, landfills, and barren land are identified as land that is currently underutilized. Through community solar development on these locations, communities will benefit from required cleanup, local jobs, and energy generation (Environmental Protection Agency, 2016). Tools needed to achieve solar development of contaminated land are grants and rebates, stakeholder partnerships, community support, and written public responses (3%). The Community Solar program incentivizes development on brownfields and landfills to maximize policy goals and benefits (NJ Board of Public Utilities, 2019; NJ Board of Public Utilities, 2020c). Barren land criteria consist of historic fill areas, gravel pits or form mines, abiding by Green Acres preserved open space, which prevents development on funded or unfunded parkland (NJ Board of Public Utilities, 2020c). With the associated complications from a heavily urbanized location, brownfields, landfills, and barren land provide an opportunity for larger site sizes with increased benefits (Chang et al., 2017).

4) Areas in Need of Redevelopment

Designated areas in need of redevelopment are defined and mapped through the redevelopment process laws (NJ Department of Community Affairs, Local Planning Services, 2020). These locations have specific financial tools and incentives similar to brownfields and landfills (Sustainable New Jersey, 2021). These locations consist of buildings that are considered unsafe or dilapidated. Area in need of redevelopment includes old industrial or commercial buildings that are past the state of repair. In repurposing of this property, land use can be optimized, and cost can be reduced (US Environmental Protection Agency, 2016). This attribute provides significant benefits to surrounding communities.

5) Residential and Commercial Properties

Historically solar development has been primarily on residential and commercial properties nationally and in New Jersey (Kurdgelashvili et al., 2016). The properties consist of a single unit and multiple dwellings and variance in population density. Development on residential and commercial properties incorporates the use of multi-purposeful structures and is supported under the Community Solar Energy Pilot Program. Rooftop solar can provide 61% of the electricity in NJ, significantly increasing the distributed energy capacity (Kurdgelashvili et al., 2016). Residential and commercial property development may be a core attribute in community solar development with a high population density.

AHP Survey Design

A review of the literature supporting community solar and development in New Jersey was conducted to create the survey. This survey did not request any identifiable questions beside the stakeholder group with which they identify. Various attributes are considered when an application is reviewed in proposing a site to be approved as part of the Community Solar Energy Pilot Program. The five criteria mentioned in the previous section were used in the pairwise comparison to determine the most influential attribute for community solar development. The survey was created on Qualtrics and distributed via publicly available email addresses, and there were weekly survey reminders sent out. The survey participants were required to answer the pairwise question but were able to skip any open-ended questions. This survey has been approved by the Montclair State University Institutional Review Board, IRB study number IRB-FY20-21-2051.

This program enables utility customers to participate in a solar energy project that is, in most cases, remotely located from their property. Shared solar resources are a more accessible, equitable, and sustainable energy source that broadens the range of residents who have access to renewable energy. This research aims to identify preferred community solar locations based on different socioeconomic and environmental conditions as stated in the New Jersey Community Solar Energy Pilot program. Data collected from our responses will be used to determine the weight of layers in a GIS solar suitability analysis. GIS is a spatial analytic tool that enables researchers to capture and analyze data. The optimal location for community solar development can be more accurately determined by comparing the significance of multiple influential variables. The survey seeks to learn about the participant's experience with the community solar industry to improve site selection of shared solar development.

Weighted-Overlay Method

In the past, the New Jersey Department of Environmental Protection (NJDEP) has released a Solar Siting Suitability Analysis that is broken up into three categories of "preferred," "not preferred," and "intermediate" locations for solar PV development based on land use (NJ Department of Environmental Protection, 2017). For this research, ArcGIS Pro was utilized to identify areas based on different layers of data to produce a more thorough analysis of potential development sites in New Jersey. The layers that were chosen were based on the evaluation criteria documented in the NJ Board of Public Utilities Community Solar Energy Pilot Program and the US Environmental Protection Agency's Re-powering America's Land Initiative. Physical characteristics include siting preferences like high solar resources, dense low- to moderate-income populations, landfills, brownfields, barren land, residential and commercial rooftops, and designated areas in need of redevelopment. In addition to these attributes, land use characteristics that should be excluded from this analysis are areas in flood zones, wetlands, forested areas, steep slopes, and farmland. This exclusion is essential to ensure the relative efficiency of potential PV panels and prevent additional unexpected expenses.

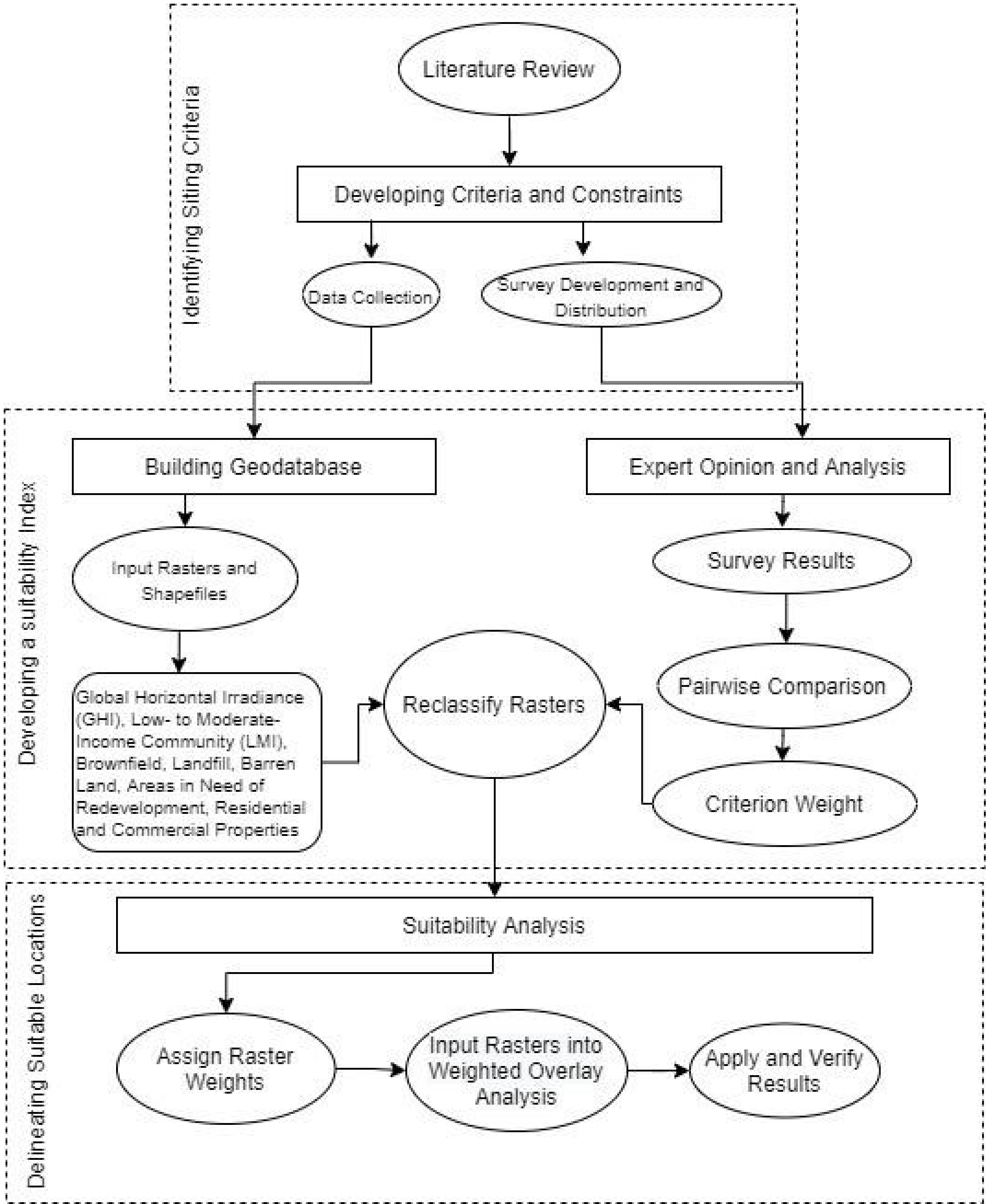


Figure 9: Workflow Diagram for Solar Suitability Assessment.

This chapter uses a weighted linear combination (WLC) to optimize the community solar site selection. The procedure that we will use is called Analytical Hierarchy Process (AHP). AHP is a common technique used in MCDA for land suitability models, which provides a systematic approach to site selection (Chandio et al., 2013). This analysis method will enable the examination of variables which influence optimal development locations. For this analysis and optimal development, location is an area of underutilized land that can provide benefits to LMI communities. New Jersey's extreme population density has resulted in expensive and scarce land availability. NJ's land resource is another restraint to community solar projects making it crucial to optimize the selection while preventing the development of marginalized land and flood zones (NJ Board of Public Utilities, 2019). The community solar suitability model will be conducted through a weighted-overlay suitability assessment. In addition, the sensitivity analysis will calculate the weight of each parameter. These parameters will be based on the community solar scoresheet found in the community solar application (NJ Board of Public Utilities, 2020c). *Figure 9* depicts the workflow for this suitability assessment using AHP and GIS weighted overlay methods as the analysis techniques. This assessment is broken into three core stages: identifying site criteria, developing a suitability index, and delineating suitable locations.

A weighted overlay method is commonly used in a multi-criteria analysis that incorporates spatial analysis (Finn and McKenzie 2020; Khemiri et al., 2018). Weighted-Overlay is used to scale the selected rasters onto a defined scale and add the rasters together (Environmental Systems Research Institute Inc, 2016). Reclassification of the raster layer is essential for conducting the overlay analysis and is done for each dataset. It is necessary to fill any data gaps and any restrictions with the correct value. Null data and land use areas that are not considered suitable must have a value of zero. Otherwise, there will be unexplained gaps in the final raster. The reclassifying method allows us to group values into a scale of 0-9, and natural Jenks (natural unequal group breaks) were used to define the groups (Finn and McKenzie, 2020). This was then scaled down to a range of 0-5 to represent the data better. More favorable locations will consist of more valuable criteria, and the total weight must equal 100 percent (Environmental Systems

Research Institute Inc, 2016). Each layer is then multiplied by the given multiplier (the weight provided by the AHP method) for each cell. The results consist of the sum for each cell, meaning that the more favorable factors will have higher value outputs.

2.3 Results and Discussion

AHP Survey Results

Data used to conduct this analysis can be found on the NJDEP and NJGIN (NJ Geographic Information Network) open-data and NREL web pages (*Table 3*). These sites are where state officials continually add and update state information in GIS format. Layers include the 2015 land use land cover, US global horizontal irradiance, and 2010 census block data. The 2015 land use land cover layer has many land attributes of New Jersey, including residential and commercial buildings, agricultural land, wetlands, brownfields, and landfills (NJ Department of Environmental Protection, 2015). The US global horizontal irradiance data is a raster that consists of multi-year annual and monthly averages of geospatial solar radiation data from the National Solar Radiation Database Physical Solar Model (Sengupta et al., 2018). 2010 census block data consists of state data on race, gender, housing, and household income (US Department of Housing and Urban Development, 2010). Each raster has been resampled to have a consistent cell size of 0.0009 degrees or 100 meters, which is an acceptable resolution quality for this type of research (Al-Ruzouq et al., 2018).

Table 3: AHP-GIS Resources.

Data Layer	Original Data Type	Source	Supporting Literature
Brownfields, landfills, and barren land	Polygon	NJDEP, 2015, NJDEP, 2018, and NJDEP, 2012	NJBPU, 2020; Guaita-Pradas et al., 2019; Jones et al., 2015; EPA, 2015b; Al-Ruzouq et al., 2018.

Residential and commercial properties	Polygon	NJDEP, 2019	NJBPU, 2020; Al-Ruzouq et al., 2018.
LMI Community	Polygon	US Department of Housing and Urban Development, 2010	NJBPU, 2020; Guaita-Pradas et al., 2019; Al-Ruzouq et al., 2018.
Global Horizontal Irradiance (GHI)	Raster	Sengupta et al., 2018	Guaita-Pradas et al., 2019; Al-Ruzouq et al., 2018.
Areas in Need of Redevelopment	Polygon	NJ Department of Community Affairs, Local Planning Services, 2020	NJBPU, 2020; Al-Ruzouq et al., 2018.

In this AHP survey analysis, the survey participants were involved in an online self-identification process. Before starting the survey, respondents provided consent and selected the most aligned group within their field of work. Five participants (n=5) for the Solar Company group and four participants (n=4) for the Environmental Organization group had completed responses. Each stakeholder group was asked to fill out the comparison judgment question to inform the pairwise comparison model. The question consists of the participant selecting on a scale which of two attributes were most important. This model determined the weights for each participant and created a summary sheet for the stakeholder group. *Figure 10* and *Table 4* show the stakeholder distribution of weighted criteria for community solar results. The consistency ratio for each group was CR <0.1.

Solar Provider Group Distribution **Environmental Organization Group Distribution**

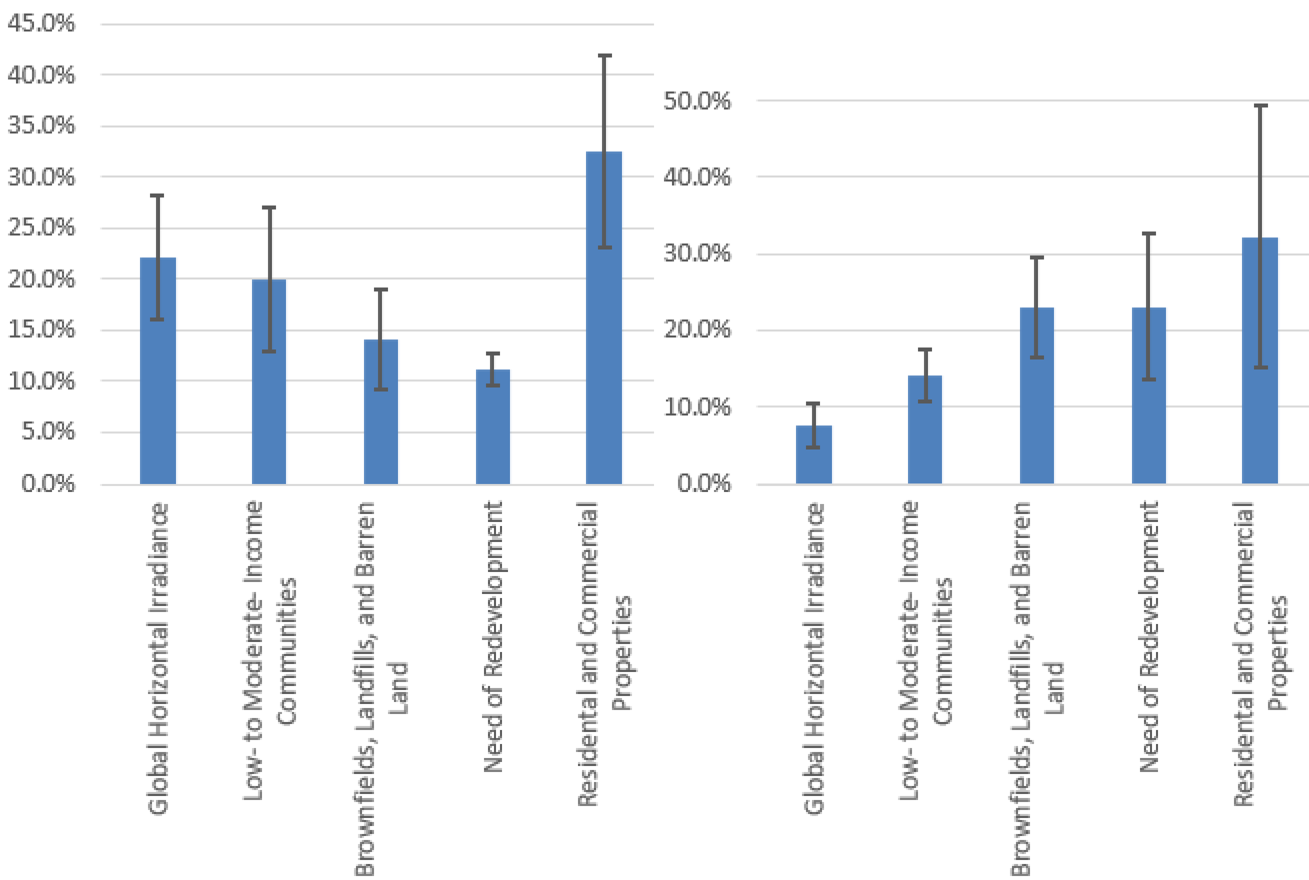


Figure 10: Stakeholder Distribution of Weighted Criteria.

The Solar Provider stakeholder group resulted in a consistency ratio of 3.8%, which is within the allowable limit. Based on this analysis, the most important criteria for developing community solar are commercial and residential rooftops (32.5%). This value is followed by global horizontal irradiance (22.2%), low- to moderate- income populations (20%), brownfields, landfills, and barren land (14.1%), and areas in need of redevelopment (11.2%). The most significant absolute error for the Solar Provider group responses is the category of residential and commercial properties (9.4%). Although this value was rated the highest priority for developing shared solar arrays, this variance can account for some respondents feeling strongly for or against this criterion's significance. The following group with the highest absolute error is low- to moderate- income communities (7.0%), global horizontal irradiance (6.1%), then brownfields, landfills, and barren land (4.9%), and areas in need of redevelopment (1.6%).

The Environmental Organization stakeholder group resulted in a consistency ratio of 6.5%, which is within the allowable limit. The consistency ratio is almost two times greater for the environmental group than the solar provider group. This discrepancy results from substantial variability of each environmental organization's interests rather than where solar providers may have more aligned interests. The weighted criteria resulted in commercial and residential properties having the highest importance (32.2%) for selecting solar sites, followed by areas in need of redevelopment (23.1%); brownfield, landfills, and barren land (22.9%); low- to moderate-income populations (14.0%); and global horizontal irradiance (7.7%). For the Environmental Organization group, the most significant variance in results is for the development of community solar on residential and commercial properties (17.1%). The following criteria are listed in descending absolute error variance: areas in need of redevelopment (9.6%); brownfields, landfills, and barren land (6.5%); low- to moderate- income communities (3.5%); and global horizontal irradiance (2.9%).

Table 4: Stakeholder Group Criteria Weights.

Stakeholder Group	**Solar Provider**	**+/-**	**Environmental Organization**	**+/-**
Criteria Weights				
Global Horizontal Irradiance	22.2%	6.1%	7.7%	2.9%
Low- to Moderate Income Communities	20.0%	7.0%	14.0%	3.5%

Brownfields, Landfills, and Barren Land	14.1%	4.9%	22.9%	6.5%
Areas in Need of Redevelopment	11.2%	1.6%	23.1%	9.6%
Residential and Commercial Properties	32.5%	9.4%	32.2%	17.1%
Consistency Ratio	3.8%		6.5%	
Consensus	53.7%		72.7%	

Each stakeholder group considered residential and commercial properties to provide the most significant influence in developing community solar locations irrespective of other environmental and economic criteria such as other governmental incentives for the LMI communities and repurposing degraded land. For each group, the model's absolute error would likely decrease with a more significant number of participants. This variance can be improved through a broadened emailing list and in-person surveys rather than exclusively through email. To shine some light on the respondent's feelings toward community solar, additional open-ended questions were asked. The variance in this outcome is the result of this firsthand experience from both groups.

Each stakeholder group was asked the same pairwise comparison question: the importance of different land use variables should be considered when selecting a location for community solar projects. However, each separate group was asked different yes/no and open-ended questions to help explain the survey results and improve our general perspective on community solar development. The participant could skip any open-ended questions they did not wish to answer. The average company age is 12 years for the Solar Provider group, ranging from 10 to 15 years. Two of five respondents have 1-25% of solar their solar projects as community solar farms. The remaining 3 have no community solar projects. When asked if they constructed only on specific land types when the response was "Yes," and the only specific land types were residential and commercial properties—the main reason for developing this specific resource response was related to business history and the available market.

Based on the survey, it was believed that the core obstacle to community solar development is within the program's ability to disperse the economic benefits of solar power and to overcome existing financial and institutional barriers to collectively owned solar. An opportunity to increase solar resource availability improving the relationship between the various organizations that coordinate development. One participant stated that there is substantial "structural complexity in relationships with utilities, commissions, other state bodies and impact on the revenue stream". Although there are many complexities to implementing a program to solve a range of social, environmental, and economic targets, the overall opinion of the future of New Jersey's community solar program and initiatives like it is expected to grow. When participants were asked on a Likert scale of expectations of increased community solar projects ranging from "Not at all expected" to "very expected", 80% of respondents selected "very expected".

The environmental organization group was asked a range of additional questions that differed from the solar provider groups. All respondents agree that the community solar program would significantly benefit their community, and 75% of the respondents actively seek to implement development. When asked about the potential impact of the community solar program, respondents believed that the program would help with socioeconomic disparities (financial and institutional barriers to solar resources). The Community Solar Energy Pilot Program and the future permanent program will have obstacles to benefiting some communities more than others due to diverse equity throughout a single community.

One respondent stated that there must be economic benefits that are being internalized by LMI communities,

“…for the program to benefit our community, there must be widespread adoption with economic benefits (utility savings and jobs) accruing to low/moderate income neighborhoods and communities of color.”

When asked about the biggest obstacle in community solar development, responses are most related to difficulty conceptualizing the goals and opportunities it provides.

“The lack of understanding on the part of the electricity consumer public and distrust of the electric utility industry and, to a lesser extent, of government. People are wary of making changes to things that are a part of their daily lives.”

General outreach and community support for areas where community solar is optimal are crucial for the program's success. When asked about solar goals, stakeholders give the impression that this program can aim at environmental justice.

[It is expected for] “…community solar development that creates local jobs and job-training, that promotes local ownership, that yields real savings for low/moderate income electricity consumers and that is adopted at sufficient scale to start changing NJ's carbon footprint”.

As this program moves out of its pilot program and onto permanent status, it carries the weight necessary to achieve a more clean and equitable energy future for New Jersey residents alike.

GIS Analysis Results

For the weighted overlay analysis, suitability was graded from least to most suitable locations. These locations were determined based on the AHP weighting analysis, and values ranged the 0–5. These results indicate the different levels of suitability for community solar development. The majority of the suitable locations reside within the electric distribution companies that have the most approved applications for community solar sites going from PSE&G, CP&L, ACE, and RECO. This analysis for the total distribution of suitable community solar locations ranges from most unsuitable to most suitable as represented in *Table 5* and visually in *Figure 11*. Electric distribution companies ranking in descending order are PSE&G with average suitability of 1.49, RECO with an average score of 0.65, JCP&L with an average score of 0.61, and ACE with an average score of 0.51.

Table 5: Range of Suitable Community Solar Sites. Suitability score from 0-5 is least to most suitable locations.

Suitability Score	Locations
0	1,733,112
1	55,562
2	4 72,020
3	246,199
4	27,189
5	2,237

This analysis determined values similar to NJBPU that approve community solar locations with minor exceptions. PSE&G has the most significant number of sites and the most suitable locations. RECO has a significant number of suitable locations, yet no approved sites may represent other externalities not represented in this model. Lastly, JCP&L and ACE have few approved sites and more suitable locations; future growth can be expected within these utility territories.

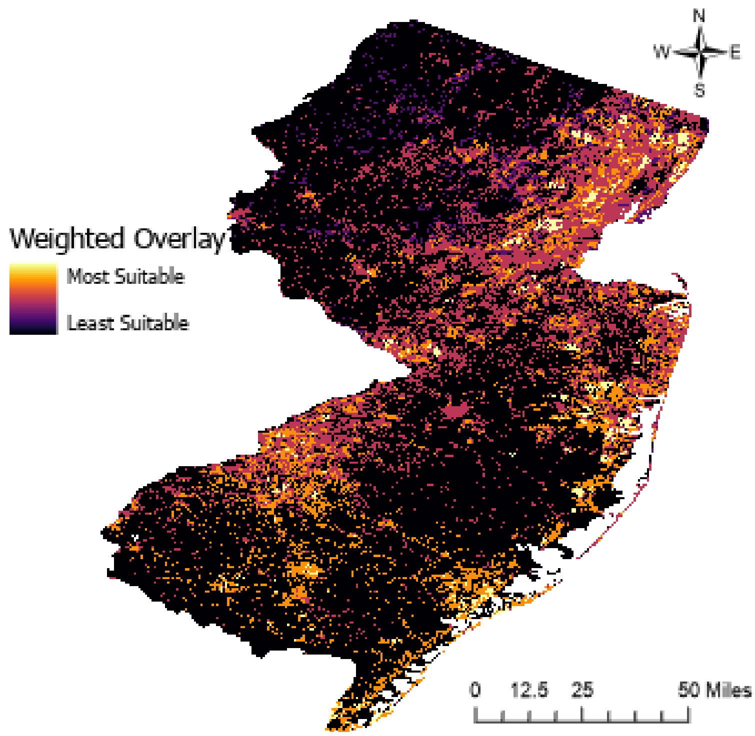


Figure 11: AHP-GIS Community Solar Suitability Analysis Results.

2.4 Conclusion

Climate scientists have unequivocally discussed and supported reducing greenhouse gas emissions to combat anthropogenic climate change (Intergovernmental Panel on Climate Change, 2007). The EMP is expanding New Jersey's renewable energy portfolio, especially with the development of the 3-year Community Solar Energy Pilot Program. Distributed solar energy generation is projected to grow significantly within the state. This study provides leverage toward stakeholders in areas where potential clean energy customers are likely to participate in the Community Solar Energy Pilot Program. Locations among EDC territories that may have limited suitable locations for community solar development may be recommended to determine if other clean energy alternatives are more suitable based on their environmental, social, and governmental factors. This research found that residential and commercial properties (32.5%) are the most important criteria for determining suitable community solar locations. There is a significant reliance on maintaining the market that stakeholders are already familiar and successful with, regardless of other incentives for repurposing degraded land. Literature supports the concerns relating to the remediation and upkeep of brownfields and landfills avoided by developing residential and commercial land resources (US Environmental Protection Agency, 2016). Based on this AHP-GIS model, PSE&G is the electric distribution company with the most suitable locations for community solar development, and ACE is the least. Based on survey responses, it is expected for community solar to grow and aid in achieving New Jersey's clean and equitable energy goals. Limitations for this research would be limited participation in the AHP survey which informed the analysis at a minimum. Future work for a similar project would include gathering more stakeholder data, improving public education to improve community participation in these LMI power projects, and repowering sites initiatives.

Chapter 3: Life Cycle Cost Assessment (LCCA) of Onshore Wind Generation in New Jersey: An Environmental and Economic Assessment

Abstract:

The energy generation sector primarily contributes to New Jersey's emissions and relies heavily on unsustainable energy sources such as natural gas and nuclear power. The current electricity generation implementation has resulted in significant environmental inputs to the state's surrounding soil, water, and air and accumulating social costs. New Jersey has begun providing the infrastructure to support change through progressive policies and programs. The state is attempting to diversify its energy generation mix to provide a more equitable energy future (US Energy Information Administration, 2020b; US Energy Information Administration, 2019). Distributed wind generation is an opportunity to provide uncommon flexibility to reach load demands, optimize the grid, and increase consumer economic impacts (Chowdhury et al., 2021; NJ Board of Public Utilities, 2019). An environmental and economic assessment can help determine robust solutions for the state's energy future. A Life Cycle Cost Assessment (LCCA) model will provide an in-depth perspective on the sustainability of onshore wind development in New Jersey, integrating Life Cycle Assessment (LCA) and Life Cycle Cost (LCC). This assessment goes beyond traditional emissions assessments; it includes additional environmental impact metrics, resource scarcity estimates, and human health impacts associated with the development and operation of onshore wind and costs. The LCCA provides constructive information to apprise policymakers to support the best renewable energy generation options. The core objective of this research is to quantify the environmental impact of a 1.5 MW onshore wind turbine operating in NJ over a 20 year and 40 year lifetime and identify any improvement in the lifetime environmental impact through scenario analyses. This study's findings consist of a significant reduction in environmental emissions through retrofitting turbines foundation but require more intense infrastructure development for disposal purposes. The scenario which

incorporated a turbine life extension to 40 years and the landfilling of fiberglass materials have least global warming potential at 5.04E-03 kg CO_2 equivalent. The LCC model determined substantial savings incorporated from emissions savings. A wind turbine is more cost effective with considering the cost of external costs associated with a comparable natural gas power plant.

3.1 Introduction

Distributed energy resources require effective planning to prevent energy system complications such as exceeding hosting capacity, high costs, and degraded performance (Taheri et al., 2021). Wind energy has been an appraised renewable energy technology that can efficiently use resources to minimize environmental inputs to the land, water, and air, such as GHG emissions and waste generation characteristics if planned properly (Panwar et al., 2010). This efficiency promotes sustainability based on current and future standards such as economic and societal. Additionally, wind energy can provide domestic cost-effective energy generation and job opportunities that will continue to grow in the future (NJ Board of Public Utilities, 2019). One of New Jersey's most ambitious projects is developing its offshore wind farm locations; however, onshore wind development has not received much interest from developers. There are many trade-offs when comparing small-scale to large-scale wind projects. While offshore wind has more consistent wind patterns with more substantial energy generation potential than onshore, installation and operation costs are significantly more expensive (Maienza et al., 2020). Onshore wind is one of the most commonly used renewable energy resources, providing a significant amount of electricity generation to populations within suitable locations (Haapala and Prempreeda, 2014). Wind energy generation has comparable emissions to nuclear power plants (US Energy Information Administration, 2020b), with fewer adverse ecological impacts and costs.

There are a wide range of sizes considered in distributed wind energy resources varying from less than 1 MW to 10 MW systems, primarily dependent on the turbine's location or capacity (US Department of Energy, 2021). Turbines are versatile and can be owned via individuals and businesses and can be used to offset retail costs of electricity, secure power costs long term, provide load for peak demand, and provide energy to remote locations (US Department of Energy, 2018). As grid independence continues to cultivate to achieve state energy goals, renewable energy resources can catalyze a more resilient and reliable community. Wind power continues to thrive where domestic manufacturers and supply chains have kept costs competitive. A comprehensive overview of the environmental and economic benefits can help guide the future of onshore wind investment in NJ and other similar locations and inform stakeholders of market opportunities (US Department of Energy, 2018).

Expanding wind energy development is crucial in achieving sustainable development goals (Ozoemena et al., 2018). This analysis focuses on the production of the wind energy life cycle model, excluding other emission reduction possibilities (such as solar and geothermal), and will utilize LCA to assess onshore wind energy generation in NJ as a potential route toward clean energy development in the state. Much of the attention relating to wind energy has gone to the offshore wind proposal due to its consistent wind speeds that can generate more electricity (Kaldellis and Kapsali, 2013). Although offshore wind production will produce more energy per kWh (kilowatt hour), obstacles relating to a utility-scale electricity generation of this size and location provide additional disadvantages compared to its onshore counterparts. Onshore wind is more accessible than offshore sites, but onshore wind requires a more in-depth analysis of site selection to ensure wind speeds, it requires preventative measures to protect humans and the environment and has greater acceptability to the power grid (Zheng et al., 2016). Due to saltwater and extreme weather conditions, offshore wind requires more frequent and costly maintenance and repairs (Mishnaevsky and Thomsen, 2020; Maienza et al., 2020). These additional costs do not support communities the same way small-scale distributed electricity generation does (Chowdhury et al., 2021). Onshore wind production is analyzed for this research to realize any environmental or economic support for future development in New Jersey. While offshore wind off the NJ coast has an undisputable energy generation advantage, onshore wind should not be ignored. Small-scale turbines could benefit from coastal winds even amongst the densely population state and improve the states' reach toward 100% clean energy.

LCA is a cradle-to-grave analytic technique that helps researchers determine the environmental impacts of a specific product or process from the start through disposal. The LCA will provide a holistic understanding of the potential environmental impacts of an onshore wind turbine. This assessment provides valuable information on emissions, environmental impact, cost estimations, and impact on human lives produced throughout the entire process from extraction to end of life (Haapala and Prempreeda, 2014). This LCA will provide insight to improve policy and decision-making necessary to achieve state energy goals. Given that there are only two onshore wind energy projects in the state (Jersey Atlantic Wind and Bayonne Wind Project), a LCA will give more insight toward potential incentives for these projects. Onshore wind can be incorporated into state goals by increasing the amount of energy generated for DERs.

Onshore wind farms conduct the most wind energy in the US, but New Jersey has not implemented many onshore wind projects (NJ Board of Public Utilities, 2019). NJ's offshore wind exploration project has preoccupied policymakers and businesses, significantly reducing the market for onshore wind production. Additionally, most of New Jersey's onshore wind suitable sites are found in wetlands and beaches, resulting in a significant land class exclusion. The most suitable onshore wind development will consist of several clusters of turbines that have the potential to generate 1-10 MW (although this size may prevent plants from reaching economies of scale) (US Department of Energy, 2021). While the state works toward improving the transmission system and supply chain development to optimize offshore wind generation, these plans may also improve onshore wind systems (NJ Board of Public Utilities, 2019). Onshore wind generation can help produce needed energy during peak hours or less than optimal wind strength (NJ Board of Public Utilities, 2019).

Currently, the Office of Clean Energy administers the NJ Clean Energy Program (NJCEP) which is meant to promote renewable energy development that lowers costs, demand, and pollution while providing other social benefits (NJ Board of Public Utilities, n.d.). However, there is a temporary hold on commitments for wind systems for the NJCEP Renewable Energy Incentive Program (REIP). The hold on the program is to ensure the public's safety and protect consumers from purchasing and installing insufficient wind systems (NJ Board of Public Utilities, n.d.). But with enhancements to technology, quality regulations, and increased transparency, the wind system programs could be reintroduced to the program. Beside this current delay, the NJCEP Renewable Incentive Program is an example of state initiative and legislation driving the industry. This incentive program was constructed by the REC (Renewable Energy Certificate) program, where systems can be financed through rebates, tax credits, Class 1 RECs, and Net Metering (NJ Board of Public Utilities, n.d.). Government incentives will play a decisive role in the progression of environmental impact reduction associated with electricity generation.

Onshore wind programs and regional correspondence provide an opportunity to increase New Jersey's distributed energy generation that is necessary to reduce costs to meet 2050's goals. Thus, it should still be explored as a potential method to reach the state's EMP goals. This research will use LCA to inform an in-depth, science-based, transparent perspective on the environmental impact associated with onshore wind energy generation to support the decision-making process for a clean energy future in New Jersey and other similar coastal states. This approach is constrained by various parameters that are supported by literature and the current market. By combining these models, the LCCA can be better informed of environmental factors, helping internalize the cost of externalities that traditionally would not have been acknowledged as part of the system. This method will help guide future policies supporting distributed renewable energy production.

Problem Statement

Consideration for distributed wind energy requires investigating resource potential, economic potential, and market potential to demystify robust opportunities (National Renewable Energy Laboratory, 2016). Currently, the US's wind resource has been left underutilized compared to its respective potential capacity. At the same time, many countries dominate onshore wind production (Haapala and Prempreeda, 2014; NJ Board of Public Utilities, 2019). New Jersey's current installed capacity (*Figure 12*) is not representative of the state's potential (*Figure 13*), showing the state has the potential to produce up to 945,000 MW of onshore wind power (National Renewable Energy Laboratory, 2020). Although wind is a shared resource outside of the US, most studies relating to LCA require a more in-depth analysis of environmental and economic impacts (Singh et al., 2003; Haapala and Prempreeda, 2014; Buxel et al., 2015; Gomaa et al., 2019). To avoid disregarding a possible feasible and effective opportunity, further environmental and economic analysis is necessary. Although onshore development has many exclusions in an urban environment, such as high land cost and limited property availability, small-scale onshore wind generation is worth exploring based on models conducted in the Integrated Energy Plan, which called for increased distributed energy generation within the state (NJ Board of Public Utilities, 2019).

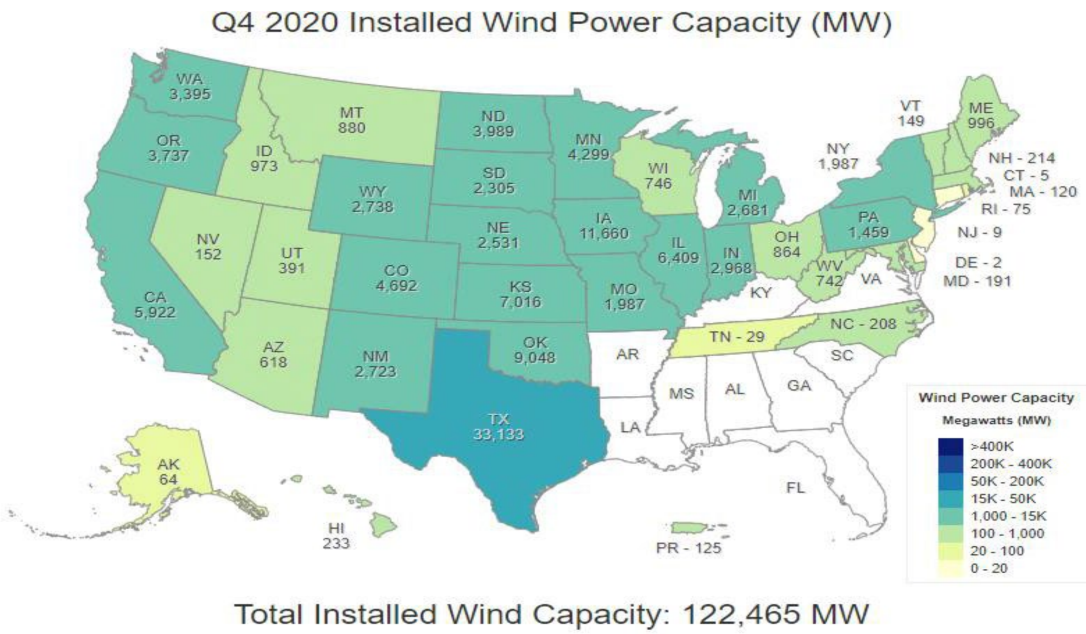


Figure 12: 2020 Installed Wind Power Capacity (US Department of Energy, 2020a).

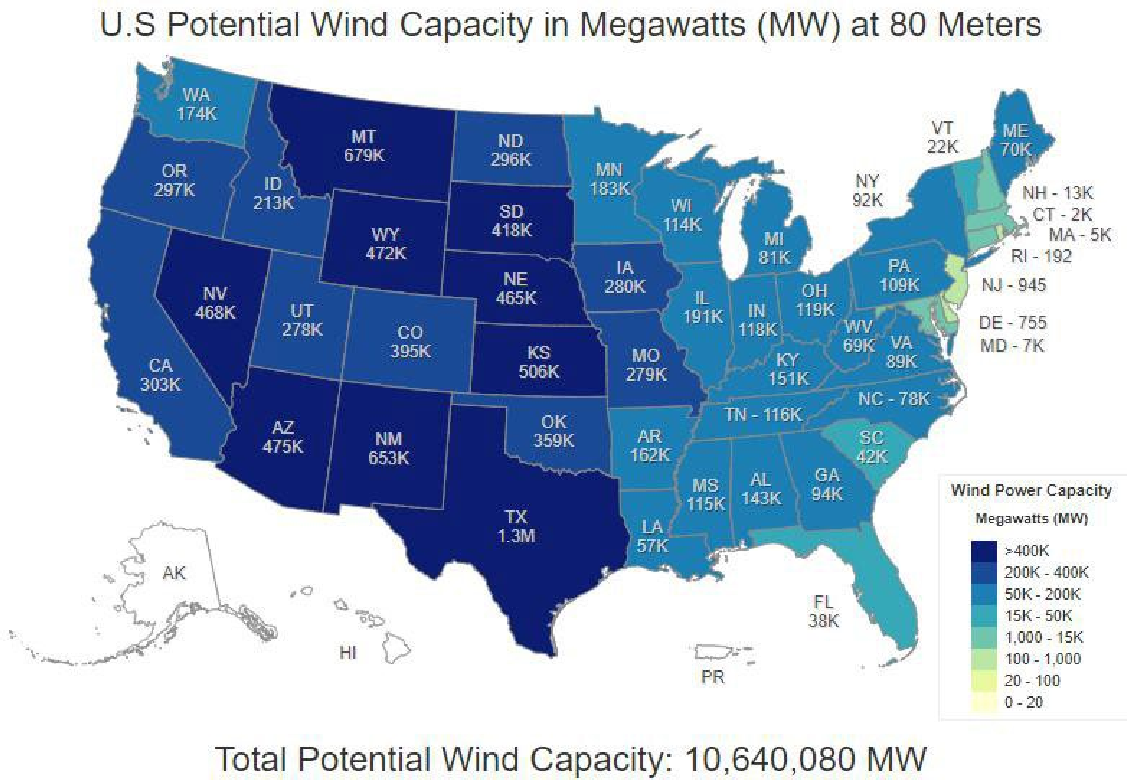


Figure 13: US Potential Wind Capacity (US Department of Energy, 2020a).

In recent years there has been a drive to repower wind projects that have been decommissioned with larger, better-made turbines (supported by detailed Renewables Portfolio Standards) at a much lower price compared to earlier turbines (NJ Board of Public Utilities, 2019; NJ Department of Environmental Protection, 2017). The life extension part of the study included implementing substantial retrofitting that would allow for the turbine to continue running longer than typically expected. Through the consideration of additional upkeep, quality assurance within turbine manufacturing, and use, there are fewer early-decommissioned and underutilized turbines compared to those constructed earlier on in the wind energy history (Jeong et al., 2020).

This analysis of onshore wind energy can provide support for future market claims and improve the general performance of products, such as turbine designs. The LCA can identify environmental 'hotspots' within the analyzed process, helping determine where improvements can be made to improve sustainability metrics in the supply chain. The LCA will also provide a thorough investigation of environmental impacts to accurately inform decisions made by stakeholders like developers, policymakers, and researchers. This analysis can provide the provisions needed to reach clean energy target goals. Life Cycle Costing (LCC) will assess an economic evaluation of present and future costs, cash flow, and discount rates to determine present value. Life Cycle Cost Assessment (LCCA) integrates LCA and LCC models to estimate actual and environmental costs of an onshore wind turbine more accurately. The LCCA can provide a holistic economic perspective from results from the impact assessment of the onshore wind turbine. An LCCA involves monitoring assets and optimizing present and future costs to help determine cost-effective decision-making (Suhu et al., 2020). This study will provide a unique perspective using a LCCA model for NJ based onshore wind turbines by evaluating turbine life cycle components such as operations and maintenance, disposal, and the inclusion of environmental externalities.

3.2 Methods

Goal, Functional Unit, and System Boundaries

This Life Cycle Cost Assessment aims to determine the environmental and economic impacts of the current and potential disposal methods for a General Electric (GE) 1.5xle wind turbine operating in New Jersey over a 20 year lifetime. GE has been the largest US-based manufacturer represented in large-scale distributed wind energy projects greater than 1 MW (US Department of Energy, 2021). The size of distributed wind energy projects with a capacity greater than 1 MW is supported by current industry trends and representative of NJ environmental and economic factors (NJ Board of Public Utilities, 2019; US Department of Energy, 2018). This baseline (S0) was determined based on supporting literature (Guezuraga et al., 2012; Gkantou et al., 2020; Zong et al., 2011; Burger and Bauer, 2007). Each product stage is designed by mass from the functional unit of 1 kWh. Each product stage is allocated by mass related to the functional unit for the study to total 1 kWh. The equation used to determine the lifetime kWh generation for the theoretical 1.5MW turbine is as follows(US Department of Energy, 2018):

([MW] x [CAPACITY FACTOR] x [8,760 hours/year] x [1,000 kWh/MWh]) x Turbine Lifespan = kWh Generation per turbine lifespan

The equation above describes the electricity generation from the turbine is (1.5 MW) multiplied by the capacity factor (35) and then by the average number of hours per year (8,660 hours). The capacity factor measures the intensity level of the energy generated, dividing the produced electricity by the maximum potential (US Energy Information Administration, 2020c). The scenario assumes that the turbine is not running for 100 hours per year, accounting for time spent on maintenance. The annual energy production is then multiplied by the turbine's lifespan and thereby creating distinctly different scenario outputs for 20 and 40 year turbines. This LCA is models from the principles and framework described in the International Standards Organization (ISO) 14040:2006 (International Standardization Organization, 2006). *Table 6* consists of turbine specifications: a hub height of 100 meters, a horizontal-axis rotor, a rated wind power of 1500 kW, and a rotor diameter of 82.5 meters (Wind Power, 2021).

Table 6: Turbine Specifications (adapted from Wind Power, 2021).

Turbine	**Rotor Diameter**	**Rated Power**	**Hub Height**	**Rated Wind Speed**	**Capacity Factor**
GE 1.5 xle	82.5 m	1500 kW	100 m	11.5 m/s	35%

The system boundaries include raw material acquisition, material processing, manufacturing, product use, and end of life (*Figure 14*). There are also specific geographic boundaries relating to onshore wind power in New Jersey. Efficiency and capacity for energy generation are significantly influenced by wind forces that can vary significantly among different geographical locations (Kaldellis and Kapsali, 2013). Locations of turbines must be in the strategic location to produce enough electricity to reach economies of scale. It is assumed that the suitability of the location has already been determined to be optimal for turbine energy production.

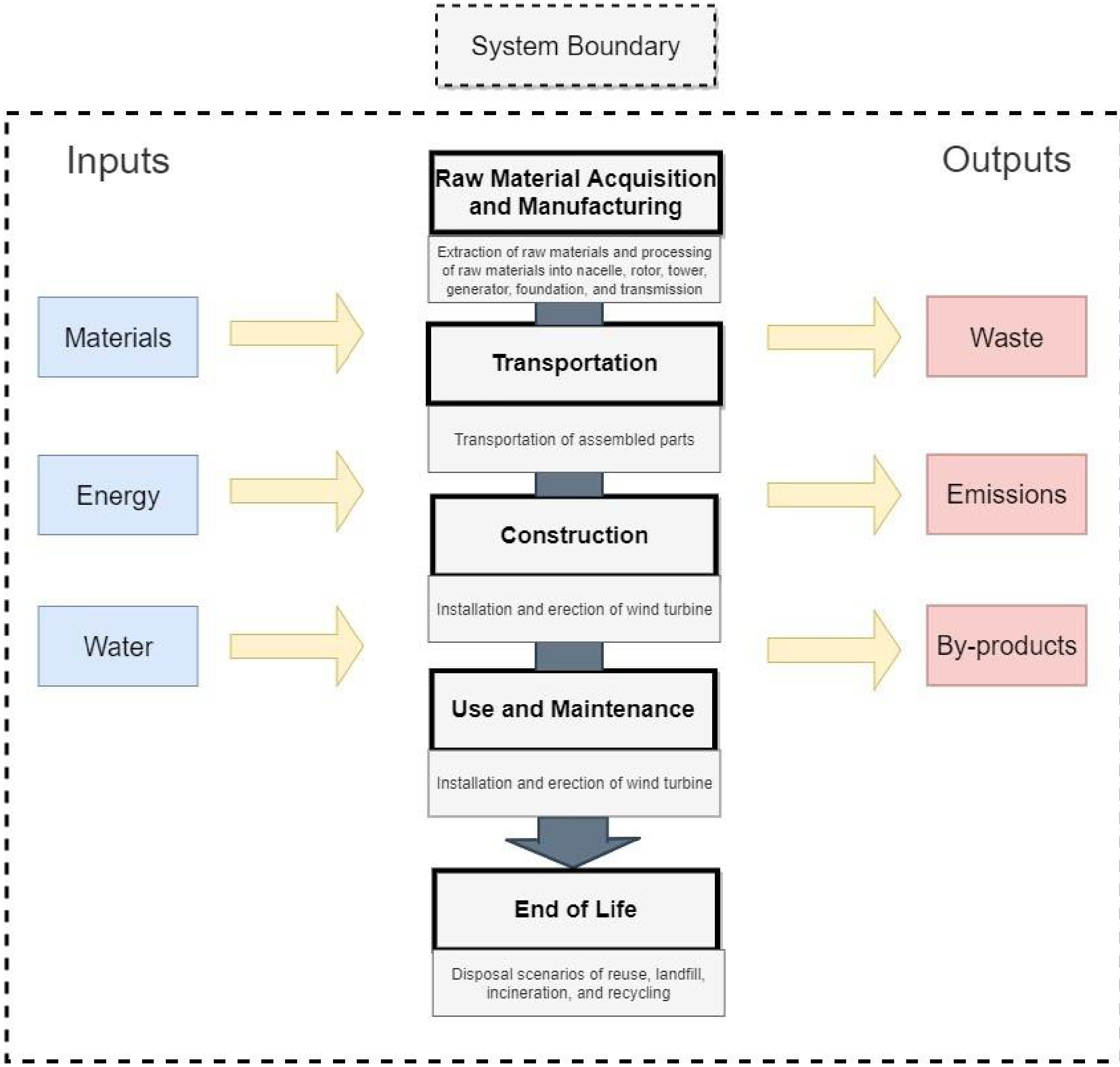


Figure 14: LCA System Boundary.

Methods and Data

SimaPro software (version 9.1) is used for this analysis. It is a reliable and reputable tool designed to conduct LCA research. Data on materials and processes were used from the Ecoinvent version 3.4 database and were modified as necessary to fit case-specific requirements. Currently, New Jersey has six onshore wind turbines, each capable of producing 1.5 MW of energy. Based on these current practices, we will explore turbines of equivalent energy generation capacity and use existing available data to inform our model. Further data used for our model is gathered from previous literature, governmental documentations, and supplier data (E.g., the manufacturer) (NJ Board of Public Utilities, 2019; Gomaa et al., 2019; Buxel et al., 2015; Singh et al., 2003; Haapala and Prempreeda, 2014).

For this LCA, we used the ReCiPe impact assessment method due to its capability to transform large life cycle datasets into midpoint and endpoint indicators to display various sustainability metrics as presented in *Table 7*. This impact assessment for the 1.5MW turbine was calculated using the ReCiPe 2016 midpoint and endpoint methods as a standard for similar scientific models. The midpoint and endpoint indicators provide a perspective on variable issues like timing or proper management. We applied the hierarchist (h) perspective to our assessment, which is a consensus model for sustainability research within a 100-year perspective based on the common policy principles concerning timeframe and other similar issues (Goedkoop et al., 2009; Pre Sustainability, 2020). A midpoint method is a problem-oriented approach which consists of 18 key indicators, and an endpoint method is a damage-oriented approach which extrapolates indicators from the midpoint approach and categorizes them into three metrics (see *Table 7*).

Table 7: ReCiPe Midpoint and Endpoint Impact Categories.

Midpoint Impact Category	**Abbreviation**	**Units**
Climate change	GWP	kg CO_2 eq to air
Ozone depletion	ODP	kg CFC-11 eq to air
Ionizing radiation	IRP	kBq Co-60 eq to air
Photochemical oxidant formation: human health	HOFP	kg NOx eq to air
Fine particulate matter formation	PMFP	kg PM2.5 eq to air
Photochemical oxidant formation: ecosystem quality	EOFP	kg NO_x eq to air
Terrestrial acidification	TAP	kg SO_2 eq to air
Freshwater eutrophication	FEP	kg P eq to freshwater

Marine eutrophication	ME	kg N eq to marine water
Terrestrial ecotoxicity	TETP	kg 1,4-DCB to industrial soil
Freshwater ecotoxicity	FETP	kg 1,4-DCB to freshwater
Marine ecotoxicity	METP	kg 1,4-DCB to marine water
Human toxicity: cancer	HTPc	kg 1,4-DCB to urban air
Human toxicity: non-cancer	HTPnc	kg 1,4-DCB to urban air
Land use	LOP	$m^2 \times yr$ annual crop land
Mineral resource scarcity	SOP	kg Cu
Fossil resource scarcity	FFP	kg oil
Water use	WCP	m^3 water consumed
Endpoint Impact Category		
Human health	HH	DALY
Ecosystem health	EH	Species.yr
Resource scarcity	RS	USD2013

The analysis categories include LCA Impact Assessment, LCC analysis, Monte Carlo uncertainty analysis, and network analysis. The impact assessment is a ubiquitous analysis used within LCA to determine the system's environmental impact based on the Life Cycle Inventory (LCI) inputs and outputs. The Life Cycle Cost (LCC) will provide a cost-benefit analysis of onshore wind turbines. The information collected for this analysis can be found in the Department of Energy 2018 Wind Technologies Market Report (US Department of Energy, 2018). Information includes capital costs, maintenance costs, annual revenue, and capital in- and out-flow. The network analysis enriches our understanding of various system processes proportionately to the total environmental impact. The Monte Carlo uncertainty analysis is a statistical analysis to describe the distribution of variability by running iterations 1,000 times to determine the accuracy of the impact assessment (Pre Sustainability, 2020). This LCA was gauged using an uncertainty analysis tool at a 90% confidence interval. A standard deviation (SD) and coefficient of variation (CV) for each impact analysis are critical determinants of the data accuracy within the LCI.

Impact Assessment Method

LCA is helpful in research studies for aggregating all system inputs into environmental impact categories. Within the impact categories, environmental performance and risk can be assessed with different system processes such as resource acquisition, transportation, construction, operations and maintenance, and reuse/or end of life (Haapala and Prempreeda, 2014). In structuring this life cycle assessment of a GE 1.5xle wind turbine, current practices and requirements were included in the life cycle stages presented in *Figure 14, LCA System Boundary*. The system boundary limits the extent of the study, excluding other neighboring system components that may take away from the purpose of the study. The limits of this study start at material acquisition and stop with various end-of-life (EOL) product scenarios. This research study entails the collection and manufacturing of materials required for construction (tower, nacelle, blades, foundation, and network connection); the transportation of these materials from the manufacturing plant to the wind farm expected location; the construction equipment required for the assembling of turbine parts and the erection, stabilization, and network connection of the structure; the general maintenance, inspections, and condition repairs; and lastly the dismantling, transportation, and processing of turbine materials.

System limitations that are considered to be outside of the system consist of two main assumptions. First, the manufacturing of materials occurred in the US, where most of the turbine materials consist of concrete and precious metals (US Department of Energy, 2021). Concrete for the foundation is typically acquired and manufactured locally, and metals are continuously recycled; therefore, mining impact is not associated with recycled materials. The interconnection of the turbine only requires a transformer and distribution lines to connect to an electric substation. However, the electricity substation is considered outside the system boundary. The state is likely to have substations that have been created before the turbine that can compensate for the turbine's relatively low capacity without additional modifications to the electrical power network (Burger and Bauer, 2007).

The Life Cycle Inventory (*Table 9*) was arranged using modified Ecoinvent version 2.2 data by Long Trail Sustainability for DATASMART. This library consists of adjusted datasets that are representative of current US operations. The DATSMART library consists of a combination of US LCI v.1.60 and Ecoinvent v.2.2 data. LCI tracks the mass of all inputs and outputs within the system's boundary, adjusted by the functional unit. Specifically, LCI includes the inputs to the environment, inputs to the technosphere, which consist of the materials/energy used, and outputs to the technosphere with the system outputs that are the by-products and emissions generated.

Life Cycle Cost Assessment

The Life Cycle Cost Assessment (LCCA) is an economic method that can assess a project's long-term cost-effectiveness compared to an alternative (usually focusing on short-term obligations). It is commonly used to evaluate the costs of owning, operating, maintaining, and disposing of a project to guide capital investment decisions, where higher initial costs reduce future costs (Kneifel and Webb, 2020). LCCA can help justify the starting economic cost of a program and focus on payback methods that recover the initial investment and determine long-term profitability. LCCA is informed with environmental emission data to help determine the cost of related externalities. LCC is determined by using the following equation:

$$\boldsymbol{LCC = \sum_{t=0}^{n} \frac{C_t}{(1+d)^t}}$$

***LCC*: Total LCC in present-value dollars of a given alternative**

***C_t* : Sum of all the relevant costs, including initial and future costs, less any positive cash flows, occurring in year t**

***n*: Number of years in the study period**

***d*: Discount rate used to adjust cash flows to present value**

The LCC model accounts for the baseline scenario to represent the cost savings of this 20 year wind generation plant compared to that of a natural gas power plant of equivalent size. This will allow us to represent the impact of transitioning from natural gas to wind power. Cost inputs are summarized in *Table 8*. Scenarios of discount rates of 3%, 5%, and 7% were used to account for present value in accordance with the discount rates for evaluating a cost-benefit analysis of clean energy in the EPA Regulatory Impact Analysis Clean Power Plan and the Department of Energy Federal Energy Management Program 2021 Discount Rates (US Environmental Protection Agency, 2015b; US Department of Energy, 2019). This report evaluates the present value formula:

$$\boldsymbol{PV = \frac{FV}{(1+r)^n}}$$

***PV*: Present value**

***FV*: Future value**

***r*: Discount rate**

***n*: Amount of time in years**

Table 8: Wind Turbine Summarized Costs

Capital Costs	Value	Reference
Site Assessment		
	$35,000.00	Wind Industry, 2021
Land Leasing NJ		
Property Leasing	$13,700.00	US Department of Agriculture, 2019
Developer Fee	$4,875.00	US Energy Information Administration, 2020
Permits		
Building Permit Fee	$7,500.00	US Energy Information Administration, 2020
Consultant	$50,000.00	US Energy Information Administration, 2020
Construction		
Feeder Line to Transmission Line	$39,500.00	US Energy Information Administration, 2020
Transformer	$32,500.00	US Energy Information Administration, 2020
Tower and Turbine	$2,100,000.00	National Renewable Energy Laboratory, 2018
Material Transportation	$100,000.00	US Energy Information Administration, 2020
Installation Costs		US Energy Information Administration, 2020
Construction Financing Fee	$35,872.20	National Renewable Energy Laboratory, 2018
Foundation	$250,000.00	National Renewable Energy Laboratory, 2018
Wiring	$41,391.00	National Renewable Energy Laboratory, 2018
Engineering and Management	$5,518.80	National Renewable Energy Laboratory, 2018
Development Cost	$4,139.10	National Renewable Energy Laboratory, 2018
Turbine Erection	$115,000.00	US Energy Information Administration, 2020
Operation and Maintenance		
WTG (wind turbine generator) Unscheduled Maintenance	$22608.00/year	US Energy Information Administration, 2020

Blade Repair Cost	$82,782.00	National Renewable Energy Laboratory, 2018; Mishnaevsky Jr. and Thomsen, 2020
WTG (wind turbine generator) 2 Wind Turbine Technician Salary in NJ	$ 112,460.00/year	US Bureau of Labor Statistics, 2020
Warranty	$30,000.00	US Energy Information Administration, 2020
Insurance	$11500.00/year	US Energy Information Administration, 2020
Administrative and legal costs	$8000.00/year	National Renewable Energy Laboratory, 2018
Decommission Cost	$25,000.00	Wind Industry, 2021
Emissions Costs		
Carbon dioxide (CO_2)	$52.00/metric ton	US Environmental Protection Agency, 2021
Nitrous oxide (N2O)	$19,000.00/metric ton	US Environmental Protection Agency, 2021

Secondary data has been constructed best to represent current land, material, and equipment requirements for this research. A Life Cycle Inventory (LCI) collects system inputs and outputs along with the interpretation and adaptation of system standards. Background data was supported by the DATASMART LCI Package comprised of a combination of US LCI v.160 and Ecoinvent v2.2 data. Adaptations for business-as-usual materials, transportation, and other system inputs and outputs are supported by literature and some materials where scales up to fit the GE 1.5xle turbine specifications found in the GE 1.5 MW Wind Turbine report (Guezuraga et al., 2012; Gkantou et al., 2020; Zong et al., 2011; Burger and Bauer, 2007).

Table 9: Life Cycle Inventory.

Turbine Part	Materials	Mass	Unit	LCI Inventory Name
Foundation	Concrete	601632.57	Kg	Concrete, normal, at plant/US* US-EI U

	Steel	26905.90	Kg	Reinforcing steel, at plant/US- US-EI U
Tower	Steel	115975.09	Kg	Steel, low-alloyed, at plant/US- US-EI U
	Resin	300.799	Kg	Epoxy resin, liquid, at plant/US- US-EI U
Nacelle	Aluminum	351.53	Kg	Aluminum, primary, at plant/US- US-EI U
	Cast Iron	11004.42	Kg	Cast iron, at plant/US- US-EI U
	Lead	0.85	Kg	Lead, at regional storage/US- US-EI U
	Lubricating Oil	99.85	Kg	Lubricating oil, at plant/US- US-EI U
	Steel	6368.30	Kg	Steel, low-alloyed, at plant/US- US-EI U
	Synthetic Rubber	169.82	Kg	Synthetic rubber, at plant/US- US-EI U
	Chromium Steel	24624.08	Kg	Chromium steel 18/8, at plant/US- US-EI U
	Tin	0.85	Kg	Tin, at regional storage/US- US-EI U
Blade& Hub	Fiberglass	16029.94	Kg	Glass fiber reinforced plastic, polyamide, injection molding, at plant/US- US-EI U
	Chromium Steel	5905.77	Kg	Chromium steel 18/8, at plant/US- US-EI U
	Cast Iron	6186.99	Kg	Cast iron, at plant/US- US-EI U
Network Connection	Aluminum	71.91654	Kg	Aluminum, primary, at plant/US- US U
	Copper	253.71	Kg	Copper, at region storage/ US- US-EI U
	HDPE	1375.4	Kg	Polyethylene, HDPE, granulate, at plant/US- US-EI U
	PP	20	Kg	Polypropylene, granulate, at plant/US- US-EI U
	PVC	434	Kg	Polyvinylchloride, bulk polymerized, at plant/US- US-EI U
	Wire Drawing	1460	Kg	Wire drawing, copper/US- US-EI U
	Transformer	1300	Kg	Transformer, high voltage use, at plant/GLO US-EI U

	Lubricating Oil	200	Kg	Lubricating oil {RoW}| market for lubricating oil | APOS, U

Datasets were adjusted to represent the scope and literature proposed by the modified Ecoinvent 2.2 version of Burger and Bauer (2007). The impact assessment results are extended to consider hotspots in a different process, potential policy implications, costing analysis, and comparison with an alternative energy source. This LCA aims to determine the environmental and economic impact resulting from the proposed Burger and Bauer (2007) and additional literature represented in *Table 10* to model current day scenarios.

Table 10: Life Cycle Assessment Scenario Analysis.

Disposal Scenarios	Materials	Disposal	Resources
S0, Baseline	Ferrous and non- ferrous metals	90% recycle, 10% landfill	Guezuraga et al., 2012; Gkantou et al., 2020; Tazi et al, 2019).
	Fiberglass	100% incineration	Guezuraga et al., 2012; Gkantou et al., 2020.
	Concrete	20 year foundation, 100% Landfill	Guezuraga et al., 2012; Gkantou et al., 2020.
	Rubber	100% incineration	Zong et al., 2011.
S1	Fiberglass	100% incineration	Guezuraga et al., 2012;Gkantou et al., 2020; He et al., 2017.
	Concrete	40 year foundation (retrofitted), 100% landfill	Jeong et al., 2020; He et al., 2017.
S2	Fiberglass	100% landfill	Psomopoulos et al., 2018; Nagle et al., 2020; Correia et al., 2020.
	Concrete	20 year foundation, 100% landfill	Guezuraga et al., 2012; Gkantou et al., 2020.
S3	Fiberglass	100% landfill	Psomopoulos et al., 2018; Nagle et al., 2020; Correia et al., 2020; He et al., 2017.
	Concrete	40 year foundation (retrofitted), 100% landfill	Jeong et al., 2020; He et al., 2017.

S4	Fiberglass	90% Mechanical Recycling, 10% Landfill	Psomopoulos et al., 2018; Nagle et al., 2020; Correia et al., 2020.
	Concrete	20 year foundation, 100% landfill	Guezuraga et al., 2012; Zong et al., 2011; Gkantou et al., 2020.
S5	Fiberglass	90% Mechanical Recycling, 10% Landfill	Psomopoulos et al., 2018; Nagle et al., 2020; Correia et al., 2020; He et al., 2017.
	Concrete	40 year foundation (retrofitted), 100% landfill	Guezuraga et al., 2012; Zong et al., 2011; Gkantou et al., 2020; He et al., 2017.
S6	Fiberglass	90% Thermal Recycling w/out energy recovery, 10% landfill	Psomopoulos et al., 2018; Nagle et al., 2020; Correia et al., 2020.
	Concrete	20 year foundation, 100% landfill	Guezuraga et al., 2012; Gkantou et al., 2020.
S7	Fiberglass	90% Thermal Recycling w/out energy recovery, 10% Landfill	Psomopoulos et al., 2018; Nagle et al., 2020; Correia et al., 2020; He et al., 2017.
	Concrete	40 year foundation (retrofitted), 100% landfill	Jeong et al., 2020; He et al., 2017.

Each resource was used to validate the life span and materials required for each specific scenario of this life cycle assessment. For each of the other scenarios, it is assumed that 90% of the ferrous and non-ferrous metal materials will be recycled, whereas the last 10% will be landfilled. This benefit will be incorporated into the disposal; this is an industry standard due to the recyclability of these materials and the cost savings produced from not mining and manufacturing virgin metals, especially steel and copper (Gkantou et al., 2020). Without incorporating recycling benefits for the tower steel, the tower would have the highest carbon dioxide equivalent emissions and validate the baseline lifespan of 20 years (Guezuraga et al., 2012). Zong et al. (2011) models different landfill disposal and recycling scenarios of decommissioned wind turbines and infers that recycling is more environmentally friendly than landfill options and reduces energy needs. Psomopoulos et al. 2018 and Correia et al. 2020 review various scenarios for thermal recycling to recycle fiberglass blades. This process requires a large amount of energy and resources.

The framework for disposal scenarios is discussed in Nagle et al. (2020) where the use of co-processing and materials substitution to reduce the impact of the turbine blades is implemented. In Jeong et al. (2020), a service life extension study was conducted for the foundation of aged turbines and demonstrated a fatigue life of 40 years or more. The operations for an effective service life extension were discovered by determining the structural safety of the current materials considering fatigue, material deterioration, serviceability, and general strength. Although turbine foundations can have an extended life of 40 years, standard structural adjustments need to be completed to ensure longevity and general safety for an operating wind turbine. In He et al. (2017), two main structural adjustments are necessary for life extension purposes. First, the addition of high-strength grout that will be added to voids within the anchorage zone. These adjustments will increase the load bearing capacity of the concrete and the addition of girders and anchoring bolts into the original foundation.

The fundamental impact assessment structure consists of characterization, normalization, and damage assessment factors. These are parameters that ensure the measurement of environmental impacts, trade-offs, and hotspots. With characterization, the inputs that contribute to an impact category are multiplied by a characterization factor that expresses the relative contribution of the substance (Pre Sustainability, 2020). Normalization references data created in characterization and divides that number by the reference, making it possible to compare impacts. Lastly, damage assessments consist of calculations using the endpoint methods, which combine several impact category indicators into a damage category (Pre Sustainability, 2020). The damage assessment allows the data to be represented in impact per DALY, daily average life years loss lived with a disability; species.yr represented the ecosystem loss of species in years and USD2013 accounts for resource scarcity with a 3% discount rate (Pre Sustainability, 2020).

Life Cycle Stages

Raw Material Acquisition and Manufacturing Stage:

This product stage represents two essential core processes of a cradle-to-grave approach, including the mineral resource extraction, collection, and processing of raw materials for manufacturing purposes. These materials consist of steel, copper, cast iron, fiberglass, aluminum, rubber, epoxy resin, and other auxiliary materials. A summary of the turbine's main components and materials is presented in *Table 9*. The manufacturing of these raw materials and energy for their production is scrutinized from economic and environmental perspectives and is considered an industry standard (Guezuraga et al. 2012; Gkantou et al., 2020). A core driver in decreasing the monetary and environmental cost of turbines is reducing the number of virgin materials used, and processing required. Potential for reducing this is through the use of recycled, reused, and retrofitted materials.

Transportation:

This product stage consists of the environmental impacts associated with the energy requirements for transportation of turbine materials and necessary construction equipment. The unit ton-kilometer (tkm) incorporates tons of materials being moved over a distance in kilometers. Tkm is calculated by multiplying the Total Load Carried (TLC), measured in terms of tons, by the Total Distance Covered (TDC) measured in kilometers (Nagle et al., 2020). This section includes materials used for moving (nacelle, rotor, and electric parts) and fixed (tower and concrete for foundation) parts. Transportation vehicles include a >28-ton transport freight truck and rail. The foundation materials are transported separately via cement mixing truck at a closer location. The GE 1.5xle turbine is produced at GE Advanced Manufacturing Works, 301 Feaster Rd, Greenville, SC 29615. The efficiency of transportation relies on the mode of transportation, distance from the wind power plant, and cargo mass. Viewed in *Figure 15*, the Turbine Mass Distribution, the foundation materials account for 76.6% of the total mass of the turbine. The foundation requires 20 round trips, and the remaining materials require 3 round trips. To avoid unnecessary transport costs and emissions, developers must obtain foundation materials locally (Burger and Bauer, 2007). Transportation is a separate product stage that is incorporated to include all required transportation aside from what is required for operations, maintenance, and additional retrofitting purposes.

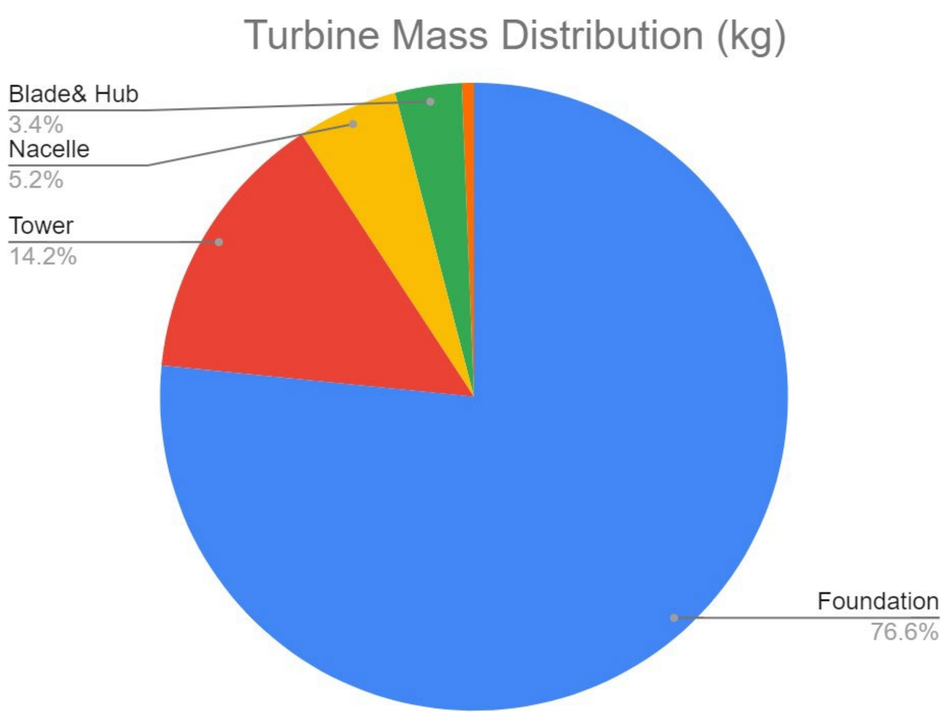


Figure 15: Turbine Mass Distribution.

Construction:

This product stage involves the construction of the combined materials, as stated in the resource acquisition stage of this LCA. This process is known as the cradle-to-gate life cycle, and core parts consist of the tower, nacelle, and rotor (Haapala and Prempreeda, 2014). These products are manufactured and transported to the wind farm location to be assembled and erected on site. The assembly and deconstruction are typically performed using construction equipment involving cranes, excavator diggers, hydraulic hammers, and the associated energy, fuel, and additional environmental impacts (Wang et al., 2019; Haapala and Prempreeda, 2014). For this LCA, the impact of these specific materials has been incorporated under the excavation digger impact to reduce the system complexity of equipment that holds a relatively small impact on the overall system.

Use and Maintenance:

The wind turbine's regular maintenance operations are performed three times annually to ensure the proper function and efficiency (Haapala and Prempreeda, 2014; Wang et al., 2019). Routine maintenance inspections entail a complete gearbox oil change every 36 months, lubrication for the rotor blade and gearbox, and fuel consumption for transportation. During these check-ups, 50 kg of diesel is used for transportation and use onsite (Wang et al., 2019; Chipindula et al., 2018). Transportation requirements are considered in part of the O&M portion of this life cycle as they are requirements specifically for maintaining the quality of the structure. For the 40-year turbine scenarios, all the energy and materials needed to retrofit and repair parts of the turbine are included in operations and maintenance. This method provides a unique view of the added environmental costs for these upkeep requirements instead of past studies that commonly incorporate retrofitting materials to the specific part of the turbine or life cycle stage.

End of Life:

Turbine life extension and reduction in disposal environmental inputs are ways to reduce the impact attributed to traditional landfilling (Tazi et al., 2019; Jeong et al. 2020; He et al., 2017). The turbine foundation contributes to most of the turbine mass and environmental impact in the business-as-usual method. Components' impact can be reduced by providing a more efficient use of the foundation and recyclability of other turbines. There are many options for disposal of materials, including incineration, landfill, mechanical recycling, and thermal recycling, that are investigated for impact.

Scenario Assumptions

Transportation Assumption:

For this analysis, the US average distance for transportation to wind turbines, collected from the DATASMART database, was used to allow this application to other future studies. It is also important to note that although US averages were used for transportation, site-specific transportation for the GE 1.5xle proposed turbine in New Jersey was conducted via Google Maps. Results from this calculation are similar to the estimation used in this study.

Assembly and Deconstruction Assumption:

Although assembly and deconstruction are part of separate phases, their assumptions are similar. Each stage includes the processing, energy requirements, and inputs to nature for either assembling or deconstruction. It is assumed that the occupied facilities must be dismantled and removed for the end of service, and land must be restored to acceptable conditions. The removed materials must be separated into their main components for incineration, landfill, mechanical recycling, or thermal recycling. Deconstruction will have fewer impacts on nature in comparison to the assembly stage which requires transformations from a natural environment to a developed one.

Operations & Maintenance Assumptions – 40 Year Scenarios:

For the 40-year turbine, retrofitting was incorporated to decrease impact and economic benefit/saving while providing a safe alternative to decommissioning a degraded turbine (He et al., 2017). For example, the foundation requires cracks to be sealed as well as additional support girders and bolts to be in place to ensure that the aged foundation is structurally secure. These additional materials are not added to the 40-year foundation but instead to the operations and attendance category because this is considered as turbine upkeep and added post-construction. Likewise, transportation, lubrication oil, energy, and replacement materials (e.g., blades, parts of the nacelle, epoxy resin, etc.) are incorporated in the operations and maintenance section of the life cycle, rather than their respected turbine structures due to the direct association to structural upkeep.

A moderate scenario for wind turbine manufacturers when extending the lifespan of a turbine is generally considered to need part of gearbox or generator to be replaced along with one entire blade (Tazi et al., 2019). To accurately present maintenance flow that can be compared to previous studies, this research will account for 2 replacements of the gearbox. It is assumed that 40% of steel and iron in the nacelle must be replaced along with an additional blade to extend the life span an additional twenty years (Tazi et al., 2019). The foundation consists of the most numerous adaptations to ensure structural reliability. These adaptations to retrofit the 15x15 meter foundation consist of 48,000 kg worth of anchor bolts (170 bolts that are 6.3 meters long and 1.25 inches thick), 6,300 kg of steel girders (6 girders), and 30,000 kg epoxy resin to fill cracks. The epoxy is applied to what is estimated to be 35% of the total surface area, and the resin thickness is ½ inch thick. Field studies support the installation of external prestressed anchor bolts, girders, and epoxy to repair continuous cracks (He et al., 2017; Gervásio et al., 2014). Six girders (6,300 kg) need to be installed on the surface of the foundation and along the circumference of the tower. Then anchor bolts can be placed on both sides of the girders. This design focuses on the seismic loading of the tower, effectively securing the foundation to the tower.

All calculations derived from the LCI are based on a functional unit of 1 kWh of electricity produced. This assembly is where the quantities units in the LCI are adjusted for the functional unit of 1 kWh shown below for the 20- and 40-year time (*Table 11*). The functional unit is a measure of the study's functions regarding the system's entire inputs and outputs. 1 kWh is a commonly used functional unit for electricity generation including onshore wind turbine studies for easy comparability and replicability. As mentioned earlier, to adjust for the functional unit, a product stage must be calculated by multiplying by the turbine lifespan. Additionally, materials and processes that vary between these sets should impact these amounts comparatively. Units for the turbine components are mostly in the unit kilograms (kg) but there are additional units for this analysis, P and tkm. P represents a part of a product and tkm represents tons-kilometer as a unit for transportation.

Table 11: 20 Year and 40 Year Turbine Assembly Adjusted for Functional Unit.

Turbine Components	**20 yr Assembly**	**40 yr Assembly**	**Unit**
Assembly	1.09E-08	5.44E-09	P
Deconstruction	1.09E-08	5.44E-09	P
Operation and Maintenance	1.09E-08	5.44E-09	P
Tower	1.90E-03	9.47E-04	kg
Transportation	2.08E-03	1.04E-03	tkm
Blades and Hub	3.70E-04	1.85E-04	kg

Foundation	8.00E-03	4.46E-03	kg
Nacelle	8.04E-04	4.02E-04	kg
Network Connection	5.64E-05	2.82E-05	kg

3.3 Results and Discussion

Impact Assessment Results

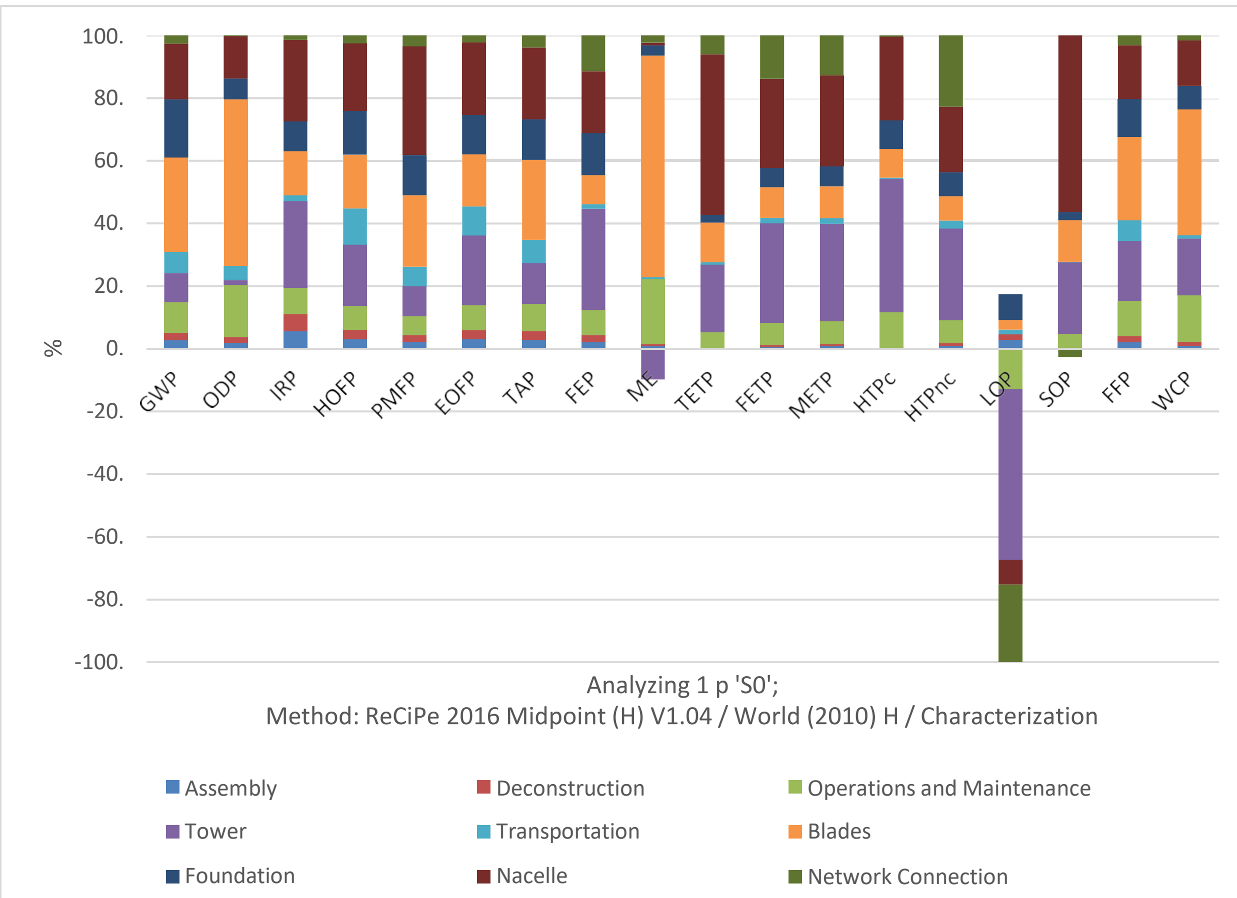


Figure 16: Baseline Impact Assessment (S0): 1.5 MW Onshore Wind Turbine System.

Climate Change (GWP); Ozone Depletion (ODP); Ionizing Radiation (IRP); Photochemical Oxidant Formation: Human Health (HOFP); Fine Particulate Matter Formation (PMFP); Photochemical Oxidant Formation: Ecosystem Quality (EOFP); Terrestrial Acidification (TAP);

Freshwater Eutrophication (FEP); Marine Eutrophication (ME); Terrestrial Ecotoxicity (TETP); Freshwater Ecotoxicity (FETP); Marine Ecotoxicity (METP); Human Toxicity: Cancer (HTPc); Human Toxicity: Non-cancer (HTPnc); Land Use (LOP); Mineral Resource Scarcity (SOP); Fossil Resource Scarcity (FFP); Water Use (WCP)

The Baseline model (S0) estimated that 6.97E-3 kg of CO_2 equivalent was produced throughout the business-as-usual life cycle (baseline model) (*Figure 16*). This analysis was conducted using ReCiPe 2016 Midpoint (H) Characterization method and represents the associated CO_2 equivalent for each associated turbine component. Overall, the foundation has a relatively low impact compared to the blades and/or nacelle regardless of accounting for most of the total mass (represented in *Figures 15 & 16*). The turbine blades substantially impact Marine Eutrophication (ME) and Ozone Depletion (ODP), attributing to the amount of fiberglass in the blades. The nylon (a material within the fiberglass) is disposed of as a spool in a surface landfill. The runoff associated with a surface landfill contributes to this result. Nylon is manufactured through chemical and manufacturing processes to create a polyamide, the flexible fiber in fiberglass. This process is emission-intensive and attributed to strategic ozone depletion (Nagle et al., 2020). The nacelle has a significant impact on Terrestrial Ecotoxicity (TETP); this is attributed to the impacts from a metal smelter (primarily Chromium and Nickle in the nacelle), which is a facility for roasting and blasting furnaces. The smelting process significantly attributes the nacelles to marine ecotoxicity (METP) and is greatly influenced by emissions of heavy metals (Borrion et al., 2012). Lastly, system benefits are represented in the negative results in Mineral Resource Scarcity(SOP), Marine Eutrophication (ME), and Land Use (LOP) impact categories. These categories are where there was additional system processing that, in turn, reduced the categories of environmental input. It is common for the benefits associated with recycling to not be incorporated into the system boundary to prevent double-counting of system benefits. However, for this study, we would like to incorporate the system benefits to gain perspective on the current impact concerning the future.

A Network Analysis calculation method determines the processes impact distribution from the total life cycle environmental emissions. The process distribution is broken up into Assembly, Life cycle, Disposal scenario, Disassembly, Reuse, Material, Transport, Processing, Market, Use, Waste scenario, and Waste treatment. Some processes are not used in this analysis based on how different materials were stored in the LCI. This Network Analysis S0 model investigated Climate Change impact category (GOP, Global Warming Potential) , units are in kg CO_2 eq, and the Characterization factor was used. This process only shows 16 of 16,867 products of this network, using a 1% cut-off, depicting the most significant processing at a reasonable resolution. This analysis helps represent which product stages or processes are most contributory to each impact category, such as the negative land use value. *Figure 17* is a Sankey diagram that depicts the flow of core products impacts from energy and material use needed for the production of steel and fiberglass. At the same time, system benefits are predominantly from the market, disposal scenario, and steel material. The benefits of recycling steel products (represented by the green arrows) significantly outweigh the environmental costs (represented by the red arrows). The negative land use value is associated with the savings related to upstream processing, specifically from resource acquisition. After a network connection analysis was conducted on the land use impact category, the main system benefit is from no longer requiring blasting and mining of Iron Ore and other precious metals. Turbine components that account for this positive inflow are 25% from the network connection, 55% from the tower, 8% from the nacelle, and 13% from operation and maintenance.

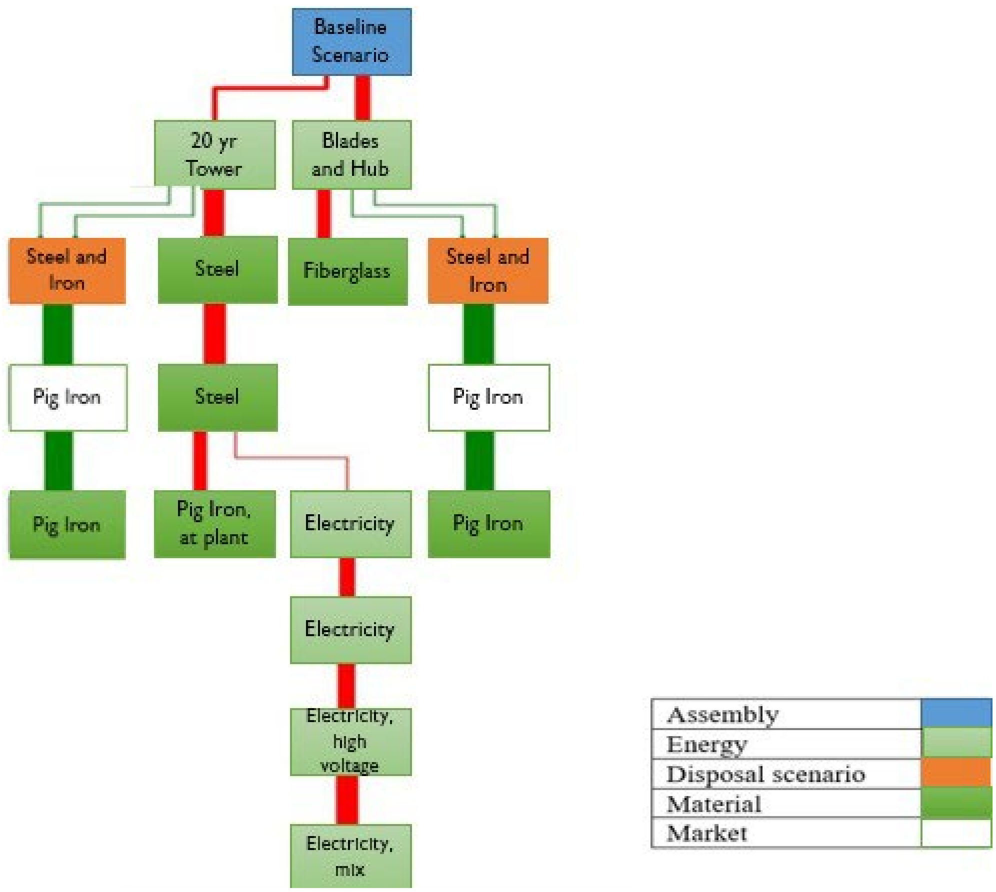


Figure 17: Sankey Diagram of Baseline Scenario, Characterization Factor for Global Warming Impact Category.

Monte Carlo Uncertainty Analysis Results

In analyzing the uncertainty analysis results, the focus is on the Coefficient of Variation (CV). The CV is a ratio of the standard deviation (SD) and the mean that enables us to compare discrepancies in data. An acceptable score is CV $\leq$ 40. The CV is a critical determinant of the data accuracy within the LCI. As shown in *Table 12,* highlighted in red are the categories greater than the acceptable value: Ionizing Radiation, Freshwater Ecotoxicity, Marine Ecotoxicity, Human toxicity: non-cancer, Terrestrial Ecotoxicity, and Freshwater Eutrophication. Water Use has the highest uncertainty with CV=564. The reasoning for a high CV is due to estimation and assumptions within the data (LCI). This is common when aggregating data from Ecoinvent and additional calculations. Typically, impact categories that are not regularly measured based on their priority require more assumptions that affect these impact categories, increasing the data's uncertainty. These include water use, ionizing radiation, human toxicity: non-cancer, ozone formation, acidification, terrestrial and aquatic eutrophication, terrestrial and marine ecotoxicity, resource depletion, and land use (Pre Sustainability, 2020). Categories are classified under either "recommended but in need of some improvement", "recommended, but to be applied with caution", or "No methods recommended" (Pre Sustainability, 2020). More original data is necessary to reduce the uncertainty within these categories. When concerning state goals to combat climate change, global warming potential is significant and highly regarded. *Figure 18* depicts the distribution of the global warming impact category. This is a normal distribution with a small skew, the value represented in the LCA is expected and when right skewed it can possibly have a lower variance. Additionally, the CV is within acceptable limits at about 14%, meaning the CO_2 eq emissions shown in the impact assessment are valid.

Table 12: Monte Carlo Uncertainty Analysis of Baseline LCA. Values in red represent a CV outside the acceptability threshold of $\leq$ 40.

Impact category	Unit	Mean	Median	SD	CV	5% CI	95% CI
GWP	kg CO_2 eq	6.96E-03	6.93E-03	9.55E-04	13.73	5.41E-03	8.55E-03
ODP	kg CFC-11 eq	3.19E-09	3.16E-09	4.79E-10	15.05	2.43E-09	3.98E-09
IRP	kBq Co-60 eq	1.05E-03	4.69E-04	1.67E-03	158.17	4.81E-05	4.25E-03
HOFP	kg NOx eq	3.43E-05	3.40E-05	6.11E-06	17.8	2.51E-05	4.51E-05
PMFP	kg PM2.5 eq	1.16E-05	1.16E-05	2.13E-06	18.37	8.21E-06	1.51E-05
EOFP	kg NO_x eq	4.44E-05	4.37E-05	8.65E-06	19.48	3.15E-05	5.95E-05

TAP	kg SO_2 eq	2.50E-05	2.49E-05	3.81E-06	15.22	1.91E-05	3.19E-05
FEP	kg P eq	2.20E-06	1.75E-06	2.26E-06	102.68	-7.60E-08	6.34E-06
ME	kg N eq	4.27E-07	4.16E-07	1.02E-07	23.78	3.00E-07	6.03E-07
TETP	kg 1,4-DCB	8.55E-02	7.80E-02	3.51E-02	40.99	5.15E-02	1.43E-01
FETP	kg 1,4-DCB	3.04E-04	2.66E-04	1.74E-04	57.01	1.20E-04	6.18E-04
METP	kg 1,4-DCB	4.84E-04	4.32E-04	2.39E-04	49.4	2.30E-04	9.09E-04
HTPc	kg 1,4-DCB	3.75E-03	3.50E-03	1.26E-03	33.66	2.18E-03	6.07E-03
HTPnc	kg 1,4-DCB	9.39E-03	7.25E-03	1.12E-02	119.42	2.83E-03	2.20E-02
LOP	m^2 ×yr annual crop eq	-3.10E-04	-2.80E-04	2.71E-04	-87.44	-8.20E-04	5.09E-05
SOP	kg Cu eq	8.60E-04	8.57E-04	8.78E-05	10.21	7.18E-04	1.01E-03
FFP	kg oil eq	2.35E-03	2.24E-03	5.67E-04	24.11	1.81E-03	3.29E-03
WCP	m3 water eq	2.96E-04	2.82E-04	1.67E-03	564.77	-2.40E-03	3.25E-03

Climate Change (GWP); Ozone Depletion (ODP); Ionizing Radiation (IRP); Photochemical Oxidant Formation: Human Health (HOFP); Fine Particulate Matter Formation (PMFP); Photochemical Oxidant Formation: Ecosystem Quality (EOFP); Terrestrial Acidification (TAP); Freshwater Eutrophication (FEP); Marine Eutrophication (ME); Terrestrial Ecotoxicity (TETP); Freshwater Ecotoxicity (FETP); Marine Ecotoxicity (METP); Human Toxicity: Cancer (HTPc); Human Toxicity: Non-cancer (HTPnc); Land Use (LOP); Mineral Resource Scarcity (SOP); Fossil Resource Scarcity (FFP); Water Use (WCP)

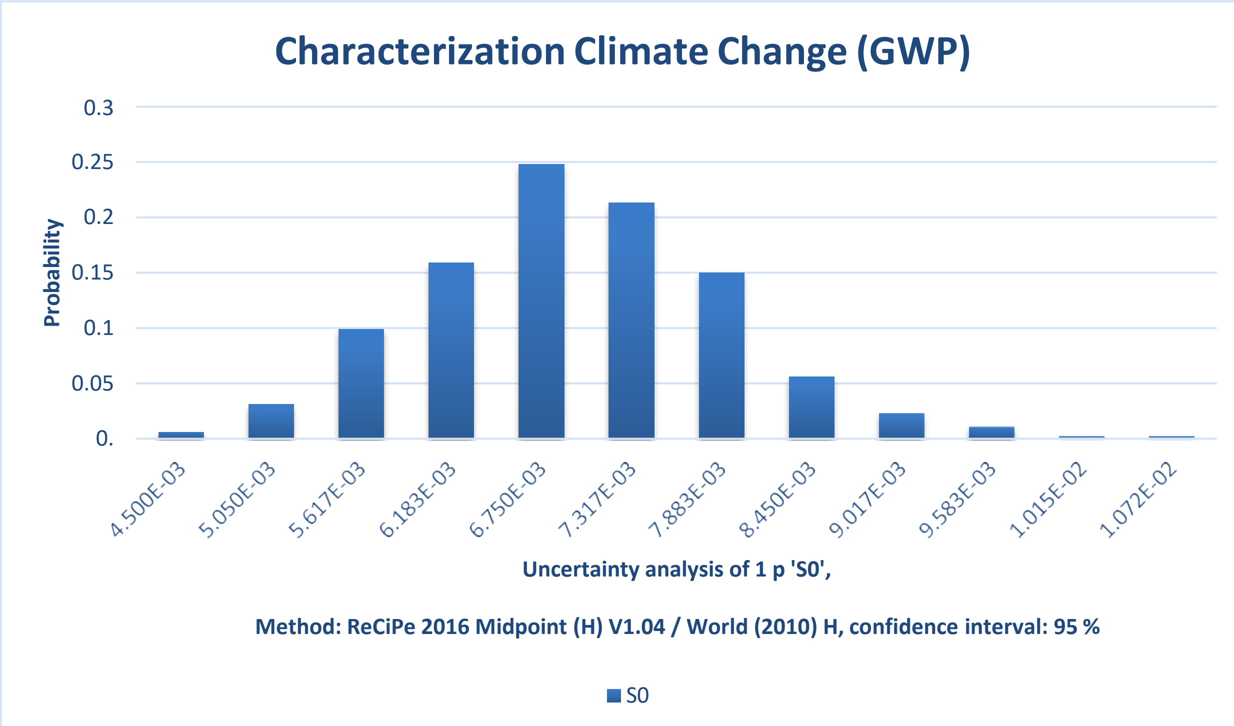


Figure 18: Distribution of Climate Change Impact Category (GWP) (CO2 eq).

Life Cycle Cost Results

Environmental impacts associated with life cycle emissions are incorporated into the life cycle cost model to determine the economic costs of environmental conditions. The Life Cycle Cost model is considered an active 20 year model (S0) and requires one year of construction without energy generation. An aggregate model decreases in emissions, or environmental savings, correlated to a cost savings. Discounting future costs to present value adjusts costs for inflation's effects over time (Kneifel and Webb, 2020). This model generates 4,599,000 kWh worth of electricity in its lifetime or 229,950 kWh annually. The discount rates of 3%, 5%, and 7% were used in this model to determine the present value and are used to provide a range of future values. EPA Regulatory Impact Analysis Clean Power Plan and Department of Energy Federal Energy Management Program 2021 Discount Rates recommend and utilize these range of discount rates for evaluating a cost-benefit analysis of clean energy (US Environmental Protection Agency, 2015b; US Department of Energy, 2019). These discount rates help reflect future changes to price within a reasonable limit. This analysis determined the cost per kWh of electricity to be at 3% is $5.84, at 5% is $4.69, and at 7% is $3.90. Net Present Value (NPV) at 3% is $26,283,197.62, at 5% is $21,575,847.72, and 7% is $17,930,366.81. The large difference between the 3% and 7% discount rate is due to the lower the discount rate the higher the net present value, implying a lower rate of risk. The additions of emissions savings incurred from the costs of emissions from a natural gas plant result in substantial savings as represented in *Table 13*. Emission costs and emission savings were calculated using the US Environmental Protection Agency (2021) report on the Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates. The report helps monetize the value of changes in greenhouse gas emissions and can help support regulations and reflect science and methodologies (US Environmental Protection Agency, 2021). The life cycle costs without emission savings utilize both standard economic analysis for a 1.5 MW wind turbine and additional emission costs. However, the life cycle costs with emission savings consider the diverted emissions from a natural gas plant of the same capacity and subtract that from the total cost (not including the system costs for the natural gas plant).

Table 13: Life Cycle Cost Assessment: Baseline Scenario (S0).

Discount Rate	Life Cycle Costs Without Emission Savings	Life Cycle Costs With Emission Savings
3%	$7,772,508.60	-$58,016,196.59
5%	$6,826,055.25	-$73,901,759.76
7%	$5,786,992.69	-$118,546,338.02

Scenario Analysis Results

Table 14: Impact Assessment Results: Scenario Analysis.

Midpoint Impact category	Unit	S0	S1	S2	S3	S4	S5	S6	S7
GWP	kg CO_2 eq	6.97E-03	5.64E-03	6.96E-03	5.04E-03	6.78E-03	5.48E-03	7.24E-03	5.81E-03
ODP	kg CFC-11 eq	3.17E-09	1.91E-09	3.17E-09	1.85E-09	3.23E-09	1.95E-09	3.21E-09	1.94E-09
IRP	kBq Co-60 eq	1.01E-03	6.00E-04	1.01E-03	5.96E-04	1.00E-03	5.92E-04	1.04E-03	6.19E-04
HOFP	kg NOx eq	3.45E-05	2.60E-05	3.45E-05	2.56E-05	3.38E-05	2.54E-05	3.57E-05	2.67E-05
PMFP	kg PM2.5 eq	1.16E-05	8.61E-06	1.16E-05	8.48E-06	1.14E-05	8.47E-06	1.17E-05	8.69E-06
EOFP	kg NO_x eq	4.47E-05	3.22E-05	4.47E-05	3.18E-05	4.38E-05	3.15E-05	4.66E-05	3.34E-05
TAP	kg SO_2 eq	2.51E-05	1.97E-05	2.51E-05	1.94E-05	2.45E-05	1.92E-05	2.55E-05	2.00E-05
FEP	kg P eq	2.23E-06	1.37E-06	2.23E-06	1.36E-06	2.29E-06	1.40E-06	2.26E-06	1.38E-06
ME	kg N eq	4.28E-07	2.59E-07	4.32E-07	2.58E-07	4.45E-07	2.66E-07	4.39E-07	2.62E-07
TETP	kg 1,4-DCB	8.40E-02	4.84E-02	8.40E-02	4.82E-02	8.39E-02	4.83E-02	8.40E-02	4.84E-02
FETP	kg 1,4-DCB	3.02E-04	1.95E-04	3.02E-04	1.87E-04	3.00E-04	1.93E-04	3.03E-04	1.95E-04
METP	kg 1,4-DCB	4.81E-04	3.08E-04	4.81E-04	2.96E-04	4.78E-04	3.05E-04	4.85E-04	3.10E-04
HTPc	kg 1,4-DCB	3.71E-03	2.73E-03	3.71E-03	2.41E-03	3.71E-03	2.73E-03	3.72E-03	2.74E-03
HTPnc	kg 1,4-DCB	9.13E-03	5.81E-03	9.14E-03	5.62E-03	9.07E-03	5.75E-03	9.20E-03	5.84E-03
LOP	m^2 ×yr	-3.37E-04	-2.54E-04	-3.37E-04	-2.55E-04	-2.65E-04	-2.10E-04	-3.19E-04	-2.43E-04
SOP	kg Cu	8.61E-04	4.93E-04	8.61E-04	4.93E-04	8.61E-04	4.93E-04	8.61E-04	4.93E-04
FFP	kg oil	2.37E-03	1.89E-03	2.37E-03	1.83E-03	2.26E-03	1.80E-03	2.43E-03	1.93E-03
WCP	m^3 water	3.05E-04	2.51E-04	3.04E-04	2.48E-04	2.95E-04	2.43E-04	3.06E-04	2.52E-04
Endpoint Impact Category									
HH	DALY	2.86E-08	2.14E-08	2.86E-08	1.96E-08	2.83E-08	2.11E-08	2.89E-08	2.16E-08
EH	Species.yr	3.22E-11	2.50E-11	3.22E-11	2.31E-11	3.20E-11	2.47E-11	3.34E-11	2.58E-11
RS	USD2013	8.82E-04	7.00E-04	8.82E-04	6.72E-04	8.39E-04	6.64E-04	8.99E-04	7.10E-04

Climate Change (GWP); Ozone Depletion (ODP); Ionizing Radiation (IRP); Photochemical Oxidant Formation: Human Health (HOFP); Fine Particulate Matter Formation (PMFP); Photochemical Oxidant Formation: Ecosystem Quality (EOFP); Terrestrial Acidification (TAP); Freshwater Eutrophication (FEP); Marine Eutrophication (ME); Terrestrial Ecotoxicity (TETP); Freshwater Ecotoxicity (FETP); Marine Ecotoxicity (METP); Human Toxicity: Cancer (HTPc); Human Toxicity: Non-cancer (HTPnc); Land Use (LOP); Mineral Resource Scarcity (SOP); Fossil Resource Scarcity (FFP); Water Use (WCP);Human health (HH); Ecosystem health (EH), Resource scarcity (RS)

Results from the impact assessment for all scenarios are represented in *Table 12*. The most significant midpoint impact phase is raw material acquisition and manufacturing, followed by the various end-of-life scenarios which correspond with Resource Scarcity as the greatest Endpoint impact category. From the Midpoint category, S3 has the lowest global warming potential, producing 5.04E-3 kg of CO_2 equivalent. Through incorporating an extended lifespan, impacts are significantly reduced. This result for S3 is unexpected from landfilling of fiberglass materials. Future investigation for analyzing the increased longevity of turbines, rather than focusing on alternative disposal paths, is recommended. Locations with the existing supporting infrastructure necessary for recycling can be better attributed for determining impact rather than recycling in general. Already existing facilities can be excluded from the system boundaries as long as it has the capacity for the process that is needed (Andersen et al., 2016). The following scenario with the lowest global warming potential is S5, 5.48E-03 C02 eq, which incorporates the reuse of the foundation and mechanical recycling of fiberglass and other materials. The scenario with the extensive environmental emissions was S6, estimating a 7.24E-3 kg of CO_2 equivalent. This process of thermal recycling has been criticized for its enormous energy use requirement and waste production.

S6 has the CO_2 eq and most significant impacts on human health, ecosystem health, and resource scarcity. Impacts from thermal recycling may not be worth the environmental and health impacts caused primarily by energy and infrastructure requirements. Other disposal alternatives are less impactful, such as mechanical recycling. Throughout scenario analysis, each scenario's highest impact was in terrestrial ecotoxicity. Processes that contribute to this impact assessment are directly related to the chromium steel within the nacelle. The mining, pretreatment, and reduction of ferronickel and ferrochromium result in significant environmental inputs and toxic by-products such as slag. The Endpoint category for Resource Scarcity is the greatest for each scenario and is related to the significant impact associated with material acquisition and manufacturing. This category represents the surplus cost of future resource production (Pre Sustainability, 2020) and can be influential in determining future viability.

The most significant difference among scenarios is in the operations and maintenance component. For the life extension of the turbine, there were required retrofitting and upkeep that was not apparent in the 20 year scenarios as stated before. A Comparison Analysis for S0 and S1 Operations and Maintenance is depicted in *Figure 19* where the turbine with a life-extending practice has increased the associated emissions. The 40 year scenario has almost doubled (49%) the associated environmental impacts of the 20 year scenario for this life cycle stage. This is associated with the is raw material acquisition and manufacturing process of heavy metals such as steel, copper, and iron which subjugates a considerable number of the turbine's life cycle emissions.

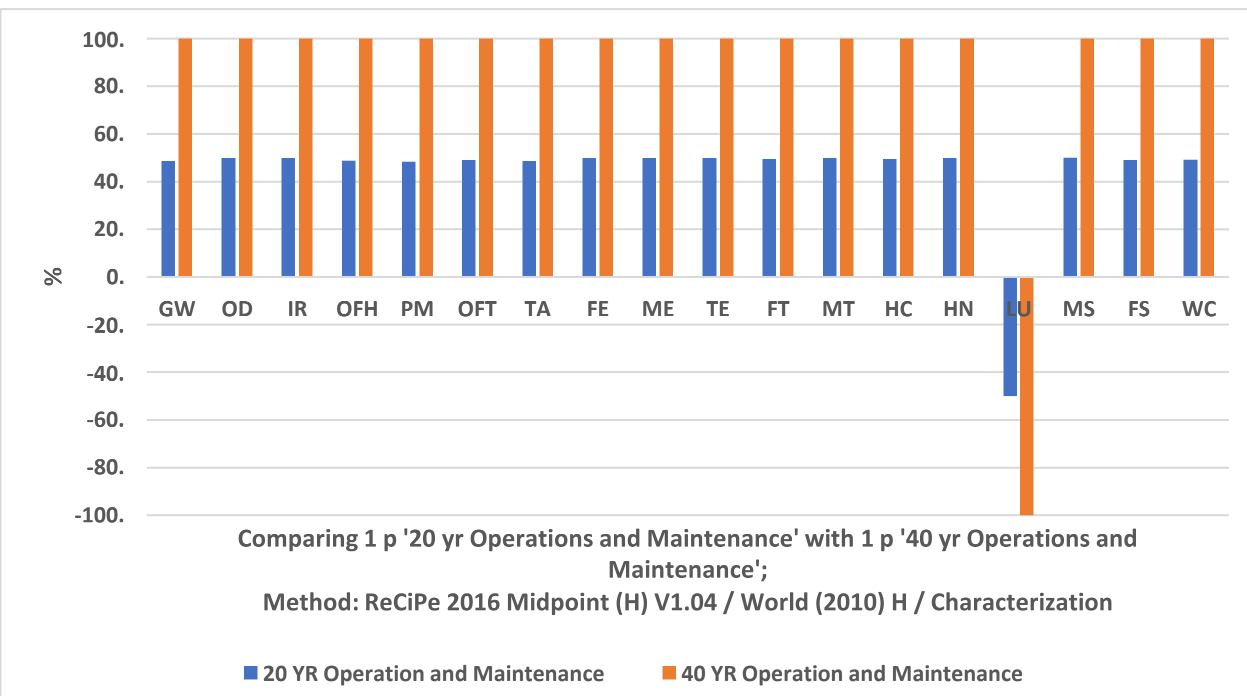


Figure 19: Operations and Maintenance Comparison Analysis.

3.4 Conclusion

Through implementing an LCCA model, we assessed the environmental and economic costs relating to a 1.5 MW onshore wind turbine. This model consisted of scenario analyses of a 20 and 40-year turbine lifespan and various disposal scenarios for fiberglass, including incineration, landfills, mechanical recycling, and thermal recycling. Each variable was adjusted to the functional unit of one 1 kWh of electricity generation. This study's findings include the significance of life extension through implementing required retrofitting processes. Although landfilling scenario S3 had the lowest environmental impacts, we can suggest an LCC on each scenario for future research. Thermal recycling may not provide the benefits we are looking for in reducing environmental impact. This process of thermal recycling has been criticized for its considerable energy use requirement and waste production. However, technical or logistical improvements may increase efficiency and reduce emissions to warrant consideration of theoretical or pilot-scale technical. Significant emissions savings are determinants of the economic suitability of small onshore wind plants in urban landscapes.

Distributed wind energy generation can provide equitable energy and costs (NJ Department of Environmental Protection, 2020; NJ Board of Public Utilities, 2020b) while helping drive the transition to a clean energy future. There are many improvements that can reduce the environmental emissions and costs of an onshore wind turbine. By extending the life of the foundation and core components of the wind turbine and efficient disposal of materials, wind energy generation can achieve competitive long term costs. Based on this study’s findings, there is support for an onshore wind project if compelled to incorporate emission cost incentives and low damage to human health and ecosystems, but future studies should incorporate other life cycle costs depending on each scenario.

Chapter 4: Policy Implications, Limitations, and Conclusions

4.1 Conclusions

Chapter 1 reviewed the current necessity to increase renewable energy development in New Jersey to meet emission reduction goals and mitigate the impacts of climate change. There are significant green energy benefits that are not commonly found in other nonrenewable energy generation. Green energy benefits include increased reliability, economic benefits, energy independence, and job creation (US Environmental Protection Agency, 2016). Strategy 2 in the Energy Master Plan outlines the necessity for accelerating the deployment of DERs within the electric generation sector (NJ Board of Public Utilities, 2019). Efforts to increase distributed wind and solar energy can encourage environmental justice, providing equitable energy and equitable costs (NJ Department of Environmental Protection, 2020; NJ Board of Public Utilities, 2020b). However, it is found that extensive investment in large-scale Distributed Energy Resources can significantly lower DER adaptation in disadvantaged communities (Chowdhury et al., 2021; National Renewable Energy Laboratory, 2019). As the industry continues to grow, policies that support these actions will continue to expand and offer increased inclusiveness and efficiency of green benefits. The goals of current policies aim to optimize site selection and maximize the number of people who have access to its benefits.

In Chapter 2, we discussed the implications of state initiatives such as those found in the Energy Master Plan and the Community Solar Energy Pilot Program to optimize site selection in New Jersey. Given that NJ's landscape is mostly urbanized, areas to place solar arrays are limited.

Due to resource scarcity, developers are obligated to select an optimal site to improve efficiency. An AHP-GIS model of the solar suitability study in New Jersey was constructed around the Community Solar Energy Pilot Program and informed stakeholder opinion on different environmental, socioeconomic, and technical criteria. The model accounted for locations with a high potential to utilize solar energy while accounting for other social and environmental characteristics to inform the AHP through stakeholder survey data. This study can help provide leverage for community solar stakeholders in areas where the potential solar development is strategic. The locations among EDC territories that may have limited suitable locations for community solar development may be recommended to a search of other clean energy alternatives that are more suitable based on their environmental, social, and potentially political factors. Identifying these alternatives may improve the state's clean energy initiatives to incorporate robust opportunities.

Significant findings include that residential and commercial properties (32.5%) are the most important criteria for determining suitable community solar locations. There is a significant reliance on maintaining the market that stakeholders are already familiar and successful with, like residential and commercial rooftops, regardless of other incentives for repurposing degraded land. Additionally, literature has identified solar developers' hesitation relating to the remediation and upkeep of brownfields and landfills avoided by developing residential and commercial land resources (US Environmental Protection Agency, 2016). Supplementary findings include PSE&G territory incorporating the highest number of suitable locations for community solar development, and ACE is the least. Moreover, community solar capacity is expected to grow in the future and will aid in achieving New Jersey's clean and equitable energy goals.

In Chapter 3, through implementing an LCCA model, we assessed the environmental and economic costs relating to a 1.5 MW onshore wind turbine. This model consisted of scenario analyses of a 20 and 40-year turbine lifespan and various disposal scenarios for fiberglass, including incineration, landfills, mechanical recycling, and thermal recycling adjusted to a functional unit of 1 kWh of electricity generation. The are many improvements that can reduce the environmental emissions and costs of an onshore wind turbine. First, through extending the life of the foundation and core components of the wind turbine and efficient disposal of materials, wind energy generation can reach competitive long term costs. Secondly, The LCC model calculated substantial savings consequential of emissions savings. Based on this study's findings, there is support for an onshore wind project if compelled to incorporate emission cost incentives and low damage to human health and ecosystems. Remarkably, the landfilling scenario S3 had the lowest environmental impacts.

Additionally, not all forms of recycling can be beneficial; thermal recycling produces significantly more emissions than mechanical recycling. Thermal recycling may not provide the benefits we are looking for in reducing environmental impact due to the facility's requirements and outputs to the environment. The process of thermal recycling has been criticized for its considerable energy use requirement and waste production. Significant emissions savings are determinants of the economic suitability of small onshore wind plants in urban landscapes. The LCCA suggests that wind energy generation would be environmentally significant and economical if emission savings were considered.

4.2 Policy Implications

State policies have significant impacts on distributed energy resource markets. The current carbon intensive energy sector has created substantial environmental impact and accumulating social costs which have driven the search to reduce these impacts. Physical and/or virtual supporting facilities and infrastructure, such as recycling centers, net metering, and SREC programs can aid in reducing the energy sector's carbon emissions. The New Jersey Board of Public Utilities and other governmental organizations aim to provide the infrastructure to support change through progressive policies and programs. Smaller energy projects that utilize modern energy systems such as net metering can benefit subscribers for small-scale wind and solar generation (Chowdhury et al., 2021). Supporting infrastructure to assist in the transition to renewable energy production can improve various aspects of the environmental impact.

There is a wide range of ways in which the integration of distributed energy resources interacts with policies and regulations on the local, state, and federal levels. One of such ways is net metering, which plays a crucial role in developing efficient shared-energy systems. Net metering consists of the total amount of energy generation shared among the participants on a subscription basis. The type of solar subscribers and capacity of the system plays a significant role in the efficiency and effectiveness of the program. Project size consideration for residential customers may have a smaller capacity than commercial customers for net metering (National Renewable Energy Laboratory, 2014). Participants and size are important considerations when attempting to set up community solar in a given location. Typically, the larger the plant capacity, the more likely the project will reach economies of scale (Chang et al., 2017), making the project financially viable.

Additionally, federal tax credits, state incentives (RECs), and interconnection policies are influential in successfully distributed energy development (NJ Board of Public Utilities, 2020b).

These programs provide the financial ability for investors and customers to attain this modern energy resource. Transparency and clarity in requirements and costs to be eligible to participate in these programs will dictate the program's effectiveness. To avoid obstacles associated with implementing community solar programs, policymakers must revise policy and regulations.

Support for distributed wind energy may perform a substantial role in New Jersey's renewable energy future, with a high economic potential for significant amounts of energy being produced on a small scale. Small-scale onshore wind projects can also be attributed to distributed energy inputs like community solar (NJ Board of Public Utilities, 2020b). As governmental mandates and initiatives call for increased efficiency and reduced environmental impacts, the market for distributed energy resources will continue to expand (Chowdhury et al., 2020). This trend offers an opportunity to provide a more stable energy sector, greater corporate transparency, and implement environmental justice (NJ Board of Public Utilities, 2020b). Parameters for achieving energy goals include high dependence on (1) electricity rates. Wind energy provides consistent, steady rates that aid peak demand charges. (2) Net energy metering policies enable renewable energy developers to provide clean energy subscriptions to an array of residents, including renters. (3) Financial incentives like renewable energy certificates, rebates, tax credits, and financing costs increase the affordability of wind programs (National Renewable Energy Laboratory, 2019). The LCCA model enables policymakers to internalize externalities related to a system typically excluded from feasibility metrics such as environmental impacts and social costs (US Environmental Protection Agency, 2021). Aside from state policies aiming to reduce environmental impacts, they also encourage and explicitly require incorporating social benefits to low- to moderate- income populations (NJ Board of Public Utilities, 2020b; Gomaa et al., 2019).

Social initiatives continue to be tied with environmental policies to aid a more equitable energy future and a form of environmental justice for marginalized groups.

4.3 Study Limitations

Study limitations in Chapter 2 can be adjusted for future studies to provide complex feedback for a Multi-Criteria Decision Analysis. First, the number of criteria could have been more significant to represent the array of options available better, such as climate, slope, and fewer aggerated groups such as brownfields, landfills, and barren land in this study. Additionally, an increase in the number of survey participants would help improve the accuracy of the results to achieve this goal with in-person surveys and a more extensive email distribution list. Lastly, rather than utilizing the weighted-overlay method, fuzzy logic can be applied to avoid traditional overlay analysis inaccuracies in representing the attribute data and geometry of spatial data (Environmental Systems Research Institute Inc, 2016). This technique will compensate for imprecision in assigning cells to specific classes and inaccuracies found in measurements. Fuzzy logic helps to remove ambiguity within classes to accurately capture the relationship among different classes/sets, functioning as a Multiple Criteria Decision Making (MCDM) method (Environmental Systems Research Institute Inc, 2016).

Study limitations prevalent in Chapter 3 can be adjusted for future work. An LCCA can include other environmental impacts such as local environmental ecology and impacts on temperature. The turbines' introduction impacts other aspects of the environment, such as bird populations, to a more complex assessment. Additionally, increasing the amount of primary data can reduce the model's uncertainty. Relying on the secondary data source for calculations and estimations for both environmental and economic models increase uncertainty within the analysis.

For future research purposes, correspondence with the manufacturer would significantly improve the certainty of the model, where minimal assumptions would be required for calculating energy and material needs. Additionally, a LCC for each scenario could be influential for determining which scenario has the lowest environmental costs and the most significant economic incentive. The various cost scenarios would aid in implementing an equal comparison of the environmental performance of a turbine to the economic advantages for each scenario, rather than only a costing model for the baseline scenario.

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