Determining alternative clean energy sources for military bases

by

Drew Holliday

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Major Professor
Fred Hasler

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Abstract

This report is meant to investigate viable energy sources and to develop a process that can be implemented to determine the best sources to supply energy to military facilities throughout the United States. A case study of Minot Air Force Base, North Dakota utilizing the process developed in this report has been conducted to ensure an appropriate system can be selected from the energy sources listed in this report.

The reasons that the military should identify alternate sources of energy to replace the common power grid and establish a process for determining the most viable option for facilities are national security, the recent introduction and improvements of energy production technology, and the opportunity to improve the public's view on the military, though not discussed in much detail in this report.

The alternate energy sources for this report were chosen to be wind, solar, nuclear power, enhanced geothermal, hydropower, hydrogen fuel cells, biomass, and tidal power. Following the goal of the Department of Energy to provide 100% clean energy, or net-zero greenhouse gas emissions, these sources were also identified as clean energy generation sources. Although there are other technologies being developed and may be in use, the energy sources selected are the most practical due to their increasing popularity and capability to be used microgrid systems, which are electrical systems with locally sourced energy that can be operated separate from the national power grid. These sources were also chosen because they are either in development or have been utilized in industry, leading to data that can be analyzed within this report. Theoretical sources that have not been assessed in some form were assumed to be unreliable until further data is collected. For this report, the source chosen with the developed process is meant to be the primary source of energy on a military base. Through the process of rating systems, other sources might also receive high ratings, indicating they might be a slightly less preferred but still viable option for energy production. To ensure that military facilities always have electrical power, the national power grid will be utilized as backup power for when the selected system is not operational.

For the process of determining an alternate source to power a military base, a set of criteria had to be chosen in which to evaluate and select the best source. The criteria that this report utilizes are location availability, security, reliability, capability, efficiency, constructability, and the maintenance of the system. Though this list is not all-encompassing of all the decisions included in selecting energy sources, this list of criteria was chosen because

together they can indicate the overall expectation of how a system might perform. Cost will not be used within this report as a rating factor as the best system may or may not be the most expensive. By not rating systems based on cost, the best system can be selected to ensure a more stable infrastructure that the military can rely on. The location availability and capability categories show whether a system can sustain the base's electrical demand in the given location and will determine the land usage needed to meet the electrical demand. The security, reliability, and maintenance categories are used to determine whether the energy system is an acceptable option for the military that supports its mission to protect the US from enemies, both foreign and domestic, and the need to always remain functional throughout the year. The efficiency and the constructability categories were chosen to determine whether a system fits the military's requirements for utilizing the best system available. The efficiency of the system can aid in determining the resource utilization of the system and constructability can include whether a system can be constructed in time to secure infrastructure stability while reducing the need for frequent replacements of a system that could lead to threats in national security. This report suggests that a rating scale from one to five can indicate how energy sources compare to each other while allowing for an energy source to be identified as the best energy source for a base to adopt.

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List of Abbreviations

AC – Alternating Current

AFB – Air Force Base

AK – Alaska

AKWH - The annual energy production in kWh/yr

As – Area of the blades sweep

AV – Turbine Availability

BESS – Battery Energy Storage System

CF – Capacity Factor

CHP – Combined Heat and Power

CLG – Closed Loop Geothermal

Cp – Coefficient of Performance

CSP – Concentrating Solar Thermal Power

DC – Direct Current

DER – Distributed Energy Resource

DHS – Department of Homeland Security

DoD – Department of Defense

DOE – Department of Energy

EGS – Enhanced Geothermal Systems

EIA – Energy Information Administration

EMP – Electromagnetic Pulse

FAQs – Frequently Asked Questions

FDI – False Data Injection

FERC – Federal Energy Regulatory Committee

FRCC – Florida Reliability Coordinating Council

GS – Generator Size

HAWT – Horizontal Axis Wind Turbine

HDR – Hot Dry Rock

HI – Hawaii

HILP – High-impact Low-probability

HK – Hydrokinetic

HTA – Homeland Threat Assessment

HTF – Heat Transfer Fluid

HTGRs – High Temperature Gas Reactors

LFRs – Lead-cooled Fast Reactors

MCFC – Molten Carbonate Fuel Cells

MISO – Midcontinent Independent System Operator

MPPT – Maximum Power Point Tracker

MR – Micronuclear Reactors

MRO – Midwest Reliability Organization

MSRs – Molten Salt Reactors

MSW – Municipal Solid Wastes

MWh – Megawatt hour

NETL – National Energy Technology Laboratory

NOAA – National Oceanic and Atmospheric Administration

NPCC – Northeast Power Coordinating Council

NRC – Nuclear Regulatory Commission

NREL – National Renewable Energy Laboratory

ORC – Organic Rankine Cycle

ORPC – Ocean Renewable Power Company

PAFC – Phosphoric Acid Fuel Cells

RFC – Reliability First Corporation

RTOs – Regional Transmission Organizations

SAM – System Advisor Model

SCADA – Supervisory Control and Data Acquisition

SERC – Southeast Reliability Corporation

SFRs – Sodium-cooled Fast Neutron Reactors

SMRs – Small Modular Reactors

SOFC – Solid Oxide Fuel Cells

SPP – Southwest Power Pool

SPV – Solar Photovoltaic

STC – Standard Testing Conditions

SUNSPOT – Stellenbosch University Solar Power Thermodynamic

TRE – Texas Reliability Entity

US – United States

VAWT – Vertical Axis Wind Turbine

WECC – Western Electric Coordinating Council

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I thank all the United States Air Force personnel, including Air Force Reserve Officer Training Corps Cadre, who aided in the development of my report and guided me toward different material I should review. With their help, I was able to gather information concerning the different energy sources already being used by the military.

I thank and praise God for His faithfulness and unfailing love. I thank Him for the wonderful and incredibly-detailed design of the universe that allows for the generation of electricity from different sources and processes.

Introduction

The purpose of this report is to investigate energy sources and to develop a process that can be used for selecting an alternative primary energy source for military bases in the continental United States (US). As the military's primary function has always been to protect the nation from both foreign and domestic powers, it has always looked for ways to stay ahead of other nations in many categories. The energy sector is one way that the military can stay ahead by becoming more independent from the public sector. To become independent of the power grid, a microgrid, in which electricity energy is produced locally and with the ability to disconnect from the national power grid, can be designed for. In this report, the microgrid will operate separately from the nation power grid, but the power grid will still have the ability to be connected for backup power.

Before discussing the improvements in security that a microgrid will bring to a base, the changing energy conditions must be addressed. With the growing environmental concerns within the US, many energy sources that directly allowed the US to boom into an economic power are starting to be phased out. This can be observed by the growing popularity and push for electric vehicles, regulations on natural gas, and the decommissioning of coal sourced power plants. The push for electric vehicles and the regulations on natural gas in regions of the US has directly led to an increase in electricity usage. The increased dependence on electricity incorporated with the increased energy generation sources has created a situation that the US has not dealt with before. The dependence on electricity has increased the damage that could be done with the loss of electricity. The increased generation sources have led to a more dispersed electrical generation that differs from the large central power plants that were popular in the past. For the military to maintain the safety of the nation, it must be willing to incorporate changes to match the rapidly changing energy conditions and the increasing threat of losing electricity from the national power grid.

The changing energy conditions have created risks within the power grid that has the potential to disrupt the primary mission of the US military. With that being said, the main reason that the military should start to transition to a microgrid system is for the increased security and reliability that transitioning would bring. The current grid has started to experience both cyber threats and physical threats that may cause electrical outages. Locating a microgrid on a military base, arguably one of the most secure areas in the US, would almost eliminate the threat of physical sabotage. While located on base, it is assumed that it would fall under the control of the military and, as such, would be protected by the cybersecurity experts in the military, leading to better security measures being put in place to protect this critical infrastructure.

The typical military base includes onsite generators for emergency purposes, but a report from the National Renewable Energy Laboratory (NREL) investigated the reliability of using these generators during extended power outage and found them to be inadequate as the time of the outage increased [1]. In the study, reliability of an electrical system was determined using the operational availability considering scheduled and unscheduled maintenance, average quantity of failure to start attempts, average time between maintenance events, average time of maintenance, and the average time for repairs. What the study from the NREL found was that for a two-week power outage, a microgrid system had a probability of 90% for supporting all the critical loads. On the other hand, a base with well-maintained emergency generators connected to every building had a 0-20% probability of supporting all the critical loads depending on the number of buildings on the base [1]. This data indicates that if used during a two-week outage, the emergency generators on a base are likely to fail to meet the critical demand due to the decrease in reliability throughout the outage. Although the microgrid in the report was based on wind and solar energy sources, the main objective of the report was to show that microgrid on a base is more reliable than the current emergency generators. As can be seen in this report, designing a microgrid system on a military base greatly increases the reliability of the system during long outages. This report and another report from the NREL both acknowledged that longer duration outages are becoming more frequent throughout the US [2].

Along with the safety and reliability of producing energy on bases, there are also potential cost incentives associated with locally produced energy sources that are considered renewable with low carbon footprints. Although not discussed further in this report so that the best functioning system may be chosen, the renewable energy sector has seen cost incentives over recent years. The cost of generating energy from solar and wind is relatively low when focused on the cost of energy generation since they do not require the use of fuel [3]. The main costs associated with these technologies are primarily for the installation and infrastructure of the system. If the military switched to a microgrid system that utilizes renewable energy, it could aid in cutting electrical costs with reduced generation costs.

The other advantage of a microgrid on US military bases is the view the public has on the military. If the military used renewable and low carbon energy sources, the perspective of the public on the military could become more favorable, particularly with younger generations who generally are more in favor of renewable energy sources [4]. In turn the favorable opinion might encourage more of the public to consider military service, further strengthening national security.

The energy sources selected in this report are wind, solar, nuclear power, enhanced geothermal, hydropower, hydrogen fuel cells, biomass, and tidal power. These sources were chosen due to their ability to meet the Department of Energy's (DOE) goal to produce 100% clean energy set by 2050 [5]. These sources can support this goal as they are classified as clean energy generation sources. These energy sources have also been identified as relevant sources due to their abilities to support a microgrid system. During recent years, these sources have gained in popularity and use when designing microgrid systems. These sources were also chosen because they are either in development or are already in operation, meaning that they can start to be designed once selected for a military facility's energy source.

Background

Current Transmission Conditions

This research and report is being conducted to investigate the process of choosing an appropriate energy source at military bases throughout the US. Military bases currently purchase energy from the nearest electric company for their location. An electric company can either be a distribution or a generation and distribution type company. A distribution only system only maintains the transmission lines and buys energy from surrounding electric producers. A generation and distribution electric company produce electricity and distribute it on their transmission lines and to other electric companies. This system of electrical companies creates an electrical grid in which electricity can be distributed across a vast amount of land without as many energy generation plants.

FIGURE 1 shows the grid connections on a conceptual scale based on the electrical demand in each region. FIGURE 1 also shows the Balancing Authority Areas in the circles with their abbreviations. These Balancing Authorities are responsible for load balancing that includes sharing electricity with other Balancing Authorities and generating enough electricity to meet fluctuating electrical demand. Besides the Balancing Authorities, there are Regional Transmission Organizations (RTOs) shown in FIGURE 2. According to the Department of Energy (DOE), the RTOs are responsible for their region's operations and management which involves reliability planning, transmission maintenance, expansion projects, and electricity markets [6]. Despite having these responsibilities, these RTOs are not part of the government although they began through the Federal Energy Regulatory Committee (FERC). RTOs also do not own any generation sources or transmission lines. Being separate from the government and not owning generation and distribution sources cause RTOs to not have any enforcement authority. Having no enforcement authority, in turn, means that RTOs can be ineffective at influencing the electrical grid. It is also important to note that the RTOs show that there are electrical connections to Canada that allows for energy production in Canada to affect the US.

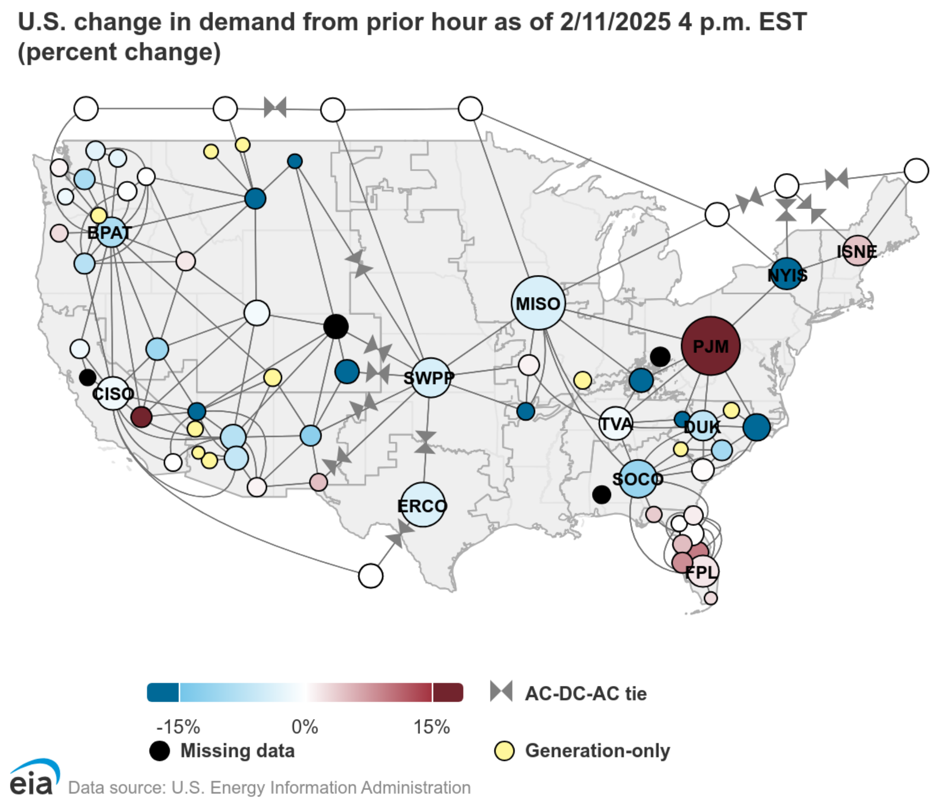


Figure 1 A conceptual map of the interconnection of the US electrical grid. Source: U.S. Energy Information Administration (February 2025) [7]

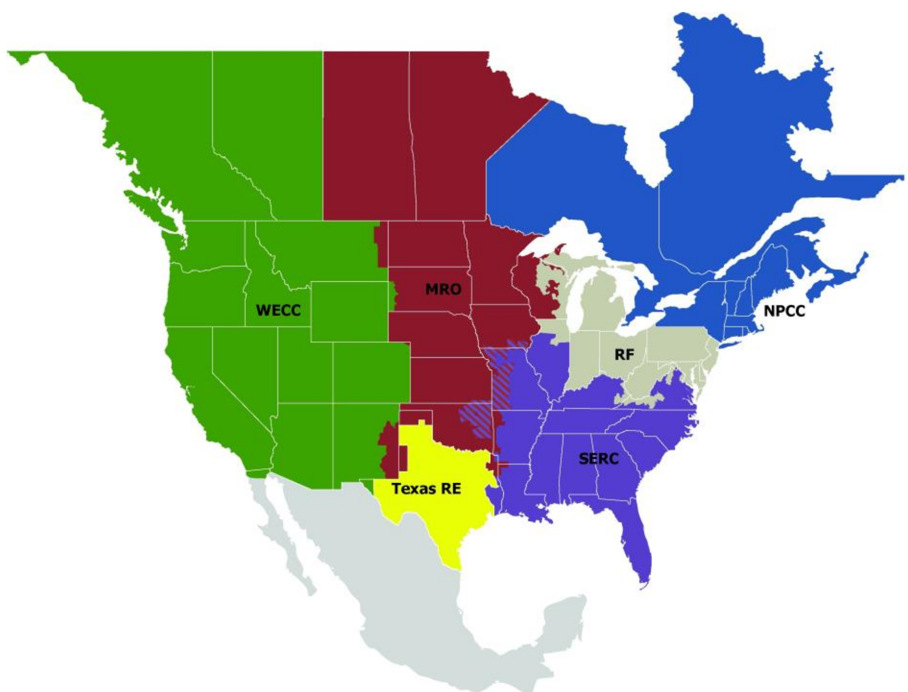


Figure 2 A map showing the Regional Transmission Organizations within the continental US. Source: North American Electric Reliability Corporation [8]

Current Grid Resiliency and Reliability

The integration of the grid has led to a more resilient grid because it aids in allowing for more distributed generation sources in different locations. Distributed generation sources aid in the resiliency of the grid because they provide different ways that electricity can be routed to locations. This resiliency can be seen by the ability for the electrical grid to resume operation after an outage whether at a power plant or on a distribution line. Multiple energy generation plants, if properly connected, allow electrical faults to be quickly isolated from other systems allowing for decreased down time by consumers. If one power plant becomes offline, the other power plants in the sector and the nation can ramp up to make up for the loss of power.

In general, the interconnectedness of the electrical grid works well in providing energy and transferring energy from one side of the country to the other. However, studies like the one performed by the National Academy of Sciences, Energy, and Medicine, which is summarized in the report *Enhancing the Resilience of the Nation's Electricity System – 2017*, indicate that the increase in the quantity in energy generation sources that improve resiliency, create a system that relies on different entities to maintain the reliability, or the ability to provide stable power, of the interconnected grid. As more distributed energy generation is connected to the electrical grid, maintaining the reliability of the entire grid will only become more complex [9].

Many energy generation sources that have become popular among electrical companies to meet state requirements for renewable energy sources are wind and solar energy. Wind and solar energy has also become more popular for individual consumers as well due to their ability to be used in low electrical demand situations and affordability. In fact, the Energy Information Administration reported in February 2024 that renewable energy was generating 21% of the electricity within the US [10]. However, as discussed previously, the added energy generation sources have a potential for decreased reliability if the systems are not properly connected.

In effect, the emergence of many different forms of energy generation sources connected to the grid has increased the resilience of the electrical grid but, without careful planning, could lead to a decrease in the reliability of the grid.

Current Grid Security

Even though the grid resiliency has increased in recent years, it is susceptible to cyber and physical threats, natural disasters, human error, and the malfunction of equipment as listed in the *Grid Modernization Strategy 2020* by the DOE. In this document, the DOE acknowledged that the even more integrated grid of the future will be able to better respond to electrical demand at any given time [11]. This swift response will optimize the utilization of all the different energy sources to ensure the grid operates at peak efficiency which would result in lower prices for consumers. However, the increase in smart devices within the grid to enable integration will also substantially increase the risk of cybersecurity threats. In terms of cybersecurity, a presentation in October 2024 by the Idaho National Laboratory showed that every device within a system should be protected from cyberthreats [12]. With the increase and diversification of energy generation sources, the grid has needed more monitoring devices and controls that can respond to a cyber-attack effectively.

Some may think that the US electrical grid is not susceptible to human threats due to the nature of being located within the US. However, a study released in 2022 recorded an astonishing number of outages caused by human attack from 2011 to 2019 shown in TABLE 1 [13]. It is important to note that TABLE 1 includes human attacks from cyber as well. However, according to the Western Electric Coordinating Council (WECC), in 2023 there were 107 physical security events reported to the DOE that affected the power grid and 2 cybersecurity events that were reported [14]. This data from WECC shows that the majority of threats reported from 2011 to 2019 can be safely assumed to be physical threats to the grid. This data also shows that threats against the current grid are increasing on a yearly basis. In October 2024, the Homeland Threat Assessment (HTA) conducted by the Department of Homeland Security (DHS) reported that, “Domestic and foreign adversaries are expected to continue to target our critical infrastructure via prepositioning, cyber, and physical attacks [15].” In the same report, the DHS also stated, “We assess that domestic and foreign violent extremists will continue to call for the physical attacks on critical infrastructure in furtherance of their ideological goals and, in response to international conflicts and crises [15].”

Table 1 Number of electrical outages in the US from 2011-2019 by NERC regions and Balancing Authorities. Referenced from [13]

NERC Regions and Balancing Authorities	Number of Outages Caused by Human Attack
AK (Alaska)	0
HI (Hawaii)	0
MISO (Midcontinent Independent System Operator)	2
FRCC (Florida Reliability Coordinating Council)	2
SPP (Southwest Power Pool)	4
MRO (Midwest Reliability Organization)	4
TRE (Texas Reliability Entity)	7
SERC (Southeast Reliability Corporation)	11
NPCC (Northeast Power Coordinating Council)	36
RFC (Reliability First Corporation)	64
WECC (Western Electricity Coordinating Council)	80
TOTAL	210

Current Grid Capability and Efficiency

When discussing the capability of the electrical grid, an understanding of how the grid functions is helpful. The grid relies heavily on the ability to monitor the electrical demand to produce the electricity required. When determining which energy sources to operate at any time, from an electricity supplier's perspective, many power plants will choose the most cost effective option. The process of choosing fuel sources can conceptually be seen by reviewing a graph showing the fixed and operational costs for a power plant when determining which sources to use, shown in FIGURE 3, combined with a load duration curve, like the one in FIGURE 4. The fixed and operational costs graph shows the points in a year which an energy source becomes more cost effective than the other options. Using FIGURE 3 and FIGURE 4, one can determine that natural gas is more cost effective than running a combustion turbine for a year even though the combustion turbine is the least initial first cost. The intersection where the natural gas becomes cheaper can then be plotted in the load duration curve to determine how much electricity it needs to produce on a yearly basis. If the electrical demand is greater than the capacity of the natural gas plant, then the combustion turbines would start to operate to fulfill the demand. Using this method allows the power plant to produce energy in the most cost-effective manner utilizing the cheapest fuel based on a per hour basis. However, using this method does not always ensure that the most energy efficient source is utilized generally because the cheapest fuel source may not always have the best energy efficiency when generating electricity.

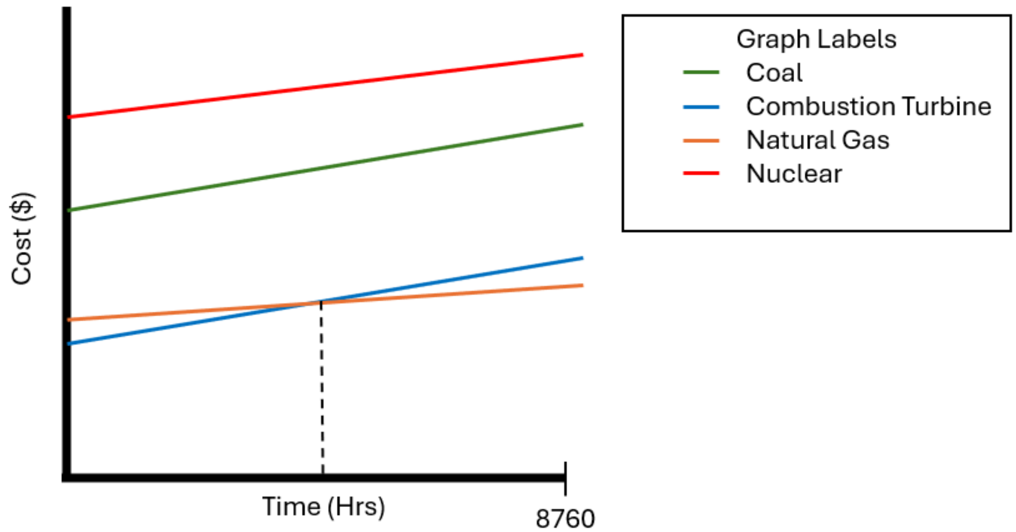


Figure 3 A graph showing the total cost vs operational hours of different energy sources throughout one year.

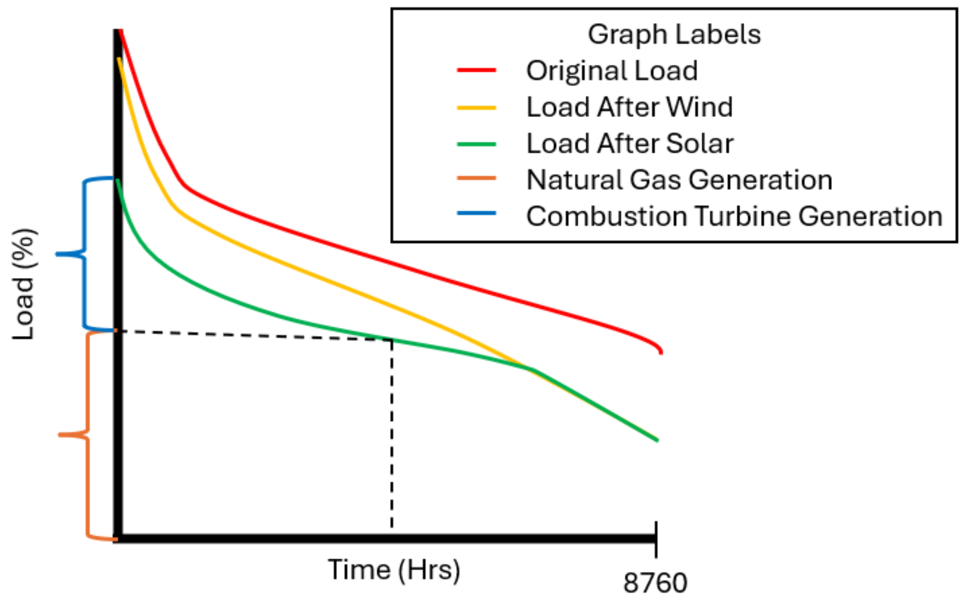


Figure 4 A load duration curve showing the amount of electrical load a source is expected to produce when used with a total cost vs operational hours graph.

Utilizing the method of the load duration curve shows how the grid reacts to an increase in energy demand. The grid follows the electrical demand by increasing and decreasing the amount of energy generated by controlling the electrical generators. To ensure the electrical grid can sufficiently generate enough electricity at any point in time, historical data and weather forecasts are used to predict future electrical demand. This can best be visualized by viewing the US electricity overview graph provided by the U.S. Energy Information Administration (EIA) in FIGURE 5. Even if the future demand proves to be incorrect, this system allows the energy generation companies to be prepared for large loads. This is helpful because, in most cases, the generators take time to start up to produce the required electricity.

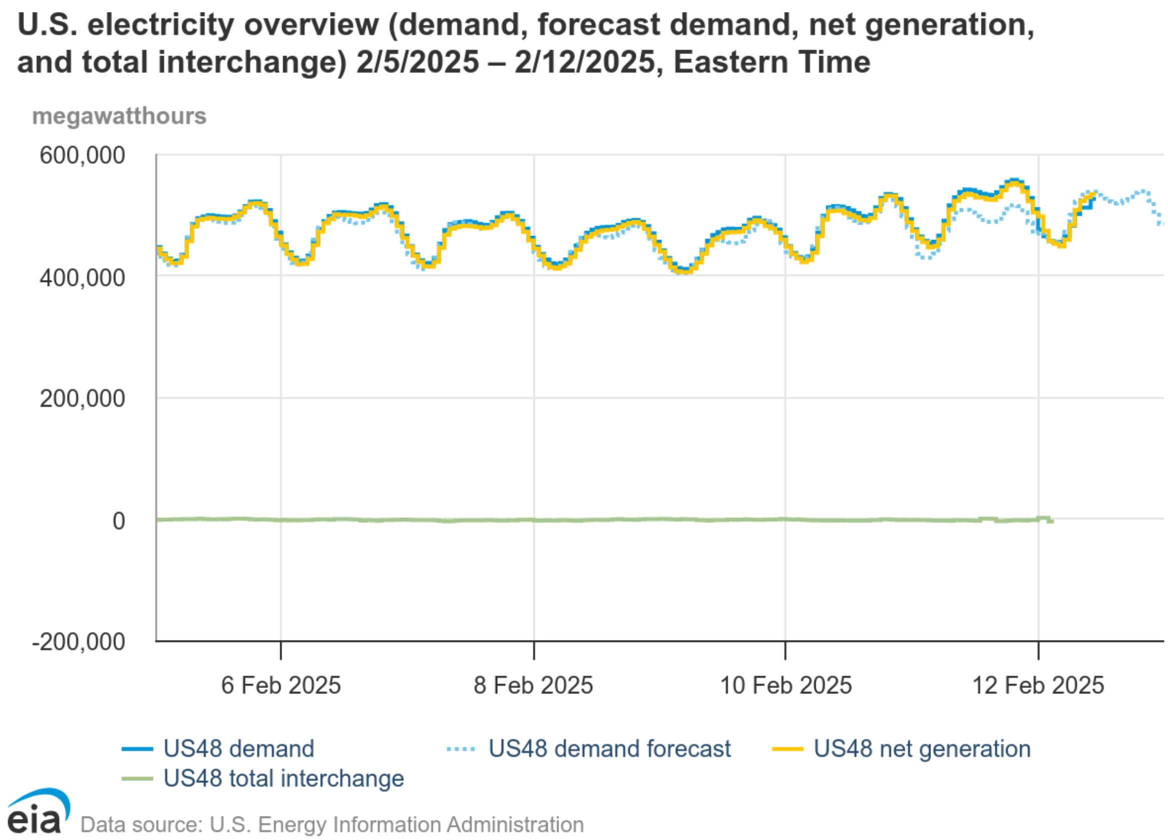


Figure 5 Electrical demand, forecast demand, and net generation graph. Source: U.S. Energy Information Administration (February 2025) [7]

Since the electrical grid does not rely on one source of energy, the capability of the grid is dependent on how much energy each source produces. FIGURE 6 from the EIA shows the megawatt hours (MWh) that each source produces in real time across the US. This graph shows that natural gas sources currently produces around 150,000 MWh, an average of around 75,000 MWh more than closest sources. The next two consistent sources that produce the most electricity are nuclear power plants with a production of 80,000 MWh and coal power plants with a production of 65,000 MWh. After those three sources comes renewable energy production with wind producing an average of 55,000 MWh, solar producing an average of 50,000 MWh, and hydropower producing around 40,000 MWh.

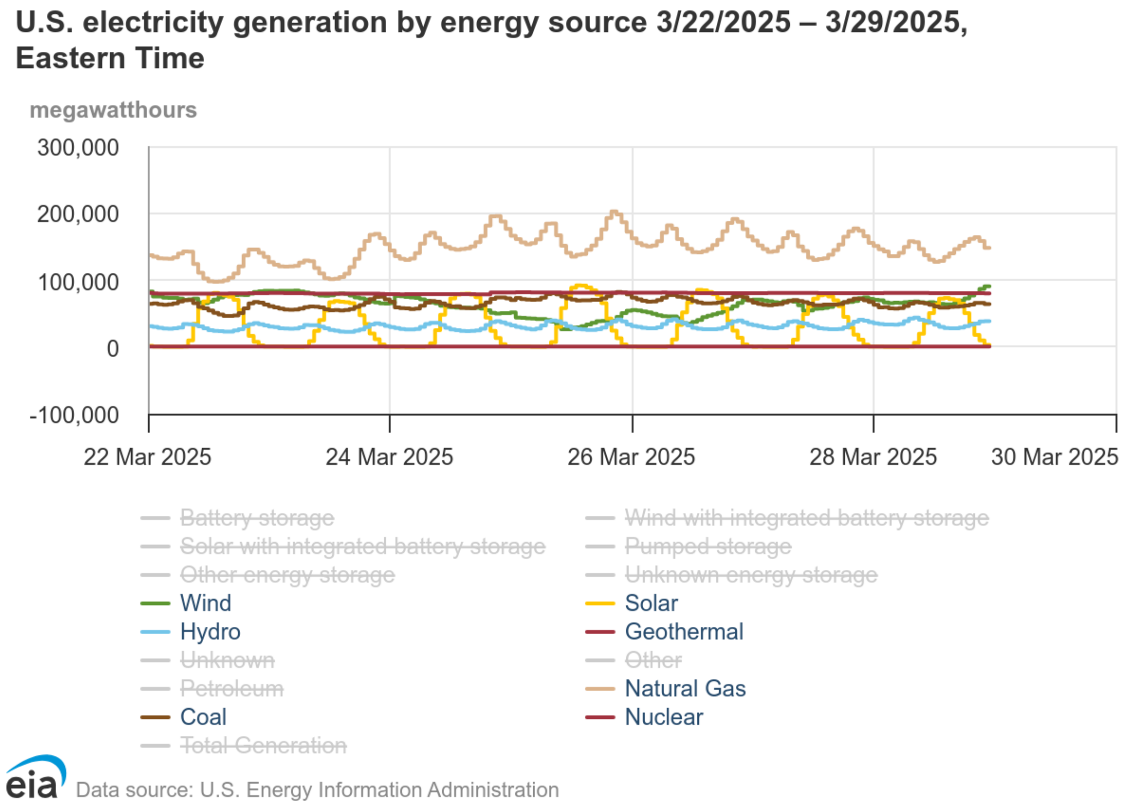


Figure 6 U.S. Electricity generation by energy source from March 22, 2025 to March 29, 2025. Source: U.S. Energy Information Administration (March 2025) [7]

When considering the energy efficiency, or the output of electrical energy in relation to the available energy, of the sources that make up energy production in the United States, the electrical grid consists of a mix of energy efficiencies. This mix of energy shows that the power plants within the US have placed a long-term value on cost-effective energy rather than energy efficient processes. This is because by choosing to use cheaper sources, the energy companies can make more of a profit compared to if they were to focus on improving the efficiency of the energy conversion process. It was found that natural gas has an energy efficiency ranging from 55% to 60% [16] with an ability to perform carbon capture further increasing the energy efficiency although not widely adopted yet. Surprisingly, the energy efficiency of natural gas, as seen in this section, is higher than any other energy process within the grid because these power plants have benefited from newer power generation technology as many of the natural gas power plants have been constructed more recently than coal and nuclear power plants [17]. Coal is considered the main producer of greenhouse gases that are harmful to the environment and have been phased out during recent years but are still responsible for a large portion of electricity production. A study performed by the National Energy Technology Laboratory (NETL) in

December 2013 showed that the net energy efficiency of coal power plants decreases as they age. In this study NETL showed that most coal power plants within the US were operating at an average efficiency of 32% but could be increased to 36% if improvements were made to recapture energy [18]. The nuclear power in the current grid is produced from the large nuclear power plants built from the 1950s to the 1960s as nuclear power became less popular in the 1980s. These nuclear power plants were also found to operate at a net efficiency of 36%. The hydropower seen in the energy mix is also mainly from dams that were built from 1920 to 1970. These dams were found to have an efficiency of 90%. Wind and solar technology and their energy production have increased more than other technologies in recent years. Even with the technological improvements, wind turbines have an energy efficiency of 40-50% while solar panels have an average energy efficiency of 20%. The approximate percentages of electrical energy production can be summarized in TABLE 2 due to the generation mix of the grid always changing.

Table 2 Summarization of percentage of electrical production for major energy sources and their energy efficiencies.

Energy Source	Percentage of Electrical Production	Energy Efficiency
Natural Gas	37%	55%-60%
Coal	18%	32-36%
Nuclear	18%	36%
Wind	9%	40-50%
Solar	9%	20%
Hydro	9%	90%

Current Grid Construction and Maintenance

A look at the US electrical grid quickly shows several factors that should be concerning for a nation that relies on energy in every aspect of life. According to the Department of Energy, much of the current grid was built in the 1960s and 1970s. The aging electrical lines are an issue because the lifespan of these wires is typically seen as 50 to 80 years. The system has improved slightly with the addition of improved automation but the fact that 70% of the nation’s electrical grid is about to reach the end of its lifespan is alarming. The increasing age of the electrical grid has created more risks with increased number of power outages and increased susceptibility to cyber-attacks [19]. As these wires age, the electrical capacity that they can safely transport decreases. This means that the same amount of power on these electrical lines when they were new now are closer to the carrying capacity, potentially leading to electrical faults when an electrical wire fails.

Some ways that the grid deals with maintenance are through reactive, planned, proactive, predictive and prescriptive methods [20]. These measures are described in more detail below.

The reactive measure, as its name suggests, occurs after a problem within the electrical grid has occurred. During these electrical faults, large damages to consumers can be accrued, especially through monetary losses. However, since these faults may be caused by large weather events, the locations of the electrical faults cannot be predicted. The aging infrastructure has also contributed to instances where the maintenance crews have been needed due to power outages caused by aging equipment. Another issue that the current grid has started to experience is that newer measures to catch these failures have led to longer downtime within the grid due to maintenance crews being less familiar with the newer technology.

The next measure of maintenance is planned. Planned maintenance involves inspections of vital pieces of equipment like generators, transformers and switches to ensure they are functioning properly. As with other processes of maintenance, the important item needed in planned maintenance is to ensure inspections are routinely conducted and any issues found are dealt with before incidents occur. With this type of approach, the faults caused by aging equipment can be addressed before it occurs.

Another type of maintenance is classified as proactive. This process involves both conditional monitoring and severity assessment through the placement of strategically located sensors. Part of the conditional monitoring involves utilizing devices that have real-time communication capabilities to monitor the electrical grid in order to identify the risk of faults before they occur. The severity assessment part of proactive maintenance uses the sensor data to identify components that have higher severity levels meaning that they have the potential for a greater effect on the system if they fail. This allows the electrical companies to address higher severity items before lower severity items. According to the report, wind turbines use proactive measures to avoid damage to the wind turbines [20].

Another measure taken is predictive maintenance. In this step, the location of faults are predicted using both real time and historical conditions. These measures can be particularly useful in determining where faults have occurred so that repair crews are able to identify and repair the system resulting in less downtime. Using this type of maintenance also allows maintenance crews to determine how the location of faults may affect different areas allowing for prioritization of maintenance when faults do occur.

The last maintenance measure taken by utility companies is prescriptive maintenance. Prescriptive maintenance uses modeling and historical data to predict where a fault may occur and either addresses it before it occurs by investing in either more infrastructure or in automated controls. An example of this type of maintenance could be the construction of different energy generation sites to increase grid resiliency or the addition of redundant electrical lines.

All these measures are utilized to maintain the electrical grid and aid in reducing downtimes caused by the aging grid.

Summary of Concerns within the Current Grid

Throughout the analysis of the current electrical grid in the US, several key items were noticed that should prompt the military to investigate alternate solutions for military bases.

First and foremost, among the concerns with the current grid is the rapidly increasing interconnectedness that has helped the grid to function but has created numerous gateways for which the electrical grid may be attacked and taken down. In fact, threats to the electrical grid have been increasing in both physical threats and cyber threats. The US has also seen the rise of many generation sources that have been proven within the grid itself and are now becoming available to the public to become more resilient but have decreased the reliability of the grid as more sources are being connected. In this aspect, the military should follow the public's example and procure generation sources that can be used to establish systems that are not dependent on the current grid. The last concern with the current grid is that it is already old and key components, particularly wires, are reaching the end of their lifetime and may cause a major grid outage. The military should be concerned about the issues with the current grid and combat them by beginning the process of switching to a microgrid system powered by adequate energy sources.

Current Military Projects

As the military explores energy sources that can supply military bases, it has moved forward with several projects already. While researching the topics contained in this report, it was discovered that many military bases have already incorporated solar panels within their electrical infrastructure.

Through research it was also found that the Air Force has started to invest in new technology to be used at Air Force bases. The two examples of this are at Eielson Air Forse Base (AFB), Alaska where the Air Force has invested in a nuclear microreactor and at Joint Base San Antonio, Texas where the facility teams are exploring a Closed Loop Geothermal (CLG) system.

At Eielson AFB in Alaska the Air Force has been planning to build a microreactor since fiscal year 2019. This project was initially supposed to be completed by 2027 but since then the design process has been halted to procure other bids from nuclear reactor companies. While the design process is halted, the Air Force has met with different key personnel for the project. The Air Force has also worked closely with the Nuclear Regulatory Commission in making sure there is an efficient review process for the project.

At Joint Base San Antonio, the Department of Defense has planned to construct a CLG system to aid in suppling the base with reliable power as discussed in this report. Joint Base San Antonio was chosen due to the subsurface heat that is closer to the surface than other locations. The system is to provide electricity power to the base but the base will still be connected to the electrical grid [21]. The process and testing of the actual capability of the power plant is in progress as the project is expected to be finished sometime between 2026 and 2028 [22].

Methodology

To determine the best energy source for use at the selected facilities, a process must be developed to ensure the best source is chosen. This process would require a set of criteria to be established to compare the different options against each other and determine whether they are better than the current grid. The judging criteria for this report will use a five-point ranking system to clearly identify which sources are better than others. Using a five-point scale will allow the systems to be compared with the current system by allowing the use of the median number, three, to represent the current system. Although, primarily used within this report to rank against the current system, this process could also be used to compare different sources to whatever source the base is using for electrical generation. The different energy options in this report will be judged on location availability, security, reliability, capability, efficiency, constructability, and the maintenance of the system. Even though a five-point scale will be used, the security criterion will use a weighting factor since it is the primary concern. For this reason, the security factor will also be used to determine which system is preferred in case the overall rating of 2 systems is the same. With the aim of this report being to investigate available energy sources and develop a process for selecting an alternative energy source for a military facilities, the cost of a system will not be discussed within this report as the defense of the nation should warrant the cost of the most appropriate system selected. Further explanations and reasons for the judging criteria are provided in this section to clearly identify how the systems will be judged. APPENDIX A also shows a form that has been created in order to simplify the process so that energy systems may be quickly but thoughtfully rated to determine the most viable option.

Location Availability

As the US has at least 320 military facilities throughout the US, one solution may not be ideal for every base. The nature of a multitude of renewable energies is largely dependent on the environment they are placed in. The complexity of choosing one system for all the military bases in the US can be seen by looking at the different climate zones found across the continent in FIGURE 7. Because renewable energy sources tend to rely on the environment around them, the climate zones within the US can indicate how renewable energy options may perform in a selected location. In this report the location rating given to different sources will be intended to describe an energy source's ability to produce its rated electrical output in a certain location. To predict how an energy source will perform, the expectations of energy mediums on a map will be used in this report. Examples of this process would be to view the expected solar irradiance, expected wind speed, and the expected geothermal energy for a selected location on a map. A further explanation of this process will be detailed in the discussion chapter.

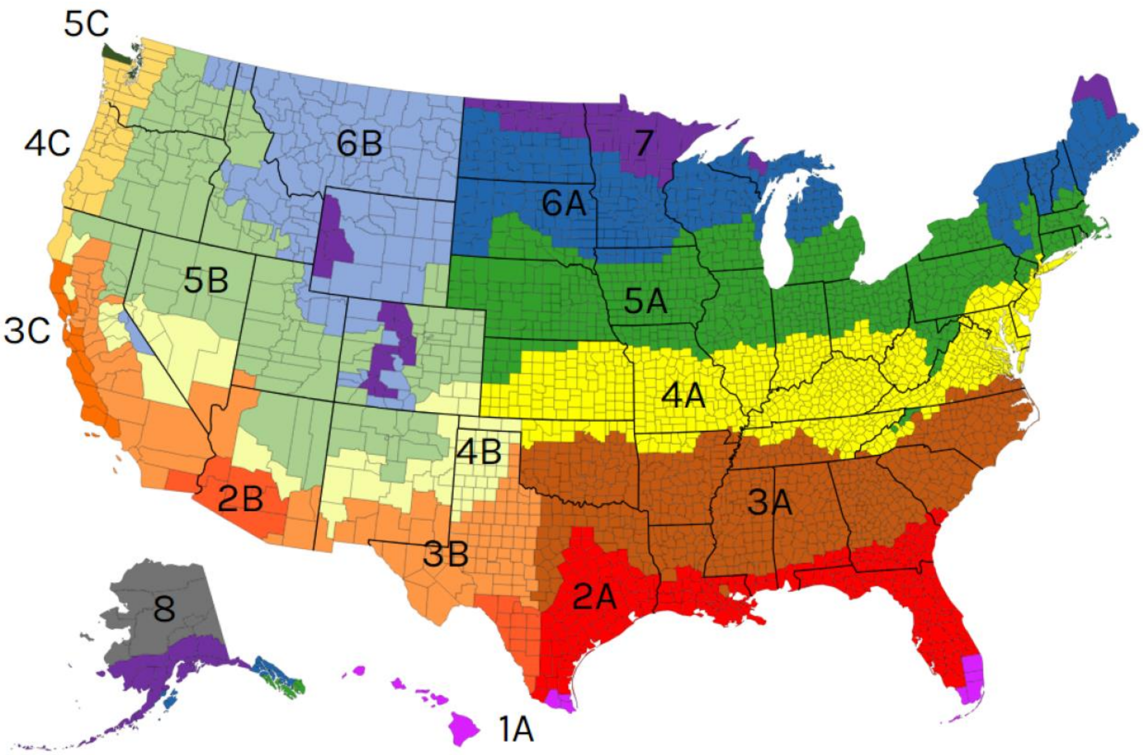


Figure 7 The different climate zones outlined within the United States. Source: Department of Energy [23]

Security

One of the most important conditions to evaluate is the security of the system in terms of cybersecurity risks and the physical risk of being compromised by hostile forces. This metric is important because of the military's mission to defend the nation. To ensure the military can accomplish its mission, military bases should be fully functional 24/7/365. Protecting the energy sources will reduce the risk of a military base losing functionality. In this report, determining the safety of a system will be based on the system's availability to be disconnected from the grid, be protected from cyber-attacks, and the ability to be located within the boundaries of a base. The reason that these metrics will be used in ranking the security of the system is because, as discussed earlier, the main threats that the current grid has seen are cyber-attacks and physical attacks at certain locations. A system's ability to be controlled via hardwired connections or firewall protected sites would greatly decrease the ability to hack the system and disrupt military operations. For the physical security of a system, being located inside the base perimeter would mitigate threats from foreign or domestic adversaries. Besides the actual generator, the physical security of the system also relies on the electrical powerlines that distribute the electricity to the base if the source is located outside of the base perimeter. For energy sources with fuel, the physical security also extends to the protecting the fuel source so it is always available.

Another security measure that will not be discussed in this report in great extent is the ability to protect the system from electromagnetic pulse (EMP) attacks. An EMP attack is essentially an electromagnetic shockwave that can short circuit any exposed wiring within the vicinity. EMP attacks are considered high-impact low-probability (HILP) events meaning that, if one occurs, it has the potential to affect a large portion of the electrical grid but the likelihood of an EMP attack is very low [24]. A summary of the impacts of different attacks in TABLE 3 shows the severity an EMP attack may have compared to physical and cyber-attacks.

Table 3 Potential impacts of different attacks on different types of equipment. Referenced from [24]

Equipment at Risk	EMP Attack	Cyber-attack	Physical Attack
Generator Stations	Direct Permanent Effects	Direct Permanent Effects	Direct Permanent Effects
Utility Control Centers	Direct Permanent Effects	Direct Permanent Effects	Direct Permanent Effects
Transformers	Direct Permanent Effects	Potential Permanent Effects and Cascading Effects	Direct Permanent Effects
Telecommunications	Direct Permanent Effects	Direct Permanent Effects	Cascading Effects if no backup power
Radio Communications	Direct Permanent Effects	Cascading Effects if no backup power	Cascading Effects if no backup power
GPS	Direct Permanent Effects	Cascading Effects if no backup power	Cascading Effects if no backup power
Internet	Direct Permanent Effects	Direct Permanent Effects	Cascading Effects if no backup power

Since they are categorized as HILP events, EMP attacks will not be discussed in other sections of this report because there is little data available for protection against EMP attacks with most protection methods being theoretical and based on the same protection methods that are used in case of a lightning strike. Another reason that security against EMP attacks will not be used to rate systems is that the threat of EMP attacks has been recognized by the United States and initiatives to mitigate the effects of EMP attacks have been in development since 2016 when the United States Congress passed the Critical Infrastructure Protection Act.

Since security is the main reason for investigating other energy sources, a factor of 2 will be used to weight this category more than other criterion. Additionally, a system that is rated as worse than the national power grid, receiving a 1 or 2 on the rating scale, will not be used as an alternative energy source. Using a minimum rating will ensure the system selected will not create more security concerns in the selected system than the national power grid.

Reliability

Building off the same reason that security is important for military installations, reliability of the energy system is equally as important. Unlike security, this category is not concerned with interference from other countries but rather is based on the ability to remain functional at all times. The resiliency of the system is dependent on the expected amount of time to restart a system if it does go offline. Due to the nature of the military needing to be functional even when in times of distress, like storms, the systems supporting the military needs to remain functional or quickly repaired.

As discussed in the introduction chapter of this report, several reports by the NREL have evaluated the reliability of emergency power generation on military bases [1] [2]. These reports recognize that many military bases are already equipped with emergency generators in case power to the installation is unavailable. In the reports, the NREL uses a two-week period in which the bases have to rely on on-base electricity generation. In these reports the generators meant for emergency situations prove to be inadequate for the two-week period due to equipment malfunctions. With the addition of some alternative energy sources discussed later in this report, the reliability of energy sources during emergency situations is significantly increased. Furthermore, by becoming independent of the grid, the electrical system will be able to be monitored much more closely, allowing for the system to become even more reliable with the increased attention to the system daily. With that being said, the reliability of the energy source selected to replace the connection to the electrical grid becomes a very important criterion for the system to have.

A part of a system’s resiliency is its redundancy level. To an extent, the current electrical grid has redundancy due to the many generation power plants it has. On the same note, the electrical source chosen for a base should also be redundant in order to be relied upon. This redundancy should be incorporated in the system so that maintenance and repairs can be performed to the system without having to reduce the system's electrical loads.

Capability

To guarantee the functionality of the electrical system, it should be sized appropriately. If a system is not sized appropriately, it may experience unnecessary blackouts. This criterion that the system will be judged on is dependent on whether the system has the capability to supply the total electrical load of the base.

A portion of this category would be based on the land usage required to meet the total electrical load as most renewable systems have been designed to be modular as needed. The reason that the land area would be relevant in this case is that it would affect security and maintenance. The amount of land required would determine whether an energy source could be located on the military installation or close by. For security purposes, a smaller land area would be easier to secure in case of an attack or would be more likely to be located on the base. Even if the energy source could be located on the base, it has the potential of taking up land that could otherwise be used for other purposes whether for training or for base expansion. On the maintenance side, much like buildings that are easier to maintain with utilities located in a central area, a system that uses less land could be monitored and maintained in an easier process.

A system should also be designed for the growth of a base whether it is by constructing more buildings or an increased number of electric vehicles. Both factors include electrical loads that could be added to a base in the future and as such the capability to meet those electric loads should be accounted for. In typical electric designs, a growth of 25-50% is usually used to size a system for future use.

Another factor that is related to both capability and energy efficiency is energy density. Energy density mainly concerns energy sources that require a fuel source. Energy density is an important factor to look at in capability because it indicates how much electricity might be produced. In each fuel source, the energy density shows the resource usage needed to acquire the target energy production. When selecting a fuel source, fuel sources with high energy potential are more desirable because they require less resources to produce the same amount of energy as less energy dense sources.

Efficiency

In the process of determining the best energy source to construct at a military base energy efficiency is an important metric to look at. Energy efficiency can be determined by the equation given:

$$\eta = \frac{E_{useful}}{E_{Input}}$$

Where η is the efficiency percentage, E_{useful} is the output of energy and E_{Input} is the total amount of energy used. As seen in the equation, higher energy efficiency occurs when more energy can be used from the total amount of energy supplied.

Efficiency is important because it shows that a system is not wasting material. In the case of energy, efficiency factors can have a large impact on the energy produced, especially when producing large amounts of electrical energy that can show large amounts of energy that cannot be used. Today's current energy sources are always trying to be improved to have greater efficiency values so that the resource will last longer. Even with the improved efficiencies of the sources, energy efficiencies differ from source to source because of the different techniques used to convert energy from one medium to electricity. Having a high efficiency rate could possibly reduce the number of units needed, affecting several different factors within a system. Fewer units would reduce connection points that could be hacked. High efficiency values also indicate that there could be longer periods of time between refueling compared to less efficient energy sources. In this report the efficiency of the sources being evaluated will primarily be in relation to the other sources due to the generation mix that the current grid has due to different energy sources.

However, energy efficiency factors of the current generation sources within the grid can indicate efficiency factors that should be looked for in an alternate energy source. As seen in the previous section, a large portion of the current grid uses coal, natural gas, and nuclear energy from older power plants. The energy efficiencies of these power plants are around 35% for both coal and nuclear power while natural gas has a higher percentage of close to 60%. Even though current energy efficiencies average around 48% in energy production, the current grid does have energy losses in the distribution phase that would affect the energy efficiency of the power grid. If the military switches to a microgrid, it would allow for less transmission line losses.

Constructability

The constructability rating in this report includes a variety of different factors that need to be evaluated. These factors include the time it takes to design and construct the system, the quality of materials used, and the life expectancy of the system. Also in the category of constructability are the environmental impacts the system may have during operation. These factors will be used in the rating to determine whether a source can be constructed and operated in a way that enhances national security while also decreasing the impact on the environment.

The first factor of this category is the time expected to design and construct the system. This factor is important in determining the constructability rating due to the threat level associated with a military base being connected to the current grid until the power generation source becomes operational. When considering design and construction time, a system should become operational, allowing the facility to become energy independent, in a short amount of time. In this case, a system that has an expected time until operation of five years is less desirable than a system that is expected to be completed within a few months due to the extended amount of time that the project location is susceptible to power outages through physical or cyber threats.

The next factor in determining constructability is the quality of materials being used. The expectation is that a system designed around lower quality of materials will be more susceptible to damage by wear and tear of operation. This factor also contributes to the life expectancy of the system as a more durable system can be assumed to have less wear and tear during operation and, as such, can be in operation for longer time periods.

The factor of life expectancy can be best seen in today's electrical grid when focusing on generation sources. Many of the generation sources today that supply the base electrical load throughout the US are primarily large power plants built from 1950-1990 and have an average age of forty years old [25]. In this factor, the precedent has been set so that a system should have the ability to be operational for at least twenty years. A twenty-year operational period follows the trend of what has occurred in the US with the construction of newer power plants. This life expectancy would allow for the development of technology while also avoiding the situation the current grid is in where it is on the verge of the mass retirement of power plants. The reason the industry has switched to a younger life expectancy for new power plants when compared to older power plants addresses the concerns many investors have concerning changes in policies in future years. Following industry and having this period as a standard in choosing alternative energy sources would ensure sources with shorter lifespans requiring a regular remodel would not be selected thereby allowing the military to focus on their mission. Using this timeframe as a standard will also aid in recognizing, during the selection process, that systems with longer expectancy will, in a sense, lock the military base into that system for that expected time in which technology may progress, but the military base could not switch to it. As military bases generally last for long periods, with some still being operational since the early 1800s, having a twenty-year lifespan would allow for secure energy production but also allow for newer systems to be considered when the time period is up ensuring modern equipment being utilized. It is expected that as equipment is introduced, newer equipment is more secure and reliable.

Maintenance

Maintenance is a category that is important to consider in a system to make sure the chosen system can be both well-cared for while not becoming a hindrance to the main objective of the military. The main factors that affect this category are the amount of regular maintenance needed to keep the system running as it is supposed to, the technical skill involved in maintaining the system, and the refueling requirements.

The amount of regular maintenance required for the system can affect the reliability of the system as seen with the NREL's study on the emergency generators and may also affect the energy efficiency of a system [1]. As stated previously, when considering this factor, the rating should be based on whether the regular maintenance to keep the system operational will be a hindrance to the base, drawing valuable personnel away from other duties they should perform. As the quantity of regular maintenance increases, there is also a greater risk that the maintenance could be neglected and cause the system to malfunction when it is most needed. For this factor, the ideal system would only require minimal maintenance in the environment of the selected base.

Another factor in this category is the technical skills that are required of the system. Much like when considering local technicians when designing a building system, care should be taken that the system does not require technical skills past what is available. This is not much of a concern for the military because it has accomplished a system of developing specialized members in certain areas. Over time, the military would be able to train specialized members that will be able to maintain and repair complicated systems. However, it should still be realized that it could take the military a few years to train members with the required skills to maintain a system.

The other factor that is contained in this category is the amount of refueling needed. This factor, much like regular maintenance, has the potential of becoming a hindrance for necessary operations. Unlike regular maintenance however, the refueling needed to produce electricity can be affected by events that occur outside the base perimeter. An example of this would be weather conditions that disrupt traffic to a military base causing a fuel shortage that leads to a power outage. In this case, the ideal energy source would be one that requires no refueling, long periods of time between refueling, or locally sourced fuel, in effect establishing the base as energy independent from the outside world.

Findings

This section investigates the different energy sources that are feasible for military bases to use for microgrid power. Understanding how each source has developed over time can aid in estimating how it may look in the future as well as show drawbacks that it has had in the past. This section also discusses the system properties that affect the rating criteria established in the methodology section.

Wind

History

Harvesting wind energy using windmills has been estimated to be in use as early as the 7th century. However, it was not harnessed to create electrical energy until the 19th century [26]. The United States began investing in wind energy in 1976 and still relies on wind energy today. Since wind harvesting does not involve the combustion process, it can be classified as clean, renewable energy making it desirable in the eyes of those looking to green energy that does not produce carbon during the energy generation process. Due to the climate, the popularity of wind turbines has grown in much of the Midwest with major wind farms in Texas, Oklahoma, Kansas, and Nebraska. The US Energy Information Administration (EIA) shows that the power produced by wind turbines has increased significantly in recent years as shown in FIGURE 8. Some of the major developers of wind turbines in the United States are GE Power, NRG Energy, and NextEra Energy Inc.

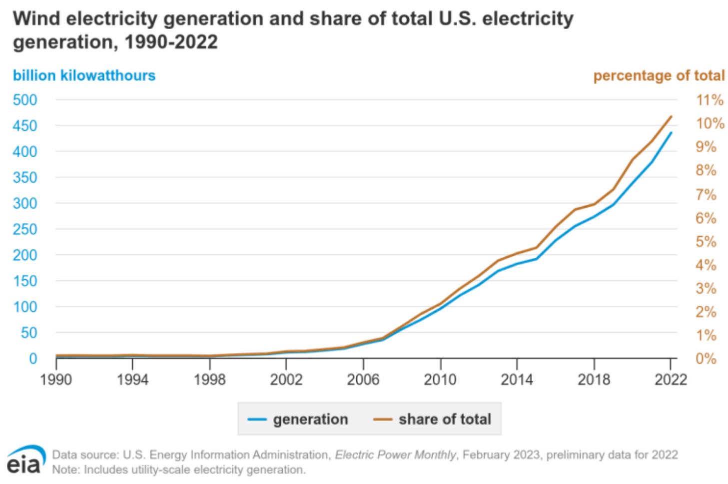


Figure 8 Graph showing the production of energy by wind from 2013 to 2022. Source: U.S. Energy Information Administration (February 2025) [7]

Energy Production Process

The standard wind turbine includes a turbine head that has a generator and drive shaft mounted on the main shaft and three blades shown in FIGURE 9.

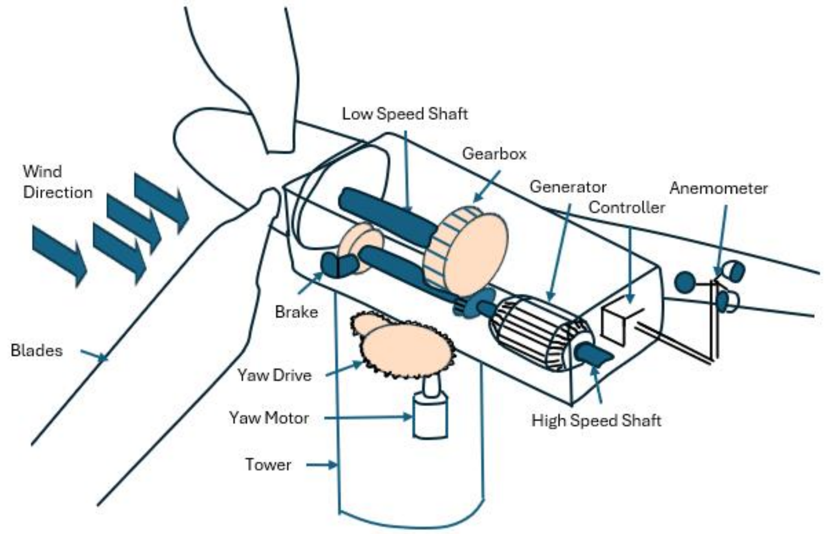


Figure 9 Diagram showing the main components of a wind turbine. Referenced from [27]

There are two main types of wind turbines, based on their blade configuration, which produce electricity. The most common type is the Horizontal Axis Wind Turbine (HAWT) with the blades rotating around a horizontal axis while the Vertical Axis Wind Turbine (VAWT) rotates around a vertical axis shown in FIGURE 10. Both types of turbines create electricity by allowing wind to rotate the turbine blades that are designed to create lift with the wind flow. By using wind to rotate the blades, energy produced is considered green and renewable as wind itself is not a limited resource. The rotation of the blades in turn rotates a drive shaft that is connected to the generator. The generator then converts the rotation of the drive shaft to electrical power for distribution. For this report, VAWTs will not be discussed in great detail as the HAWT is the main turbine being used for energy production in areas that wind energy is harvested.

Due to the nature of wind being variable throughout the year, wind energy typically uses batterie that can store excess energy for when it is needed. The use of batteries can aid in keeping power output consistent when wind energy is not enough to meet the electrical demand. However, added batteries can create a more integrated system that can add maintenance and add cybersecurity risks due to the added controllers.

To allow for wind generation but also to protect the equipment, many wind turbines are characterized by a wind speed curve shown in FIGURE 12 under the reliability subsection.

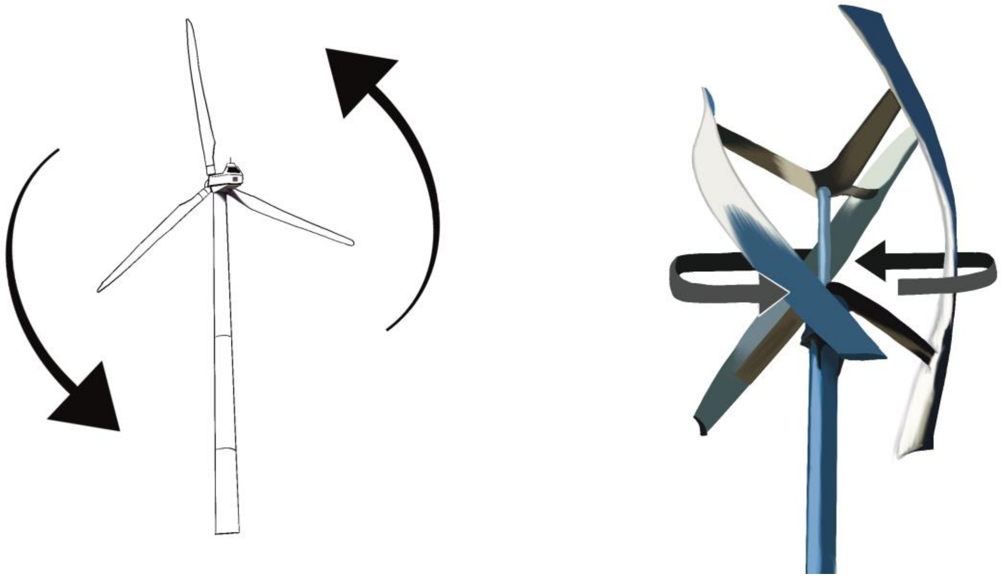


Figure 10 Figure comparing the HAWT (left) to the VAWT (right). Referenced from [28] and from [29]

Location Availability

By being dependent on the wind to rotate the turbine blades, wind turbines are limited in locations where they can produce energy. When choosing the location for wind turbines, locations with an average of nine miles per hour are ideal because, at that velocity, the wind turbine is producing the maximum amount of power [30]. The optimal location of wind turbines relies on the landscape of the surrounding area such as open, flat areas, on top of rounded hills, and in the gaps of mountains that funnel wind. Wind turbines also need to have areas in which they can tower above the ground without obstacles that may block the wind. HAWTs often range from 500 to 900 feet tall to use wind speeds that are not influenced by the ground. Thought should also be placed on the seasonal availability of wind. Since the wind turbines are being used to create electricity, they should be in areas where the wind speed is more constant or intense at times when electrical demand is close to its highest. Fortunately, to help in identifying locations where wind can and cannot be relied on, the EIA has gathered data shown in FIGURE 11.

This data shows the wind speed that can be expected in locations around the US. As observed on the wind speed map, there is a large portion of the Midwestern US that has wind speeds that are close to the desirable wind speed. Not shown on the map is the wind speed over the ocean along both the East and the West coasts. These coasts have also been identified as areas that are desirable for wind power generation and have led to installations of large off-shore wind turbines.

Even though a large portion of the Midwest is suitable for wind turbines, there are certain restrictions placed on where wind turbines should be located, which is summarized in TABLE 4.

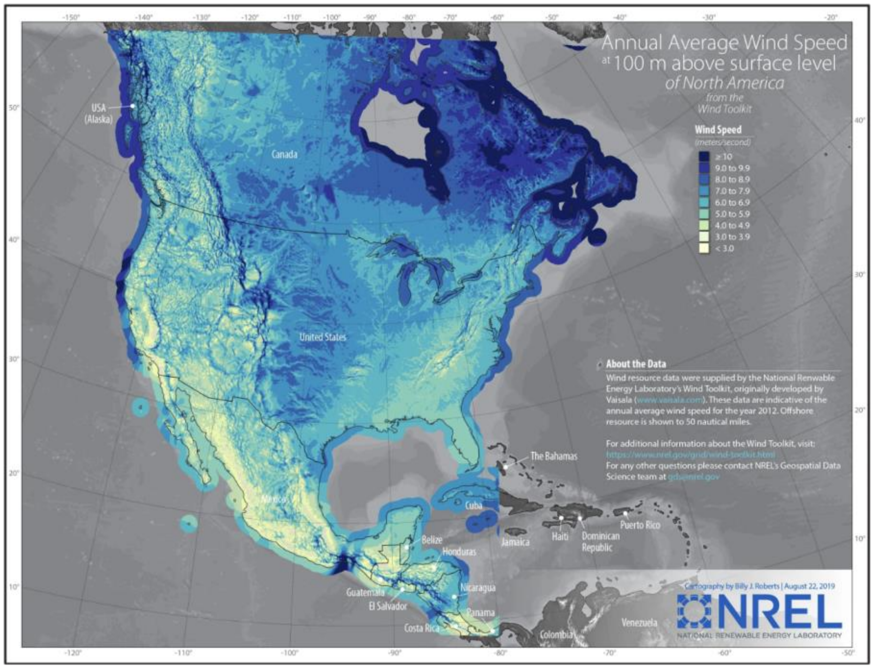


Figure 11 Map showing the average wind speed throughout the United States. Source: National Renewable Energy Laboratory [31]

Table 4 Restrictive factors for wind plant locations. Referenced from [32]

Restrictive Factor	Description and Minimum Distance
Road Networks	500m away to minimize loud noises and constant moving shadows in the roadway
Urban Areas	1000m – 3000m to avoid negative health impacts caused by low-frequency noises produced
Protection Areas	500m – 5000m to minimize potential damage to ecosystem being protected
Slope	Must not be above 25º slope for safety reasons
Military Zone	5000m from facilities due to possibility of affecting facilities
Species Migration Route	Due to the spinning blades and tall heights, known migratory routes should be avoided
Airports	2500m from airports to minimize disturbances in telecommunication networks

As seen in this table, there is a restriction around military bases meaning that any wind turbines for a military base would need to be located at least 5 km from base facilities. The primary concerns with locating wind turbines on military installations is the interference they can have on telecommunication systems and the obstructions they can cause when maneuvering aircraft.

Security

As pointed out in the location availability category, due to the interference that wind turbines could have on telecommunications systems, they should be located at least five kilometers from base facilities. This fact can make the physical security of a wind turbine plant harder than if it was on base. However, the height of wind turbines makes them harder to interfere w. Some physical concerns about this system are mainly focused on equipment that could be affected with minimal effort. On the cyber side of threat, wind turbines rely on the supervisory control and data acquisition (SCADA) system to aid in the control of the system. The SCADA system is what the current grid uses and has been shown to be hackable in the past with one of the major incidents being the attack on Ukraine's electrical infrastructure through SCADA in 2015 [33]. Another cyber threat to wind turbines is False Data Injection (FDI) in which the communication between the rotor speed sensors and wind turbine controls is targeted. In the FDI, false inputs are given to the wind turbine controller with the intention of either overloading the turbine to cause damage to the unit or causing the unit to turn off to decrease electrical generation [34].

The battery storage involved with wind turbines should also be protected from both physical and cyber-attacks. These systems can be protected physically by being placed in a secure location as they do not need take up the large amounts of land common with wind energy. Cyber-attacks on this system are possible due to the controls needed to allow for monitoring of battery conditions and the controls that determine whether the batteries are being charged or discharged.

Reliability

Since wind itself does not remain constant from one time to another, the power generated by a wind turbine can be inconsistent on an hourly basis. This can be best seen in viewing the Wind Speed Curve of a wind turbine shown in FIGURE 12. As shown in the Wind Speed Curve, electricity is not generated at every wind speed. Manufacturers will include the cut-in speed, rated speed, and cut-out speed in the specifications of a wind turbine. The cut-in speed is the wind speed in which it becomes economical to start producing energy and in the case of FIGURE 12 it would be 4 meters per second. The rated speed is the wind speed in which the electrical capacity of a wind turbine is produced and correlates to where a wind speed graph starts to level out and in the case of FIGURE 12 would be around 11 meters per second. The cut-out speed is the restrictive measure that helps protect a wind turbine from intense wind speeds. At the cut-out speed, the wind turbine can see very high loads that can damage the wind turbine so the wind turbine can be shut off. This approach is typically used when storms with fast wind speeds are expected. In the case of FIGURE 12, the cut-out speed is shown as 22 meters per second but in many cases, it is usually assumed to be 25 meters per second. An important observation of the Wind Speed Graph is that the maximum energy produced occurs with any wind speed from the rated speed to the cut-out speed, but any speed before the rated wind speed will produce less energy than is expected from the turbine.

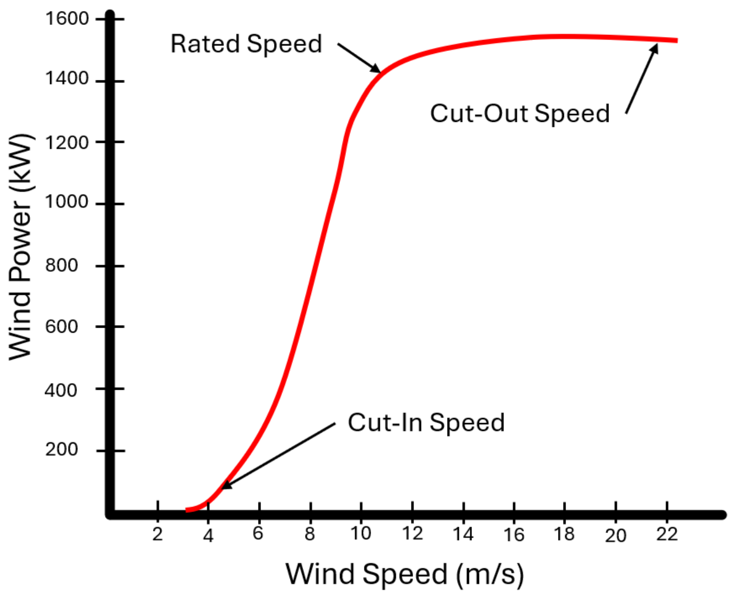


Figure 12 Wind speed curve of wind turbines showing the cut-out, rated, and cut-in speeds in reference to the power produced at given wind speeds. Referenced from [35]

As wind can fluctuate and cause power output to fluctuate, Battery Energy Storage Systems (BESS) are typically designed with wind power. BESS can utilize many different battery types, but most have a maximum discharge of 12 hours at the rated power output [36]. These BESS operate in charging and discharging modes. In charging mode, the power output from wind turbines is higher than the electrical demand so the excess is stored in the battery. In discharging mode, the power output from the wind turbines is less that the electrical demand so the battery supplies the remaining electrical power to reach the electrical demand. The BESS can only supply energy if it has sufficient charge stored in it. This means that if the wind energy is not able to charge the battery for 12 hours and the battery has to supply 12 hours of energy at the maximum output, the battery may run out of charge.

Capability

The power capability of a wind turbine relies heavily on the rated wind speed of the turbine. With the space restrictions that on-shore wind turbines generally face, off-shore wind turbines are usually bigger and result in more power output. A generalized power equation for any given time can be shown as:

$$P = 0.5 \times \rho \times C_p \times A_s \times v^3$$

As the equation shows, the power produced by a turbine in watts (P) is affected by the area the blades sweep in m^2 (A_s), the coefficient of performance (C_p), the density of the air in kg/m^3 (ρ), and the wind speed in m/s (v). As seen in the equation, the wind speed can affect the power output of the wind turbine more than any other factor which is why locating the system where a fast average wind is important. Another important factor shown in the equation is the area that the blades sweep which will determine how large the wind turbine will need to be in terms of height and will also affect the other wind turbines placed around it. The density of the air can be found by looking at the height of the wind turbine and the temperature of the air. When improving the power output through increasing the air density, the solution is to locate the wind turbine in a location that is either colder or higher in elevation than the current location. This is because air density increased with elevation and a decrease of temperature. The coefficient of performance is the energy efficiency of the turbine and as such will be discussed in the next category.

When designing wind farms the annual energy production can be found using the following equation:

$$AKWH = CF \times AV \times GS \times 8760\ hrs/yr$$

Where the annual energy production in kWh/yr (AKWH) is equal to the product of the capacity factor (CF) generally between 20-50%, turbine availability (AV) typically between 95-98%, and the selected generator size (GS) in kilowatts. In this equation the capacity factor is defined as the annual energy of a wind turbine divided by the amount of power it would have generated if it produced the full amount of power the whole year. This can be determined by using the average wind speed of a location to calculate the expected power output and then using the rated power to calculate the total amount of power it could have produced throughout the year. The turbine availability incorporates an expected maintenance factor within the equation. For generator sizes, General Electric, a manufacturer of wind turbines, has 2 MW, 3 MW and 6 MW options available.

For the land use involved with wind energy, a report from 2017 noted that that average wind farm uses around 60 acres for every MW produced. This land usage is a factor of distancing requirements between units and their general size. However, unlike most energy sources, wind energy does allow for the land beneath the turbines to be utilized and is most often used as agricultural land [37]. The military could use this land as space for training exercises that do not involve weapons so the equipment is not damaged.

Efficiency

As shown in the power equation for wind turbines, the coefficient of performance can be identified as the energy efficiency of the wind turbine when converting the rotation of the drive shaft to electrical energy. The accepted coefficient of performance of a wind turbine is generally in the range of 40-50%. Although wind energy has become more efficient throughout the years, it has been found that the theoretical limit, otherwise known as Betz limit, of a wind turbine is 59.3%. This means that, despite improvements, a wind turbine is only capable of generating 59.3% of the wind energy it is harvesting.

Constructability

Wind turbine sites consist of more than the wind turbines themselves. First, the layout of the plant must be carefully coordinated. Unlike the other sources, wind turbines require careful planning to ensure that the wind turbines do not affect each other. For designers of wind farms, models must be designed to evaluate the wake that a turbine could have. This wake is caused by the rotating of blades and can affect any turbines downwind of any turbine. The wakes caused by turbines, if not carefully avoided, can cause increased loads on the turbine blades, reduce operational life expectancy, and limit the amount of wind energy that can be captured. Once a layout is planned, the site itself needs to be prepared. Site preparation can include building the necessary roads to each wind turbine location, constructing concrete foundations, and preparing necessary electrical infrastructure like trenching for underground cables that go to the substation [38]. Once the site is prepared the wind turbines themselves need to be transported to the site, usually by trucks. Once the turbine arrives at the site, they are placed on the foundations and the blades need to be connected. Besides the turbine, a wind farm will also need to include a transformer to step up the voltage to be able to connect to a high voltage line. In the case of military bases, a five-kilometer electrical line will need to connect the wind farm to the base's transformers.

Once a site is constructed, the typical life expectancy is twenty years. Throughout the twenty-year life expectancy, certain equipment may be replaced to ensure that the wind turbine remains functional. One issue that the industry has seen recently is that the wind blades from older wind turbines are unable to be reused or recycled so most wind turbine blades are discarded into landfills.

The permitting process for wind energy projects involves both permitting and zoning procedures with local governments. The Office of Energy Efficiency and Renewable Energy states that most jurisdictions allow for wind turbines to be installed through permitted use, accessory use, or conditional use permits. A conditional use allows installation in areas that are not specifically prohibited while an accessory use permit allows for installation on land that is used for another activity [39].

Maintenance

Because wind energy utilizes kinetic wind energy, it does not require any refueling to be able to produce energy. However, due to the stress on the turbine caused by the wind, wind turbines should be inspected at least once a year. During the inspection, any bolts that are loose or any poor electrical connections should be fixed, the different parts of the drive shaft and generator should be inspected for wear and tear, and the turbine should be inspected for any corrosion from weather. Besides the yearly inspection, expected maintenance includes replacing the blade leading edge tape every 2-4 years and a blade or bearing replacement should be expected every 5-10 years. It should be noted that due to their large size and height, special equipment is needed to be able to inspect all of the different parts. To aid in annual inspections, drones have started to be utilized for off-shore wind turbines in general but could also be used for land-based turbines as well. Overall, the expected maintenance of a wind turbine can be seen from the annual power generation equation where the turbine availability is between 95-98%, showing that 2-5% of the year, a turbine is expected to be down for maintenance purposes.

System Summary

When evaluating wind energy systems there are items that the evaluator should consider listed in this section.

Location Availability

For the location availability the main item to consider is the expected winds of the location. To be a valid option, the wind speeds should be in the desired range to have the ability to produce electricity.
Another item to consider is the actual physical area around the installation. Is there enough space to have multiple wind turbines?

Security

For the security of the system, an evaluation should be completed using the location the project will be located. Is the physical location close enough to the base for reasonable response times if needed? How large is the project site that will have to be secured and what might the security around the site look like?

For cyber security, an important item to consider is the quantity of turbines that will be needed. This should be evaluated because each unit can be an entry point for cyber-attacks. For the control of the system, research should be looked at to see what the control scheme of the turbines is and whether the control system puts the system at risk of being hacked.

Reliability

The reliability of wind energy can also be location based. Even though the wind maps show the average wind speeds across the US, the consistency of the wind should also be evaluated. Another item to consider is the expected redundancy of the system. What are the peak loads of the installation and how do they compare to the average load of the system? This information can aid in determining how much capacity is left over in case maintenance needs to be performed. How much battery storage needs to be incorporated to allow for the power output of the system to be consistent.

Capability

For the system capability, the available turbine sizes from manufacturers should be considered to determine the quantity of units needed. Determining this will also aid in the location availability and the reliability of the system. Future electrical loads can also be considered to determine what the addition of turbines could look like in the future.

Efficiency

When looking at energy efficiency, there are typical values mentioned in this report, but manufacturer data should also be looked at. How does the manufacturer's data compare to the average values expected by industry? Are there additional measures that can be taken to improve the efficiency of the wind turbines such as new technology?

Constructability

For the constructability category, how will the construction process affect base operations through the pouring of turbine foundations, creation of transportation routes between sites, and the trenching needed to install electrical conduits? When the wind turbines arrive on site, what equipment will need to be used for installing the turbines on their foundations?

Maintenance

For the maintenance of the system, maintenance options manufacturers should be reviewed in order to relieve some of the maintenance performed by the base maintenance squadron. To also aid in the maintenance time, the spacing and quantity of turbines needed should be evaluated and compared to other systems. Does the base have the equipment needed to perform maintenance on the high structures or does it need to be obtained?

Solar

History

Solar energy is another source of renewable energy. The first solar panels to generate electricity were created in the mid-1900s. At first solar panels were not used on the ground but instead largely used on satellites in space. Through government contracts, the development of solar panels grew quickly as seen in the rapid growth of efficiency from 8% to 14% in two years. The popularity of solar panels in space did not grow very much in terms of aiding in the power supply of buildings until the mid-1970s when oil prices increased and caused many governments to start programs that funded research for alternative energy sources. It was at this time that the National Renewable Energy Laboratory (NREL) was created to research renewable energy options. To further incentivize the use of solar energy, the government offered tax credits to both residential and commercial buildings for the installation of solar panels. Despite these tax credits, the majority of solar power was used for larger companies and in particular large oil companies invested in solar panels.

In the 1980s, the price for oil plummeted and the US lost much of its interest in solar power. With this sudden plunge in the price of oil, it once again became less cost effective to pursue renewable sources of energy within the US. However, other countries such as Japan and Europe became major producers of solar panels and solar technology at this time. Solar power remained unpopular in the US until the mid-1990s when the US once more became interested in solar energy due to the rise of environmental concerns with carbon emissions. This interest has kept up throughout the years since the 1990s, and with research, have become less expensive to install and more efficient at converting energy.

Energy Production Process

The two types of solar energy collection are solar photovoltaic (SPV) systems or by concentrating solar-thermal power (CSP) systems [40]. SPV systems are what most people think of when it comes to solar power and involve solar panels laid out in a grid style arrangement. SPV systems rely on two different materials to establish a flow of current. The two layers are the n-layer, at the top of the panel, and the p-layer, on the bottom of the panel. The n-layer is established by the excess of electrons while the p-layer is established through the absence of electrons. In the middle of the two layers is the p-n junction in which the two layers are in equilibrium. In this system, photons found in sunlight hit the surface of the panels and create a movement of electrons in the p-n junction. The movement of electrons then are forced to the n-layer due to the polarity difference between the n-layer and the p-layer. The electrons are then able to flow back to the p-layer through conductors establishing the flow of electricity. This process is shown in FIGURE 13.

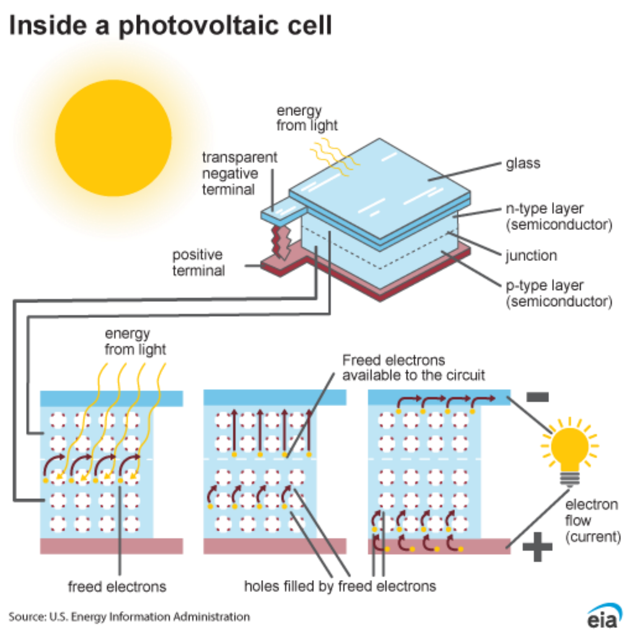


Figure 13 Photovoltaic diagram of how electricity is produced by flow of electrons. Source: U.S. Energy Information Administration (February 2025) [41]

Although the SPV system is the most common, this report will also investigate the CSP that involve a central tower and mirrors, known as heliostats [42]. In this process, the heliostats surrounding the tower, also known as the central receiver, are used to reflect and focus the sunlight on the central receiver. Focusing the sunlight on the central tower can produce temperatures between 500° to 1000°C. Inside the central receiver is a moving liquid known as the Heat Transfer Fluid (HTF), usually water, that absorbs the heat and can then be used to generate electricity using a steam turbine. To show an overview of this process, FIGURE 14 shows what CSP systems can accomplish. An important part of a CSP system is the use of thermal energy storage that allows for the generation of electricity even when solar radiation is not available [43].

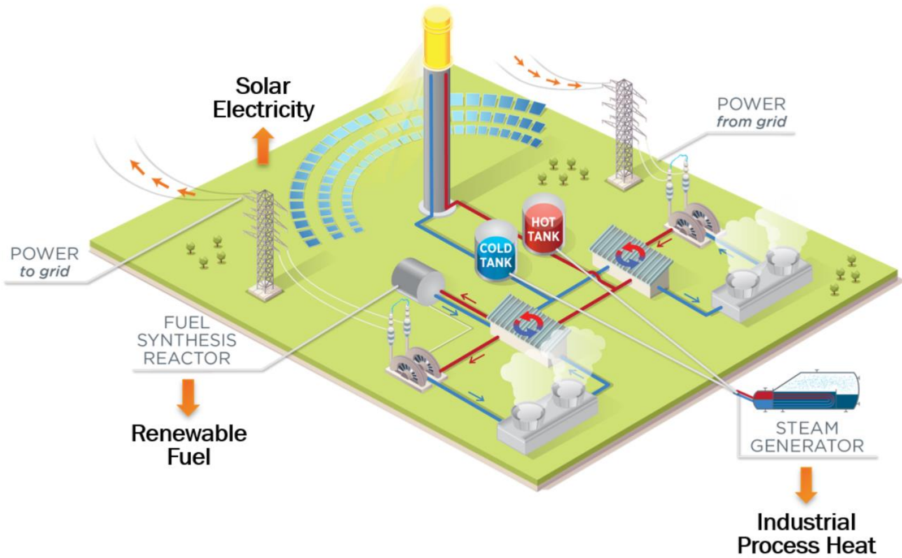


Figure 14 A diagram of the different functions and equipment of a Concentrated Solar Thermal Power system. Source: U.S. Department of Energy [42]

Location Availability

Much like wind energy, solar energy relies very heavily on its environment in generating electricity. Unlike wind energy, solar locations can be broken into two different types of solar rays. The first solar ray is the direct normal irradiance. This type of solar energy available is available for both SPV and CSP systems to harvest. The direct normal irradiance is the sunlight that comes directly from the sun. The other solar ray is the global solar irradiance which can only be collected by an SPV system. Global solar irradiance differs from the direct normal irradiance in that it can include diffused sunlight that is reflected off surfaces as well and at an angle to the solar panel surface. Much like wind energy, the EIA also produces maps based on historical data showing the average direct normal irradiance per day in FIGURE 15 and the average global solar irradiance per day in FIGURE 16. As a guideline for locations that are desirable for solar power, SPV systems are evaluated and rated in environments that have an irradiance of 1000 W/m^2. Besides the locations shown in FIGURE 16 for direct normal irradiance, CSP systems are generally recommended in regions between 15° and 40° in both North and South latitude where the direct solar irradiance is around 5 kWh/m^2/day.

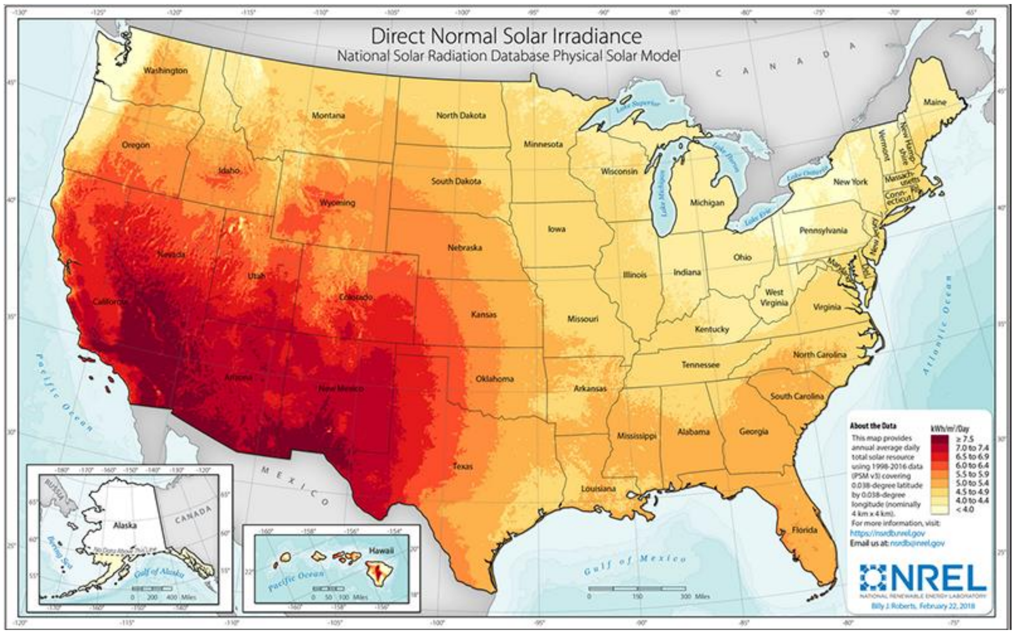


Figure 15 Map showing average direct normal irradiance per day throughout the US. Source: National Renewable Energy Laboratory [44]

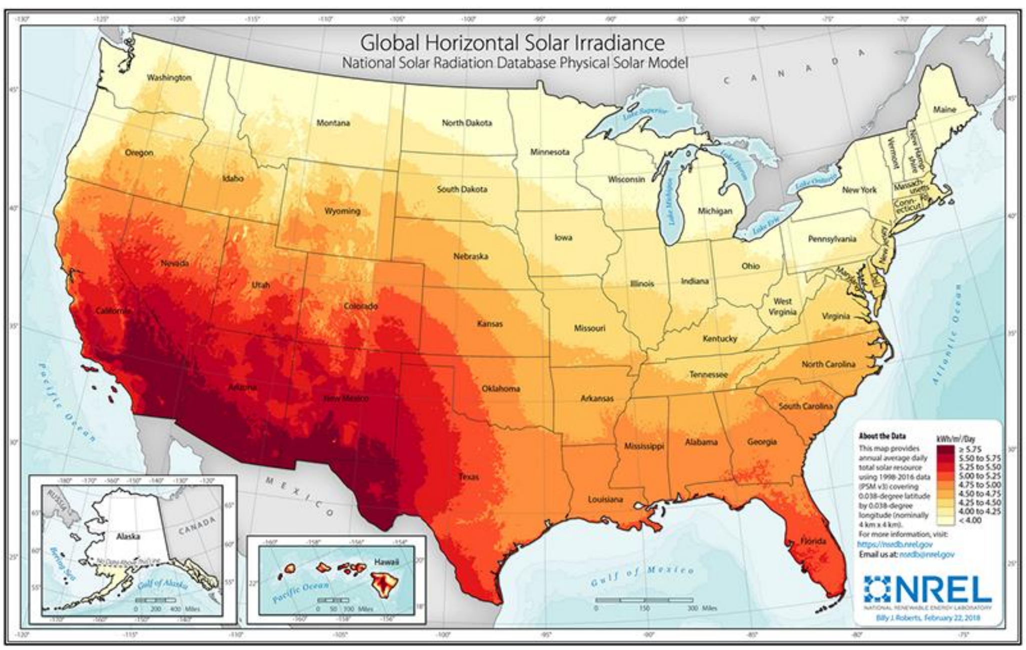


Figure 16 Map showing average global solar irradiance per day throughout the US. Source: National Renewable Energy Laboratory [44]

Security

The physical security of solar panels can be dependent on the placement of panels. SPV systems, although typically seen on the ground, can also be mounted on building roofs and facades. This could allow for the solar panels to be located on a base with large amounts of open space like on building roofs or along airstrips where electricity generation equipment is not typically located. Being located on the base decreases security threats to the system as it can be completely independent from the outside world.

Although solar panels themselves do not have internet connections, there are other pieces of equipment and connections that are in risk of being hacked. This equipment and connections include inverters, data acquisition devices, communication networks, and battery storage systems. The inverter has been a target for cyber-attacks due to its ability to bring other components offline by changing the electrical frequency. The data acquisition device monitors the solar panels and are typically seen as a starting point to gain entry to the electrical system. The communication network is used for remote monitoring and control which has benefits when it comes with maintenance, but it creates an avenue to control equipment in a cyber-attack. A cyber-attack on the battery storage system would not necessarily be seen in the moment but can lead to a lack of electrical energy when sunlight is not available. Solar powered systems have seen cyber threats before, and in May 2019, a cyber-attack led to 500 MW of power from both wind and solar, with the main effect on solar systems, being brought offline [45].

Reliability

Since SPV systems rely on the sun for energy production, they are highly reliant on being located in areas with ample irradiance. To aid in making these systems more reliable, battery storage is typically designed to be utilized within an SPV system. Depending on the battery system and sizes selected, batteries may provide power for a few hours to a few weeks [46] with most battery systems being sized for 12 hours [36]. As discussed in the wind power section, the BESS rated for 12 hours can charge and discharge depending on the electrical generation compared to the electrical demand.

Unlike both SPV systems and wind systems, the ability to utilize thermal energy storage allows CSP systems to be more reliable during times when the sun is not shining. Not only can CSP systems utilize thermal energy storage, but they can also utilize co-firing in which a combustion chamber, using conventional or biogas, is also located on the site to further improve the energy efficiency of the system and allowing it to be even more reliable when sunlight is not available. These thermal energy storage units are rated on the number of hours they are expected to be effective for. These values for thermal energy storage units can range from 1 hour of capacity to 15 hours of thermal storage.

Capability

The capability of solar energy can be determined based on the type of panel selected and the solar irradiance at the project location.

For SPV systems solar panels have a maximum power generation defined by the equation:

$$P_{max} = E \times A \times \eta$$

Where P_{max} is the maximum power in W, E is the solar irradiance under Standard Testing Conditions (STC) in W/m^2, A is the area of the solar panel module, and η is the module efficiency discussed in the next subsection. The maximum power can be plotted on a current vs voltage graph as shown in FIGURE 17. The maximum power of a panel is determined under STC with an irradiance of 1000 W/m^2 and temperature of 25°C. According to data from manufacturer information within software released by the NREL called System Advisor Model (SAM) some of the maximum power outputs from solar panels are around 700 W. To aid in maximizing power for an array of solar panels, a maximum power point tracker (MPPT) controller can be utilized within the system. The MPPT controller measures the irradiance at the location of the SPV system and controls the voltage produced by the array in order to produce the maximum power at the time. With the SPV systems currently installed, a report from the NREL shows the average land usage has been 7.9 acres per MW [47].

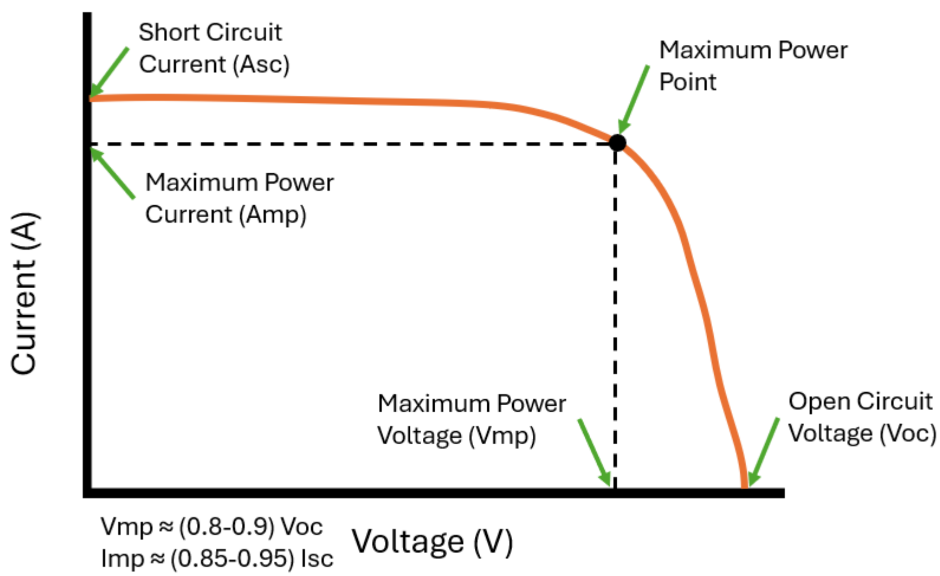


Figure 17 Current vs voltage graph for solar panels showing the maximum power point. Referenced from [48]

For CSP systems, the average capacities seen in plants currently in operation are between 10 and 200 MW although several CSP systems are in development that will produce up to 500 MW. Since the CSP heliostats do not directly convert sunlight to electricity, this system relies on the ability to focus enough sunlight at the central receiver to heat the HTF. In the same report from the NREL, CSP systems produce 1 MW per 10 acres of land.

Efficiency

The efficiencies of solar panels are mainly dependent on what type of photovoltaic technology and materials the solar panels utilize. There are three main types of panels, and each has its own expected efficiency. The first type is the first-generation silicon technology that has been around for a while. This type has been commonly used by commercial industries and has an expected efficiency of 16%. The second type of solar panel technology is known as thin film. The development of thin film panels was primarily to reduce the cost of solar panels. Since it is a very thin, low-cost option, it only has an efficiency of around 10%. The newest technology for photovoltaic panels is known as multi-junction technology. Multi-junction technology has been created to help keep manufacturing costs down but also has increased efficiency significantly. In fact, the multi-junction technology has been shown in laboratory tests to have an efficiency of 45%. However, when looking at results between laboratory tests and the efficiency of what commercial areas typically see, the commercial efficiencies are around 10% less efficient than what the lab reports show. The progression of PV systems with focus on the multijunction technology can be seen in FIGURE 18.

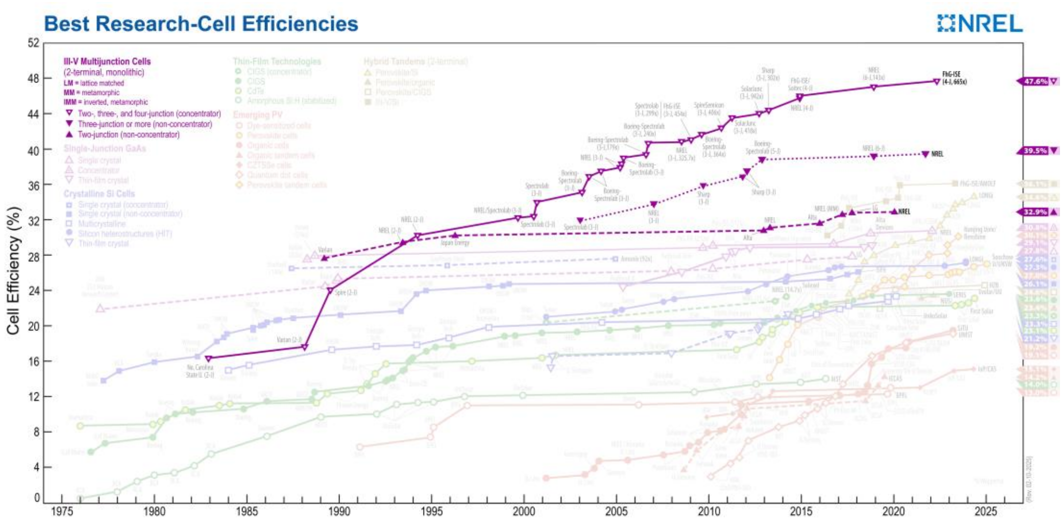


Figure 18 Progress of PV cell efficiencies with emphasis on the multijunction technology. Source: National Renewable Energy Laboratory [49]

Although these are the typical efficiency values associated with each solar panel type, the efficiency values of photovoltaic panels differ within the field based on the temperature of the panels and the cleanliness of the panels. According to research, a 1° C rise in temperature can correspond to a 0.2-0.5% drop in electrical power production showing the effect that temperature has on solar panel efficiencies. To combat this effect, solar panels can be designed to float on water allowing for the panels to be cooled or can be designed with pumps and fans that can actively cool a solar panel. Use of these cooling techniques have shown that the efficiency of the solar panel does not decrease as much due to heat [50]. Other studies have also been performed regarding how the cleanliness of the solar panels affects the efficiency of the panels. It was in one particular study in Saudi Arabia that a single dust storm reduced power output by nearly 20%, and over a period of six months without cleanings, the power output had decreased by 50% [51].

Since the CSP systems utilize the Rankine cycle to produce electricity, the overall plant energy efficiency can be regarded as between 30 to 40%. However, when looking at several operational plants, PS10, one of the first CSP plants, performed at 15.4 % energy efficiency in 2021. This data shows that as operation continues, the efficiency of the plant can be expected to decrease. One of the main factors of energy loss can be identified as the heliostats used to direct and focus sunlight on the central receiver. The heliostats can become dirty or weathered, which leads to a decrease in the ability to focus on sunlight at the central receiver. To improve the efficiency of these systems, utilizing a combined cycle has been proposed in several circumstances. In a notable model, the Stellenbosch University Solar Power Thermodynamic (SUNSPOT) cycle was developed using the combined cycle of a gas and steam turbine with air being the HTF. In this process, energy efficiency increased from 27% to 44.6% [52].

Constructability

When designing an SPV system to use solar power there are several key pieces of equipment needed to ensure the system functions properly. This equipment includes PV modules, inverters, transformers, mounting racks, wiring, switchgear, equipment that protects and monitors the SPV system, and a battery for storage. The modules and mounting racks should be oriented in the direction that receives the most sunlight. In the Northen hemisphere, the panels should be oriented towards the South. Depending on the desired electrical output of the system, a tracking system can be incorporated within the mounting equipment to allow the panels to orient themselves towards the sun as it follows its western course across the sky. The inverter in a system is necessary in order to convert the direct current (DC) energy into alternating current (AC) which is used on the grid and what building equipment is designed for in the US. The transformer is especially needed if the SPV system is connected to the grid due to the high voltage being transported. The switchgear is utilized to connect the SPV system to the grid. Due to safety measures, the switchgear for the solar power system is controlled by a remote connection to disconnect from the national power grid in case of loss of electrical power. The disconnect from the grid is needed to protect electrical line repair crews that may be working on lines. The protection equipment is used primarily for protecting the SPV system from fault currents and voltage surges that can be particularly harmful to the wiring required for the solar panels. In their entirety, SPV systems are predicted to last 20 to 40 years depending on the amount of maintenance received [53].

A CSP system is generally built in two different geometries depending on the latitude of the location. In areas closer to the equator, the heliostats are built in a circle with the central receiver located in the center of the pattern. In location farther from the equator, a wedge shape is often utilized to better reflect the sunlight toward the central receiver. The heliostats utilized in CSP systems are the majority of the land usage as it takes many heliostats to track the sun and focus the sunlight on the central tower to get the desired temperatures in the HTF. For instance, the Ivanpah Solar Electric Generating System in the Mojave Desert in California, which produces 392 MW uses 173,500 heliostats [54]. However, with so many heliostats, the expected lifespan of a CSP system is 30 years [55]. Along with the heliostats and central receiver, a CSP system uses thermal storage equipment, heat exchangers, steam turbines and a generator.

Maintenance

One of the challenges that solar panels face is that power generation is affected by the amount of sunlight hitting the panel surface, the temperatures of the panels, and the angle at which the sunlight is hitting the panel. This means that to get maximum efficiency, the surface of the panels must be kept free of any obstructions such as dust, shadows, and snow. If a system is actively cooled, meaning that fluid is pumped or air is being utilized to transfer heat from the panels, the pumps and fans need to be maintained to keep the same efficiency levels. To aid in the maintenance of the systems, several monitoring techniques have been investigated. One technique is the introduction of remote metering and data logging data that can be observed by the solar grid operator. Another monitoring technique utilizes the symmetrical connecting of panels in strings to compare each string with others in the same location to highlight any strings of panels that are not producing the same electricity as other strings [56].

The maintenance involved with the CSP systems is similar to SPV systems with the use of a monitoring system. The maintenance in CSP systems involves the central receiver, thermal storage units, electricity generation equipment, the control system, and the heliostats [57]. A large part of the maintenance for this system is the heliostats followed by the thermal storage units. In several reports, the heliostats have been noted as either dirty or broken due to weather conditions, age, and generally the environment they are located in. The other item that has been reported as needing to be consistently checked is the thermal energy system these plants have due to the chemicals used in the fluids [58]. The chemicals used in the fluids can cause deterioration in the thermal energy storage that can lead to leakage.

System Summary

To aid in the evaluation of a system, these items should be considered to determine whether solar energy generation should be utilized.

Location Availability

For the location availability, the average solar irradiance of the area should be considered to determine whether the solar irradiance will allow for the rated power production of the system to be reached. What is the area around the installation, and can it be used for solar fields? Is there space available on the installation that can be utilized?

Security

For the physical security of the system, the location of the system is the most important factor to consider. Is the project site easily secured and available for quick responses to physical threats?

For the cyber security of the system, identification of equipment connected to the internet and control mechanisms should be looked at. The quantity of interconnected equipment should also be considered because, much like wind turbines, each point provides a way for the system to be hacked.

Reliability

For the reliability of the system, the expected weather patterns around the base should also be considered. Are there weather patterns that will affect the production of electricity at certain times in the year? What are the expected electrical loads, and do they match the electrical generation? What kind of energy storage can be designed for the system?

Capability

When considering the capability of the system, the most important criteria is that the electrical demand of the base can be met. Can the selected system meet the electrical demand by using a reasonable amount of equipment?

Efficiency

For the efficiency of the system, SPV systems especially, the equipment needs to be looked at for the energy efficiencies given by the manufacturers. How does the change in efficiencies between different panels affect the design of the system with the quantity of equipment needed? Additionally, how does the efficiency of the selected panel type compare to other energy sources being considered?

Constructability

For the constructability of the system, the process of construction should be viewed and evaluated. An item to be considered is the quantity of solar panels or heliostats needed as they can take up vast amounts of land that cannot be utilized for other reasons like wind turbines allow. The location of construction should also be considered if the system will be located on base in areas such as beside the runway and on buildings.

Maintenance

For the maintenance of the system, the expected amount of time to be able to keep the system operational should be evaluated since this system involved a large quantity of solar panels or heliostats. This can also include any weather conditions that might cause the system to be maintained outside of the routine maintenance needed.

Nuclear Power

History

Nuclear energy is not as popular as it was predicted to be when nuclear energy plants were first designed and constructed in the 1950s. Nuclear power was first discovered during World War II and used to create atomic bombs. The first nuclear power plant was designed and constructed in the US in 1957 in Shippingport, Pennsylvania. By the 1970s nuclear power was starting to lose popularity within the US due to cheaper alternatives with natural gas, stricter enforcement that made constructing nuclear power plants more expensive, and several nuclear power plant accidents. In 1979, the core at the nuclear power plant at Three Mile Island partially melted adding to the distrust of nuclear power production. A few years later, in 1986, the core in the nuclear power plant at Chernobyl melted and lead to the deaths of people in the area as well as radioactive contamination. This accident also added to the fears that the US already had with nuclear power plants. As a result of both of these accidents, the US stopped the construction of nuclear power plants. Today we are seeing a growing interest in nuclear Small and Medium Reactors or Small Modular Reactors (SMRs) and micronuclear reactors (MR). The SMR is designed to produce 20 to 300 MW of energy while the micronuclear reactors are designed to produce up to 20 MW of energy. These two nuclear technologies are essentially condensed, safer, more advanced nuclear reactors than their predecessors.

Energy Production Process

As discussed in the history subsection, the rising interest in SMR and MR technology has given way to what could be a valid source of energy for military bases. In this report, both SMRs and MRs will be reviewed and discussed. Both systems have been developed by manufacturers to be modular in nature, allowing for more custom applications to be designed. The nuclear process itself currently relies on nuclear fission where the nucleus of a Uranium-235 atom is bombarded by a neutron. The neutron is able to cause the Uranium atom to split with a release of energy and several neutrons. The neutrons that are free from the fission then collide with other Uranium-235 atoms creating a chain reaction and releasing energy in the form of heat during the process. This process of fission can be seen visually in FIGURE 19. The heat from the fission reaction is then harvested by heat transfer fluid. The most common nuclear reactor in operation today is the Pressurized Water Reactor and as its name suggests, uses pressurized water as the heat transfer fluid. The pressurized water then is used to heat another water circuit through a Boiling Water Reactor. The Boiling Water Reactor is where steam used in a steam turbine is generated. Through operating the steam turbine, the heat energy is converted into electrical energy for distribution. As the process of generating heat does not involve the combustion of elements with carbon, the process itself does not release greenhouse gases but instead releases both solid and liquid waste that needs to be disposed of.

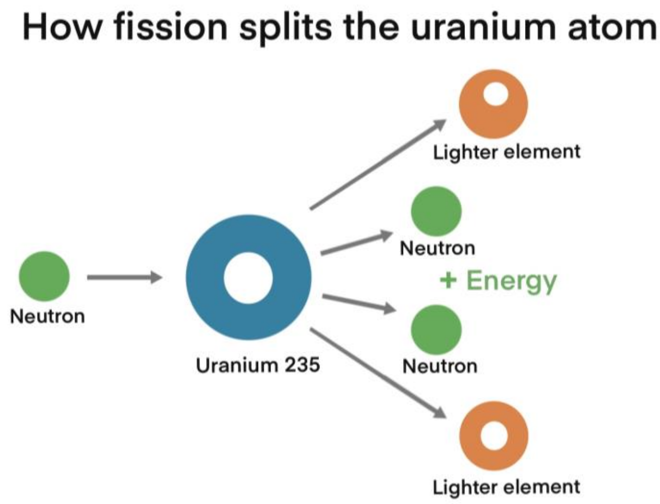


Figure 19 Diagram of the nuclear fission process that generates energy. Referenced from [59]

Location Availability

As both SMRs and MRs are smaller versions of traditional nuclear power plants, they are more ideal for locations that do not have the large electrical demand that justifies building large nuclear power plants. These systems have been designed to be used in areas where a microgrid would be suitable and specifically for areas that are not able to connect to the electrical grid. Promotions for SMRs and MRs suggest that they can be a direct replacement for diesel generators [60].

Since SMRs and MRs do not rely on the location resources like many renewable energy sources, these small power plants can be located anywhere within the US. Some care must be taken when considering how the nuclear power plant may affect the population around it. For instance, some of the main concerns that have been proven in the past is the threat a nuclear meltdown could have, particularly the Chernobyl incident where the space around the once nuclear power plant is no longer able to be lived on. The safety factors of SMRs and MRs have been designed to be better than traditional nuclear power, by incorporating passive safety features that can shut down the plant and allow for more dependable cooling during operation. These improved safety features allow these systems to be located closer to larger populations.

Security

Since SMRs and MRs have been developed to be located in areas that large power plants cannot be placed, the systems have been designed around using limited space. NuScale's SMR is said to need only 0.16 acres which is around 7000 square feet. With the power plant contained within a space of 7000 square feet, it has the potential for being located inside the base perimeter greatly enhancing the physical security of the plant. If located off-base, the smaller size of the power plant will allow for the area to be better monitored as the system is not spread out over a large area like wind turbines and solar panels.

In terms of cybersecurity, the development of passive cooling systems for safety against nuclear meltdowns has led to SMRs and MRs being less dependent on human or programmed shut down measures. This measure of reduced dependency on technology to shut down a plant can boost the security of the system from cyber-attacks. However, controls may still be used for to control the electrical generation of the power plant.

Reliability

As shown in the older nuclear power the US has integrated within the grid already, nuclear power has been proven to be a stable source of energy. When viewing the electricity generation sources from the EIA in FIGURE 20 it can be observed that the nuclear sector is always shown as a constant power source and does not ebb and flow as much as other energy sources. It is modeled this way due to the nature that nuclear power operates constantly. This is largely due to nuclear power not being able to fluctuate with electrical demand as much as other sources but it also shows that nuclear power is reliable and has been proven to be able to run on a 24/7 basis.

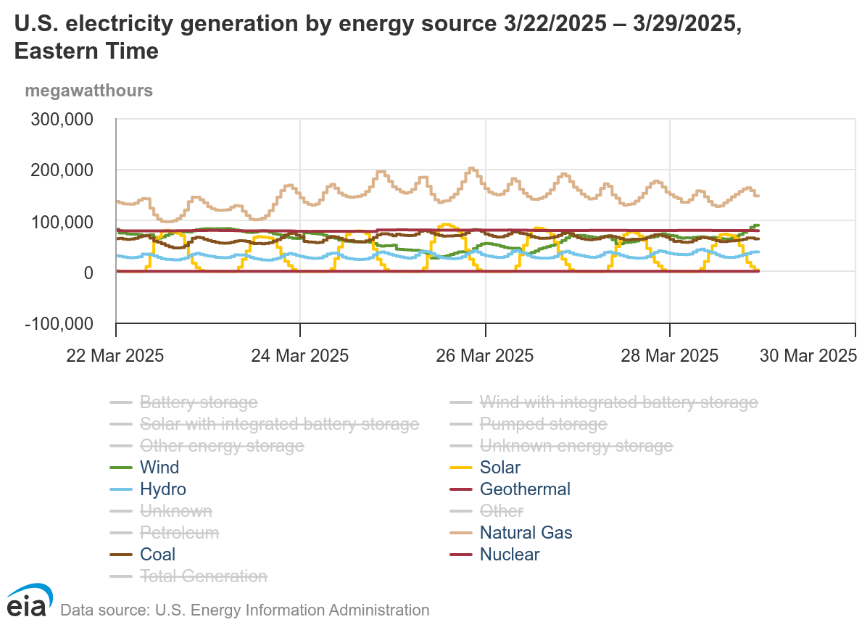


Figure 20 U.S. Electricity generation by energy source from March 22, 2025 to March 29, 2025. Source: U.S. Energy Information Administration (March 2025) [7]

When looking at SMRs and MRs in particular, they carry the same reliability due to the same process of converting heat into electricity. SMRs and MRs have also been designed to be able to fluctuate power output more to better follow the electrical demand like the existing grid does. However, as of yet, no SMR plants are currently in operation on a commercial scale, so the reliability of these plants is still untested in the United States mainly due to the long process of getting a design approved by the US Nuclear Regulatory Commission (NRC). Likewise, MRs are in the earliest phases of development and as such have not been assessed in commercial markets yet.

Capability

Since both SMRs and MRs are designed to be modular in nature, the capability of the systems are based on how many modules are designed for. NuScale, an SMR manufacturer has developed modules that produce up to 77 MW each and allow up to 12 modules to be connected, known as VOYGR-12, allowing for a combined output of 924 MW of electrical output which is similar in output to a traditional large nuclear power plant [61]. This nuclear SMR has been the only SMR design to have been certified by the NRC on July 29, 2022.

Since MRs are even earlier in development than SMRs, they are further from being certified and constructed. However, a common electrical generation unit manufacturer, known as Westinghouse, has received funds and has started to design an MR known as the eVinci Microreactor. The development of eVinci is based on the design goal to create a highly mobile nuclear reactor. With this as Westinghouse's goal, the eVinci has been designed to fit on the trailer of a semitruck [62]. To aid in the size of the reactor, a heat transfer process utilizing an in-house developed heat pipe eliminates the need for coolant within the system. Its small design is also made more possible to achieve with the expectation that the MR is expected to produce up to 5 MW of electricity.

Efficiency

As nuclear reactors generate electricity through the Rankine cycle shown in FIGURE 21, similar to coal, they have an expected energy efficiency of 35%. Part of the energy efficiency related to nuclear power is that in the process of producing electricity, water has typically been used as a heat transfer fluid. The newer generations of SMRs that are in development are starting to incorporate different methods of heat transfer. Some of these heat transfer methods were studied when nuclear energy was just starting to become popular in the 1960s but were scrapped at the time due to limited technology. These new systems utilize sodium in sodium-cooled fast neutron reactors (SFRs), lead in lead-cooled fast reactors (LFRs), molten salt in molten salt reactors (MSRs), and high temperature gas in high temperature gas reactors (HTGRs) [63].

Developing SMRs with these newer technologies allows for more heat to be extracted from nuclear fission and potentially boosting the overall energy efficiency of the system to an efficiency between 40 and 50%.

Other approaches to SMR and MR design that could increase efficiency has led to cogeneration methods, using systems for both electricity production and heat production. The expected energy efficiency increases from 35% to a high 80% due to the reclaimed heat.

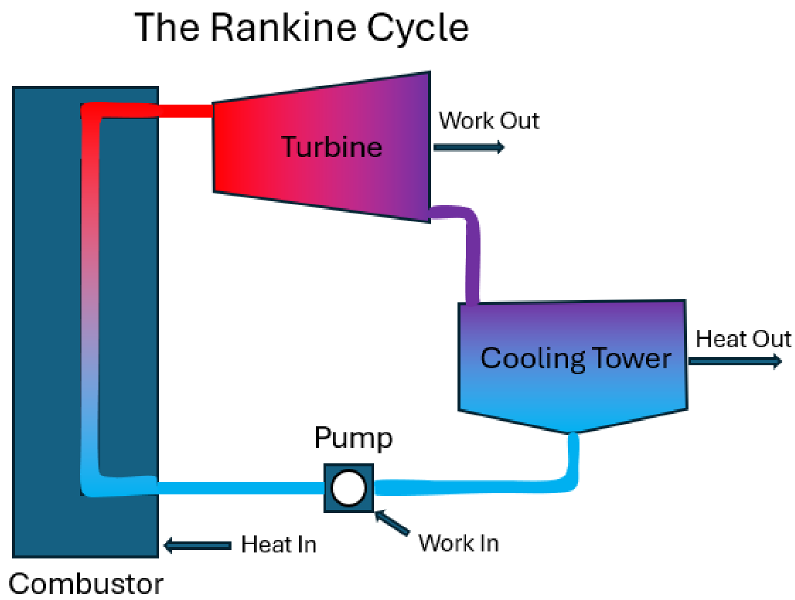


Figure 21 Process of the Rankine Cycle showing essential equipment, inputs and outputs. Referenced from [64]

Constructability

Due to the technology and regulations surrounding nuclear reactors, the design of even the SMR and MR projects is estimated to take from 5 to 10 years [65]. Part of this expected time is due to the United States needing to develop regulations around SMRs in general. Some of the process of establishing regulations around SMRs have already been developed through certifying NuScale's VOYGR SMR discussed in the capability's subsection [66]. In fact, now that the first nuclear SMR has been certified by the NRC, the time associated with certifying SMRs and MRs is expected to decrease. The NRC is responsible for permits required for the design and construction of nuclear power plants. They issue Early Site permits that last for 10 to 20 years and Combined Licenses that allow for the construction and operation of a nuclear power plant for 40 years [67].

To aid in the reduction of the expected time until operation, SMRs and MRs have both been designed to be manufactured in a factory [68]. By being produced in a factory, SMRs and

MRs are expected to be quickly constructed since there is not as much construction on-site. NuScale's VOYGR plant is expected to have an estimated 700 tons of shipped material with a boasted estimated construction time of 3 years instead of the previously projected 5 to 10 years [69]. However, as stated before, NuScale remains untested currently but will be tested in recent contracts to construct VOYGR-12 plants in Ohio and Pennsylvania with expected start dates in 2026 and first electrical generation date in 2029 [70].

Maintenance

One of the main concerns for nuclear power is the technical skill needed to ensure it is maintained properly to avoid the catastrophes seen in history. However, some of this is addressed by the fact that the United States Navy utilizes nuclear reactors in both nuclear-powered submarines and nuclear-powered aircraft carriers [71]. Also addressing some concerns related to large nuclear power plants in the past, SMRs and MRs have been designed with passive cooling features that rely on natural circulation, convection, gravity, and self-pressurization rather than human intervention to shut down in emergency situations.

The other large concern for SMR and MR technology is the nuclear waste that needs to be disposed of safely afterward. One report on SMRs in general showed that SMRs can actually produce 40% more waste than other nuclear reactors [72]. This can be a concern because ethe nuclear waste needs to be properly disposed of or stored to avoid negative environmental impacts. However, an advantage of using SMRs is the expected infrequent refueling they require. In the development of SMRs, the typical refueling frequency is every 3 to 7 years. It has also been reported that some SMR manufacturers, aiming towards off-grid clients, claim to be able to meet electric load demands for 30 years without refueling.

System Summary

Location Availability

For the location availability, what type of system is being designed for and what are the space requirements of that system? What are the risks associated with the occupants living around the military base?

Security

For the security of the system, the main determinant for physical security is whether the system can be located on base? If the system cannot be located on base, how close will the electrical generation plant be?

For the cybersecurity of this system, what control measures are utilized to ensure safe operations and the threats associated with any remote connections should be evaluated.

Reliability

For the reliability of the system, the main issue around nuclear energy is the lack of redundancy. Even with being designed to be modular, the large electrical capacity of a single module may cause the system to be oversized even when considering future growth. When determining reliability, how will the lack of redundancy be compensated for?

Capability

For the capability rating, how will the electrical load be met by nuclear energy? How many modules will be needed to meet the electrical demand?

Efficiency

For the efficiency of the system, how energy efficiency affects the design of the system should be evaluated. Is there wasted energy that could be reused? Does the efficiency of the system require more refueling than another system by causing more resources to be used.

Constructability

For the constructability of the system, what are some of the lead times for equipment since nuclear energy uses more specialty equipment? How long does the construction process take and what kind of permits are needed to be able to construct and operate the system?

Maintenance

For the maintenance, the main concern is the technical expertise required. To aid in this category, are there specialized companies or are there already experienced individuals within the maintenance squadron that can aid in the maintenance of the system? Since nuclear energy has different refueling expectations, these should also be looked at to determine how dependent the system is on being refueled.

Enhanced Geothermal

History

Enhanced Geothermal Systems started as what is known as the Hot Dry Rock (HDR) concept of geothermal systems. This concept was studied in the mid-1970's by the Los Alamos National Laboratory. Upon a successful trial in which 10 MW of thermal capacity was produced from the site, other research laboratories began to design and study these HDR systems. Since then, the improvement of technology has allowed these HDR systems to develop into today's Enhanced Geothermal Systems (EGS). Following the improvement of technology, in May 2013, the Geodynamics plant in Australia opened as the first private commercial EGS plant that has been used for large-scale energy production. This project was considered a success as it resulted in a 1MW plant. Another form of enhanced geothermal systems involves using sealed wells and pipes essentially creating a loop, giving this type of system the classification of CLG system. The use of a CLG avoids issues associated with EGS involving the complexity of artificially fracturing rock in order to create adequate flow through the tight rock formations and decrease any fluid loss.

Energy Production Process

EGS are based on traditional geothermal systems in that it uses the heat in Earth's crust to heat water. However, unlike traditional geothermal systems, enhanced geothermal systems have been designed around hot, low-permeable rocks that must be artificially fractured to create pathways where water can flow through. Due to the advancement of technology to create fractures in low-permeable areas, EGS are able to be designed and used in a greater number of locations that would not be ideal for a traditional geothermal. However, due to concerns around seismic risks, CLG systems are preferred in areas where EGS systems are being considered [73]. As CLG systems are a form of EGS, they both follow the same process of converting heat from Earth's crust into electricity. In both processes, a hole is drilled into the Earth anywhere from 2 kilometers to 5 kilometers deep. In CLG systems, a pipe is inserted into the vertical well, installed in a horizontal configuration at a certain depth and returns to Earth's surface through the same or another well. In both the CLG and EGS the bore that is used to inject fluid into the system is the inlet well and the bore that is used to extract the fluid is the production well. Unlike the normal EGS, CLG systems do not face the issue of losing fluid and so they are easier to scale up when needed. When the fluid returns in the production well, it can be used to create steam to generate electricity through the use of steam turbines in different configurations shown in FIGURE 22.

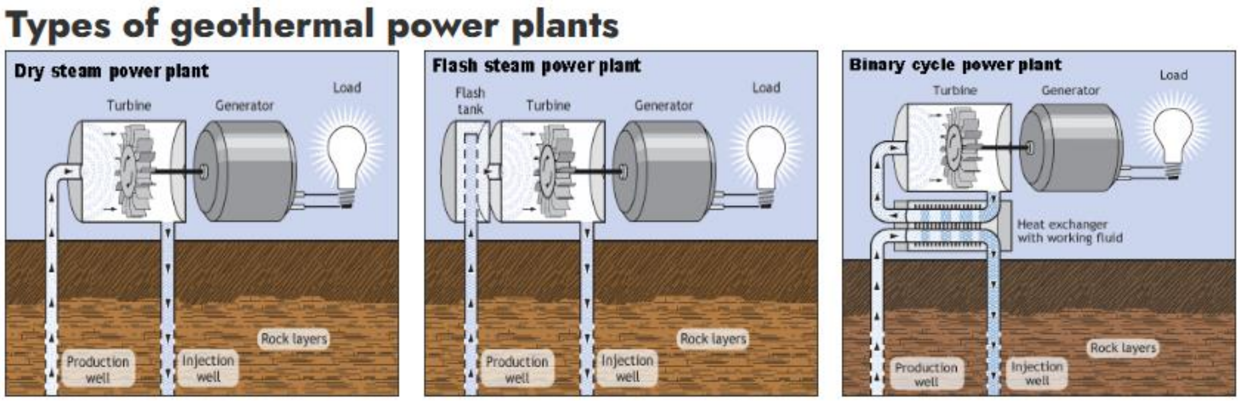


Figure 22 The processes of different steam turbines. Source: U.S. Energy Information Administration (March 2025) [74]

Location Availability

As discussed in this section, enhanced geothermal systems can be utilized in more locations around the globe than traditional geothermal systems that rely on high-permeable rock. In fact, due to the nature of enhanced geothermal systems, as long as there is heat in the core, the EGS can be located anywhere. With that being said, some locations could be more desirable than others depending on how deep a site will need to be drilled to reach desirable temperatures. When considering the systems that have been designed up until now, most wells drilled for EGS are up to 5 km deep. As with most of the renewable energy sources discussed so far, wind and solar, the NREL also provides an informative map that rates locations on how well enhanced geothermal systems are expected to perform. This map is shown in FIGURE 23.

Although the Earth's crust contains heat that can be utilized in many locations, FIGURE 23 shows the areas where the heat is predicted to be closer to the surface allowing for more shallow drilling. There have been studies that show that the mean temperature difference in Earth's crust is 25 to 30°C per kilometer. In areas estimated to have higher temperatures closer to Earth's surface, where CLG systems are highly recommended, the temperature gradient is predicted to be 70°C per kilometer. Between the two temperature gradients are places that could benefit from CLG systems due to a temperature gradient of 50°C [75]. Many locations could use CLG systems but as the heat of the Earth is farther from the surface, deeper bores must be performed to use the thermal energy.

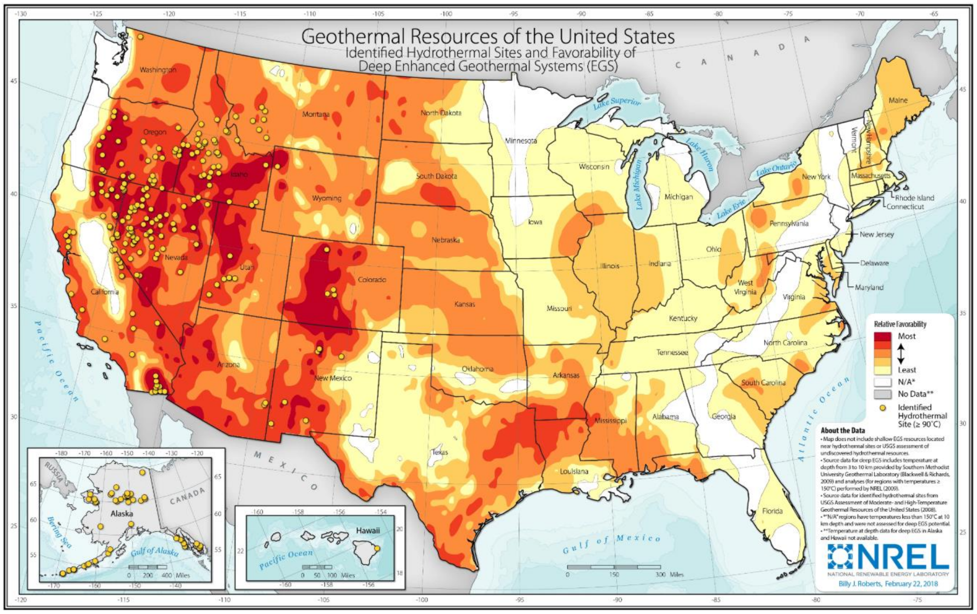


Figure 23 Map of enhanced geothermal systems potential in the US. Source: National Renewable Energy Laboratory [76]

Security

Physical security of EGS depends on what type of system is selected for the site. If a U-Loop configuration is chosen, then both the inlet and production wells need to be secured as well as the distance between them. If the inlet and production well are the same, then the physical security of the system becomes easier. In both cases, the actual area needed to be secured is smaller than the actual size of the system due to a large portion being underground where it cannot be harmed.

One of the main companies investing in CLG systems is a Canadian company known as Eavor-Loop. Eavor-Loop has already developed a system to be used as an example of how projects can use a CLG system. With the primary energy source being heat from the Earth and the medium being a fluid moved with a pump, a CLG system can be operated without connection to anything outside of the system. Without this connection to the outside world, this CLG system is safe from being compromised by cyber-attacks [77]. Some EGS do have monitoring and controls that rely on the internet that could allow them to be hacked.

Reliability

As geothermal energy is available at all times of the year and is not dependent on the weather, EGS and CLG systems can be expected to be able to always produce energy, making it a very reliable resource. In fact, when the NREL evaluated a CLG system, the capacity factor used in the report was 0.95, indicating that the system is expected to produce electricity for 95%

of the year. In the case of CLG systems, the closed loop system allows for redundancy in that there can be multiple runs of pipe in the ground. Because of the system not being dependent on fuel, there is also less risk of being affected by weather patterns that disrupt the fuel supply chain. Overall, these different factors come into play with many reports being around a potential hybrid system using wind or energy to fulfill part of the load but, with EGS supplying the base load for the system and being there when wind or solar is not available [78]. With that being said, it is important to acknowledge that the system can still require repairs to equipment such as turbines, pumps, heat exchangers and the pipes that contain the fluid being injected into the Earth [79].

Capability

As CLG systems have not been designed for a commercial sector, there are no commercial projects to draw energy capability from. Several case studies have been performed to estimate the actual capability of a system. In a case study, 10 laterals were designed with a vertical bore 3 kilometers deep and a horizontal bore of 4 kilometers, resulting in a 10-kilometer U-loop underground. With a temperature of 150°C, this theoretical model was discovered to produce 9 to 11 MW of heat over 30 years [73]. In a project outlook for the Netherlands, an Eavor-Loop design was predicted to have a capacity of 13 MW in the winter and 9 MW in the winter [80]. Even though the values given in the report are the capacity of the system, it confirms with other case studies that these systems can be capable of supplying electrical loads of around 10 MW. A different report showed that to increase the capacity of a system, multiple wells should be designed for. To ensure the wells do not interfere with each other, studies have shown and recommend using a spacing of 75 meters between each lateral well [73].

Efficiency

Depending on the medium being used for heat transfer, the temperature of the wells decrease over time, thus decreasing the overall energy efficiency of the plant. To aid in maintaining energy efficiency of the plants, the use of CO_2 instead of water in both EGS and CLG systems has been investigated. In EGS, the advantage of using CO_2 would be that unlike water, it would not cause short circulation by opening new pathways through the rocks or clog other passageways due to chemical reactions [75].

To further improve the efficiency of EGS and CLG systems, different fluids can also be utilized in the Organic Rankine Cycle (ORC). An example of this can be seen in the NREL's test of the Eavor-Loop system. The report shows the usage of propane, butane, and isobutane in the

Rankine Cycle to see which performed the best with the CLG system. In the study, it was found that the net efficiency of the power plant ranged from 10.3% with propane to 18.9% with isobutane [81].

Constructability

With today's technology, the wells that are drilled for the use of CLG systems are expected to remain in operation from 20-40 years. However, the drilling of the wells can also take a large portion of the construction time. In a report by the NREL, the drilling rate of 40 feet per hour needs to be reached in order to cut the on-site construction time significantly. It also noted that conventional geothermal well drilling has achieved 40 feet per hour and another drilling project reached 50 feet per hour showing that it is possible.

Some other equipment that is used in an EGS to produce electricity is a heat exchanger, turbine, and a pump with piping in between each of those systems. The heat exchanger is used to exchange the heat from the fluid used to capture the heat from Earth to a water loop that is used to generate steam. The turbine is used to convert the energy into electricity through the rotation of its blades. The pumps are used to move the working fluid throughout the ORC.

The permitting process for EGS and CLG systems involves permits from the local and state government primarily but also has several permits that are controlled by the Bureau of Land Management [82].

Maintenance

Since EGS utilize underground lines, there is limited maintenance when compared to other systems. When NREL studied the Eavor-Loop, they assumed that once the pipe is in the ground it will not need to be maintained. The main components that will need to be maintained in this system are the equipment above ground like the pumps, heat exchangers, and the turbine as well as any pipes above ground.

As this system relies on the ability to pump water, this system doesn't rely on refills of fuel. This means that unless there is a leak in the system, once the system is installed there should be no concerns about the production of energy unless equipment fails. In fact, Eavor claims, and the NREL has verified, that their system does not need a pump due to the thermosiphon effect where hot liquid rises to Earth's surface while cooler liquids flow down to be heated. The NREL also noted that maintenance was minimal due to using pure water as a HTF so there is less cleaning in the heat exchanger or of the surface pipe. However, if using EGS that are not CLG systems, there is cleaning involved due to the addition of minerals and dirt in the water that is pumped up from the reservoir.

System Summary

Location Availability

For the location availability of EGS and CLG systems, the map showing the feasibility of locations can be used. However, even when the map is used, there should be tests performed to ensure that the location is suitable for geothermal sources electricity production.

Security

For the security of the system, even though most of the system is underground, the locations of the electricity generation plant, production well and the inlet well should be secured physically. If the system is located outside of the base perimeter, how are the identified locations secured?

For the cyber security of the system, the controls and how they affect the system should be evaluated. Are any of the control processes based on an internet connection?

Reliability

For the reliability of the system, EGS and CLG systems are considered reliable, how many additional energy generation units should be in the system to ensure the system is redundant?

Capability

For the capability of the system, what additional steps will need to be taken to ensure that the electrical demand is met. As these systems could be harder to add to, does the system have enough electrical generation to accommodate future electrical loads?

Efficiency

For the energy efficiency of the system, how does it compare to other sources being evaluated? Are there ways to increase the efficiency of the system through different HTF?

Constructability

For the constructability of the system, how is the drilling going to be performed and how long will it be expected to take? Do the site conditions show that the drilling process will be able to maintain a planned schedule or is it more dense and harder rock layers?

Maintenance

For the maintenance of the system, although these systems are expected to have little maintenance, is the other equipment selected for electricity generation expected to have maintenance similar to other sources?

Hydropower

History

Hydropower itself has been used for many purposes, much like wind, with some of the earliest technology being utilized by the Greeks as mills and other machinery [83]. The first hydropower dam used to create electrical energy was built around 1880 in the US. The technology to convert potential energy into electrical energy took some time to catch on, with the majority of dams within the US were built between 1920 and 1970 [84]. Construction of dams for electrical power generation started to slow down in 1970 due to the lack of locations that would be worth the time and money to build a dam. Dams also started to lose popularity during this time due to the environmental concerns around how they affected the river ecosystem. Since 2006, the removal of dams within the US started to occur and has continued with a report in 2018 finding that 60 dams per year were being removed due to environmental concerns, maintenance costs, and the decaying structural integrity. As a result of the loss of power generation of dams, alternative solutions and more restrictive policies have been looked at to make hydropower a viable power generation option once again. The main generator that is growing in popularity due to its ability to harvest energy as long as there is a 1 m/s flowrate and its environmental friendliness is the instream generator. Several companies have already developed and tested prototypes for this hydrokinetic (HK) technology. The findings of this report will mainly focus on the hydrokinetic generators rather than hydropower that relies on potential energy. The reason for this is due to the decline in popularity for potential energy that requires dams and the rise in popularity in hydrokinetic sources.

Energy Production Process

The type of hydropower influences how the energy is harvested from the water. Traditional hydropower with dams use potential energy based on the height of head. The equation to determine the amount of power produced by a hydropower generator is shown as:

$$P = 9.81 \times Q \times H \times \eta$$

Where P is the power generated in kW, Q is the discharge in m^3/s, H is the head in meters, and η is the efficiency of the generator. As you can see in this equation, the power generation of the generator relies on the feet of head and the discharge of the water [85]. This means that in order to generate more power, taller structures would need to be built. This equation also shows how reliant these systems are on the storage of water for larger dams in order to get the maximum pressure for discharge. In dry months, the systems that require large amounts of water storage will not be as effective.

The equation for the kinetic energy does not use the height but rather is calculated using the velocity of the stream as shown in the following equation:

$$P = \frac{1}{2} \times \rho \times A \times V^3 \times C_p$$

Where P is the power output in Watts, ρ is the fluid density in kg/m^3, A is the area swept by the turbine in m^2, V is the fluid velocity in m/s, and C_p is the power coefficient of the turbine. As shown in the equation for the hydrokinetic power, the main factor that affects the power output is the velocity of the stream. In this case, as long as the stream velocity is above 1 m/s, the turbine will produce energy. In imperial measurement terms, assuming that the measurement is taken in a cubic meter of water to achieve the discharge rate, it can be calculated that water must flow at 35.3 ft^3/s. Several models that are currently in production range from producing 130W up to 40 kW.

Location Availability

As this technology relies on water as the medium that carries energy, it can only be located in channels of water. Although not all encompassing, a map of rivers throughout the US is shown in FIGURE 24 showing that there are potential spots for hydropower throughout the US. To locate the best areas to place HK turbines, the stream must be carefully studied to ensure that adequate velocity can be achieved. An adequate velocity as mentioned above is 1 m/s or 3 ft/s. At this velocity, the hydrogenators can produce electricity as seen in the equation. To increase the velocity within a stream the cross area of the stream can be decreased. The stream must also be studied to ensure that the placement of an HK turbine would not negatively affect the stream by causing flooding, silting and scouring. To help avoid these negative effects, it has been suggested that the best use of HK turbines is in canals.

Figure 24 Map showing the major waterways throughout the US. [86]

For hydropower that relies on the potential energy of water by building a dam, a site should be chosen that allows for a large reservoir of water to be stored on the upstream side of the dam. The environment around the dam should also be evaluated to determine the negative effects a dam might have on the area [87]. One of the main negative effects from dams can be blocking the river and causing migratory fish from reaching their spawning grounds. Another negative effect from these systems is that the large reservoir can endanger both natural habitats as well as handmade establishments through flooding. In terms of constructing dams on rivers, it is important to determine everything on the downstream side of the dam that is at risk in case the dam experiences failure.

Security

Due to their unique location requirement of being located on bodies of water, these systems' physical security is dependent on how close streams or rivers are to military bases. Any river with adequate space to build a dam or with sufficient velocity on base would be ideal for this system. Dams themselves would be generally harder to disrupt power efficiencies unless high damage weapons were involved. Since the generators and turbines are housed within the dam, there are safety measures in place to ensure that they are not tampered with.

However, even though the turbines are physically secure, the integration of technology has led to an increasing threat from cyber-attacks. A report in 2023 by the NREL noted that, since 2003, over 40 cyber-attacks have been focused on disrupting hydropower plants [88]. The range of cyber-attacks can be from just blocking sensors or overloading channels to controlling the system to cause damage to it. There have been many studies recently on the cybersecurity side of electrical infrastructure with many reports acknowledging that the threat of cyber-attacks on the grid and hydropower plants are relevant in today's age of remote connections.

Reliability

Although water is less variable than wind and sun on a daily basis, it can still be variable based on the season [89]. In fact this seasonal output can be seen when looking at the typical capacity factors, which is the amount of times hydropower is expected to be utilized throughout the year. Data collected from the EIA shows capacity factors from 2015 to 2017 of all the hydropower in the US shown in TABLE 5. The data shows that although hydropower does not vary much on a daily basis, the seasonal variations add up and, as seen in TABLE 5, the production of power was less than half of what it could have been.

Table 5 Capacity factors of hydropower from 2015 to 2017. Referenced from [90]

Year	Capacity Factor
2015	36%
2016	37%
2017	45%

Capability

The power outputs of hydropower from traditional dams has long been recorded due to the age of dams within the US. In the US, a total of 65% of dams produce 0.1 to 10 MW, while 2% of the dams produce more than 500 MW. The other 33% of the dams generate 10-500 MW. Since hydrokinetic generators use kinetic rather than potential energy, they are not able to produce as much power. This is also the case because they rely heavily on the velocity of the stream or river they are located in. Most of the hydrokinetic generators are rated to produce anywhere from 100 W with a 1 m/s flow up to 40 kW with a 3 m/s flow [91]. Some notable manufacturers that have designed and evaluated hydrokinetic turbines are New Energy Corporation and Ocean Renewable Power Company (ORPC). New Energy Corporation has developed vertical axis turbines to be used within a river that have electrical outputs of 25 kW and 50 kW [92]. New Energy Corporation also makes a 250-kW turbine but due to its depth requirement of fifteen feet, may not be suitable for river deployment. ORPC on the other hand, has developed a vertical axis style turbine but have rotated it to allow for shallow river use. This system is rated for 35 kW and has been used in Alaska to power a village since July 2019 [93].

Efficiency

Generators used within the traditional dams have high energy efficiencies depending on the type of turbine used. The main turbine used for large river projects with a height difference of 300 to 400 meters, known as the Pelton turbine, typically has an efficiency between 85 to 95%. The Francis turbine, used in dams that have a moderate height difference of 100 to 300 meters, generally have an energy efficiency of 90 to 95%. The Kaplan turbine, used for dams with a height difference of less than 100 meters has a high efficiency range of 90 to 93% [94].

Much like wind turbines that rely on kinetic energy to generate electricity, hydrokinetic generators also rely on kinetic energy. This dependency on kinetic energy gives these systems a maximum energy efficiency of 59% [95]. However, in some cases with small yet high velocity waterways, the turbine can create a height difference between the upstream and downstream levels leading to the test showing a coefficient of performance over 1, indicating that potential energy was utilized to some extent.

Constructability

As conventional hydropower relies on the design and construction of a dam, the design and construction of the system can take, on average, 5 to 8 years. Some of this time, like nuclear power, is used in getting permits. Construction usually requires the use of more heavy machinery than many other renewable energy sources because of the earthwork required to ensure the dam remains functional. However, the durable materials, such as using earthwork and concrete, used in the construction process allows dams to have a long-life expectancy of 100 years. As discussed in the history subsection, some of the hydropower dams producing energy for the grid today have been operating since the 1970s.

Hydrokinetic systems, on the other hand, can be deployed rather swiftly due to the ability to manufacture turbines offsite. However, the process of deploying units can still take a considerable amount of time as a preliminary permit must be obtained first to conduct site research. The preliminary permits can be issued for 4 years. When considering hydropower, it is important to note that the main enforcement and permitting agency is FERC. This is important because it shows that unlike some other energy sources, permitting is done at a federal level [96].

Maintenance

The type of hydropower used can heavily influence the amount of maintenance needed for the system. Traditional hydropower using dams are very important to maintain due to the amount of damage they can cause if they fail. The dam itself is under constant stress from the water pressure and so the structural integrity of the dam must be evaluated and maintained. In fact, a report from 2019 found that 64% of dam failures are due to structural deficiencies such as foundation defects, slope instability, hydraulic failures, inadequate spillway design, debris blockages, and the settlement of the dam over time [97]. FERC has classified dam safety as one of its top priorities and as such conducts regular inspections that consist of informal inspections, formal inspections every 5 years, and special inspections after unusual events such as large amounts of flooding or earthquakes [96].

Hydrokinetic power on the other hand requires less maintenance and comes with less risk to the public. These generators still need to be checked for debris to ensure they do not get blocked. However, the companies that manufacture these systems have created systems that can be easily brought out of the river to allow for maintenance to occur through the usage of buoyant systems.

As neither the dams nor hydrokinetic turbines use refueling methods, both systems only have to worry about the production of energy during the specific dry seasons discussed in the reliability subsection.

System Summary

Location Availability

For hydropower, the location availability is different than many other systems in that it has to be located in water. In this case, are there rivers in the area with ideal flow conditions that could lead to the rated power of turbines being met? Are there locations where a dam can be built?

Security

For the security of the system, how will physical security be implemented in the operation of the plant, especially hydrokinetic turbines to ensure they are not in threat of anyone on the river?

For cybersecurity, what pieces of equipment are operated with remote connections that can be hacked?

Reliability

For the reliability of the system, is the area supposed to have consistent rainfall from year to year that would allow for the year-round use of hydropower? Does the design of the system incorporate redundancy in the quantity of units or will it need to be addressed in another part of the design? Are there measures to ensure power can be supplied to the base in dry spells?

Capability

For the capability of the system, can the electrical demand of the installation be met with the design and power rating of the turbines selected? If using turbines in dams, how will the system address increased electrical demands in the future?

Efficiency

For the efficiency of the system, what are the efficiencies identified for the turbines selected? In the case of hydrokinetic turbines, does the energy efficiency create the need to design for more turbines to be used?

Constructability

For the constructability of the system, which process is more suitable in the location as it will greatly affect the construction times? In the case of electricity production from dams, what is the expected construction time of the dam itself? In both cases, how long is the expected permit process?

Maintenance

The maintenance category also depends on the type of hydropower selected. If building a dam, what is the expected amount of time the regular structural inspections will take throughout the year that may draw maintenance staff away from other areas? If a hydrokinetic system is designed, the manufacturer of the turbines added items to allow for easy maintenance of the system.

Hydrogen Fuel Cells

History

The potential for hydrogen fuel cells was first realized in the 1800's through the work of Anthony Carlisle and William Nicholson who experimented with the process now known as electrolysis to split water molecules into hydrogen and oxygen. This idea was later expanded on through the work of Michael Faraday and Willim Grove by describing the Laws of Electrolysis and the creation of the first fuel cell. At this point in time the fuel cell was largely an experiment rather than used in actual industry, but then Francis Bacon developed the alkali electrolyte fuel cell in the 1930's. Through the work he did, Francis Bacon was able to demonstrate the potential of the alkali fuel cell for Britain's National Development Corporation and received a contract allowing these types of fuel cells to be used on Apollo spacecraft.

Since then, many different fuel cell technologies have emerged. The different technologies have led to a classification of fuel cells based on the electrolyte used. These different fuel cells all have different qualities that make them beneficial in a variety of power application scenarios. In the power industry, the usage of Solid Oxide Fuel Cells (SOFC) is used for large buildings, Phosphoric Acid Fuel Cells (PAFC) are used for high energy demand situations like hospitals and schools, and Molten Carbonate Fuel Cells (MCFC) for providing primary and back-up power to utilities and businesses [98]. All these technologies are used over other fuel cell types due to their ability to handle fuel impurities and their ability to function at high temperatures. In this report, all three types of fuel cells will be discussed in general because they utilize the same process to create electricity and have similar load capabilities.

Energy Production Process

When discussing fuel cells, it is important to note that hydrogen itself is not classified as an energy source, meaning that it cannot produce energy by itself. Instead, hydrogen is considered an energy carrier like gasoline and electricity. The advantage of using hydrogen within a fuel cell is that hydrogen is an abundant resource and can be produced using different processes. This means that hydrogen fuel cells can only be described as low-carbon if the process of storing the energy in hydrogen is a low-carbon energy source. In most locations in the US, fuel cells can be connected to the natural gas which is then reformed into the hydrogen due to high operational temperatures. Hydrogen fuel cells can connect to natural gas either using a fuel processor or by operating at temperatures high enough to reform the natural gas. Both the SOFC and MCFC operate at temperatures that reform natural gas into the hydrogen needed .

Fuel cells are best described as a battery that uses hydrogen and an oxidant to produce electricity and heat through a chemical reaction. In this process, hydrogen is introduced on one side of the system while oxygen enters on the other side of the system. The electrons then break free of the hydrogen atom allowing hydrogen, now with a positive charge and alternatively known as a proton, to pass through the membrane. The electrons cannot go through the membrane but instead flow through the circuit creating a current, and in turn, electricity. Once the electrons make it to the cathode side, they combine oxygen and the protons, creating heat and water. This process can be seen in FIGURE 25. As seen by the diverse types of fuel cells that have emerged, the main factor in the fuel cell that affects output is the catalyst that is chosen within the fuel cell. Despite the catalyst used, the output of a fuel cell is an electrical current, water, and heat which makes it available as a low-carbon source if the process for producing the hydrogen is low-carbon as well.

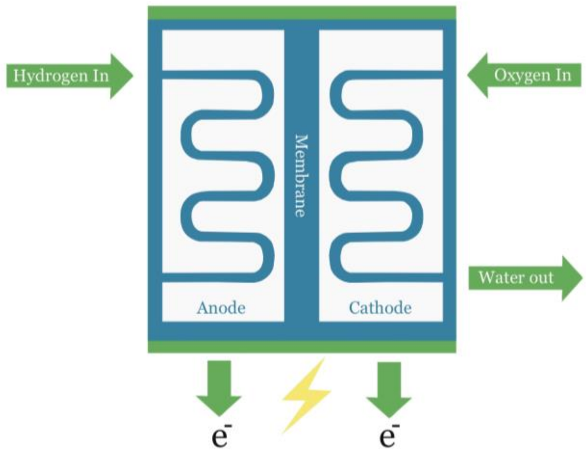


Figure 25 A diagram of the fuel cell process to create electricity. Referenced from [98]

Location Availability

As fuel cells are similar to batteries and generators, they can be used in many different locations. In fact, due to their size and low emissions, hydrogen fuel cells can be located both indoors and outdoors. Relatively small, an estimation for the amount of power through land usage can be 10 MW of power on a 1-acre plot. The limiting factor that affects the locations of fuel cells is the ability to supply enough hydrogen to keep the fuel cell running. As discussed in the energy production process, the ability to connect to natural gas infrastructure using equipment that processes natural gas into hydrogen allows for these systems to be located in most cities. The natural gas pipeline, shown in FIGURE 26, is similar to the electrical grid in that it is an interconnected system of pipelines to help distribute natural gas across the US.

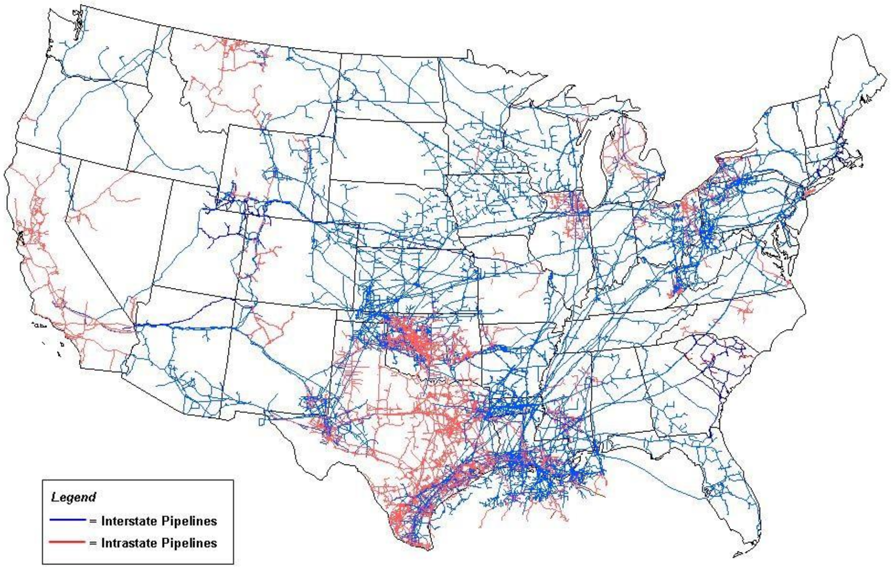


Figure 26 Natural Gas Pipeline across the US. Source: U.S. Energy Information Administration (2009) [99]

Security

In terms of physical security, fuel cells range in size based on their power rating but using the 10 MW per acre estimation seen under the land availability subsection, this system could be located within the perimeter of a base. Knowing this, it can be determined that fuel cells can be secured physically with relative ease. On the cyber side, these systems have options to be controlled remotely to allow for more convenient controls for operators but can create an avenue in which a cyber-attack could occur.

Reliability

Due to the nature of fuel cells, they can be considered as a highly reliable source of electricity. This is because, unlike many other power generation sources, the process of generating electricity is done with very few moving parts. The elimination of these moving parts has the effect of reducing wear and tear within the fuel cell that could cause system failures. Due to the limited amount of wear and tear during operation, these systems do not require as much maintenance as other systems. In fact, in studies performed by the NREL, fuel cells showed that they were 99.5% reliable [100].

Fuel cells can also be considered reliable because of their redundancy in part due to their modularity. This allows for maintenance to be performed without shutting down the entire system. Having multiple units can also help keep the system online if a unit failure is experienced.

Fuel cells have followed the trend that many electrical companies are seeing in that they encourage the growth of microgrids. Due to their power output, it is possible to power different electrical loads from a single household up to a community. This goal of converting to a microgrid system can greatly enhance the reliability of the electrical system in that there are many more generation sources that are able to take over the load if the national power grid fails.

However, it should be considered that fuel cells rely on hydrogen as a fuel source and as such, could potentially be dependent on deliveries if natural gas was not present or onsite hydrogen production was not available. Fortunately, natural gas pipelines are buried so they are harder to affect than the electrical grid.

With the high reliability of fuel cells being realized by many entities, the Department of Defense has already started to switch emergency generators over to their fuel cells in 43 states following the destruction left in the wake of Hurricane Sandy in 2012 [101].

Capability

Much like other renewable technologies being considered in this report, multiple fuel cells can be used together in order to increase the capacity of the system. Due to this feature, a various range of loads can be met with the relative ease of adding more units based on the power rating of the fuel cell selected. Each individual fuel cell can range from a power rating of a few watts up to 3 MW. This range can be attractive for the selection of units.

One fuel cell manufacturing company produces a 2.8 MW unit that takes up an area of 53 feet by 70 feet or 3710 square feet [102]. Besides this option, there are also smaller types of fuel cells that are designed to power single buildings that are modular as well with one common rating being 5 kW.

Efficiency

Hydrogen fuel cells are advantageous over systems that use gasoline due to the fuel cell's high efficiency at part-load and peak load conditions. The typical fuel cell system has been shown to operate at 50-60% efficiency while a hydrogen combustion generator has an efficiency of 20-25% [103]. The high energy efficiency of fuel cells are due to the electrochemical process used to generate electricity. Since the process does not use moving parts, there are fewer mechanical losses through equipment. The fuel cell does not rely on the Rankine cycle either so less thermal energy is lost through the conversion process.

Like other sources in this report, a benefit of utilizing fuel cells is the ability to reclaim heat generated in the electrical generation process. Reports show that if a Combined Heat and Power (CHP) system is utilized, the energy efficiency can reach as high as 95%. However, this efficiency value will not be used in the ratings so that the efficiency rating use the same efficiency parameters. Another reason that the CHP efficiency value will not be utilized is that it is assumed that locations that are swapping over to on-site energy production have heating systems already installed.

Constructability

The modular nature of fuel cells allow them to be manufactured in factories. The manufacturing process can speed up the construction process while ensuring that the system is designed correctly. This can speed up the process because it means that construction of the site can occur before the units arrive or are even fully complete.

Another advantage of manufacturing fuel cells is that it can increase quality. The design and construction of the fuel cell is important, especially when considering the electrochemical process occurring within the fuel cell. For such a process to occur, careful manufacturing must occur to ensure the system does not leak in the electrochemical chamber. In this regard, factory manufactured equipment can undergo more rigorous testing and quality control than in the field.

On-site equipment besides the fuel cells can include the wiring needed to connect all of the equipment, a hydrogen tank for remote areas or backup hydrogen, disconnects for maintenance, and a transformer.

Regarding the life expectancy of fuel cells, several manufacturers claim their units have a 20-year lifetime. As fuel cells are currently some of the newer technology, the claimed lifespan from manufacturers has not yet been observed. However, the Department of Energy has set the expectation for these systems to be capable of lasting 80,000 hours [104], which corresponds to just over 9 years of continual operation.

Fuel cells are designed and constructed using standards from the National Fire Protection Agency (NFPA) and the International Code Council (ICC). The permitting and licensing of these power plants are typically under state jurisdiction [105].

Maintenance

The maintenance involved with fuel cells is less than other systems, once again benefiting from a system that has no moving parts. Much of the maintenance involved with this type of system relies on the inspections of equipment to ensure it is operating properly [106]. One inspection that should occur on a regular basis should be a check inside the chamber where the electrochemical process takes place. The main maintenance issues involved with fuel cells has been corrosion on bipolar plates, a dissolution of the catalyst and the oxidation of carbon-based material within the unit [107].

Besides the inspections of the fuel cell, other maintenance that is possible is the refueling of the system. If the fuel cell is not connected to natural gas, there should be a hydrogen storage tank on site that will need refilled. The Department of Energy, in a report, showed that emergency fuel cells usually have 72 hours of onsite fuel [104]. However, if used as the primary source of energy, large tanks should be designed for based on the fuel consumption of the fuel cell to allow longer periods between refueling. Plug Power has created three different hydrogen storage solutions that involve using either a bulk storage tank of 18,000 gallons of liquified hydrogen, compression pumps that compress gaseous hydrogen to 7,000 pounds per square inch, or tubes that contain 120 kg of gaseous hydrogen [108]. Using this information combined with a fuel consumption rate of 60 to 69 kilograms/MWh from one of their fuel cells [109] can lead to an estimate that this fuel cell can produce 7 MW of electricity before needing to be refueled.

System Summary

Location Availability

For the location availability of hydrogen fuel cells, a decision should be made whether the system will be located in one spot or scattered throughout the base. Knowing this will help estimate the footprint of the construction later on. Are there natural gas lines that can be used as connection points?

Security

For the security of the system, fuel cells are expected to be located on base. Is there any restrictions that would require fuel cells to be located off base leading to a decrease is physical security? Examples of this would be if the base did not want continual refueling to be performed on-base or whether there are natural gas lines on the base.

For cybersecurity, are there control schemes with the fuel cells being evaluated that could compromise the system due to being connected to the internet?

Reliability

In general, fuel cells are expected to be reliable. However, are there certain concerns with the selected fuel cell type that would decrease the reliability of the system? Is redundancy built into the system or are larger units being chosen that would decrease the redundancy.

Capability

A factor to consider when looking at the capability of the system is how the electrical demand will be met. Fuel cells are expected to meet the demand, but will it be done using more units that are smaller or does the design utilize larger units?

Efficiency

When looking at the efficiency of the fuel cell, does the efficiency reported by the manufacturer match the expected values used in industry? How does the efficiency of the system compare to other sources being looked at? Will waste heat be able to be used?

Constructability

With the constructability of the system, the main item to consider is the system infrastructure. Is natural gas utilized on the installation that can be used to provide fuel for the fuel cell or will the system require the addition of hydrogen storage tanks that will need to be refueled? Another item to consider, as they are a more unique energy generation source, is the lead time required for the procurement of equipment that will affect the construction time.

Maintenance

When considering the maintenance of the system, will the system have natural gas piped to it or will it require fuel storage that will need to be refueled? If there is a need to be refueled, calculations should be performed to determine the amount of time between refueling stages. Another item to consider is that even with less maintenance in this system, is there training or specialized companies that can be used to aid in the maintenance of the system?

Biomass

History

Biomass has long been used for heating through the burning of wood since humans first discovered fire. The use of biomass, besides heating, has been in the electrical production process through firewood and charcoal, and more recently through wood chips and pellets. Besides electricity production, biomass has largely been used as fuel in automobiles. The use of ethanol was first used in an engine in 1826. During the civil war, an ethanol tax was placed to help raise funds and at that point stopped being used [110]. After the Civil War, Henry Ford used ethanol in automobiles once again. However, it was not long after this time that the availability and cost-effective fossil fuels such as coal and crude oil became dominant in the market and have remained a large part of energy production [111]. Today, the usage of biomass in the production of electricity is being revisited in order to decrease carbon emissions. Although the current electricity generation mixture does not contain large contributions from biomass, it is relevant due to the many processes used to convert it into other useful forms including forms that can be used in existing fossil fuel-sourced power plants.

Energy Production Process

Biomass energy relates to using animal waste and plant waste as energy sources. In fact, the biomass energy sources that have been used as fuel include crop residue, fuel wood, aquatic plants, annual crops, animal manure, and municipal solid wastes (MSW). There is some controversy with biomass because it is required to be burned much like coal. As such it may not be as environmentally friendly as other sources considered in this report. However, with it being a resource that can be grown it can be considered a renewable resource.

In the electricity production process, the usage of wood biomass, MSW and biogas are the main fuel sources. The use of these fuels occurs through a variety of processes with the main one being combustion to produce heat. The heat from combustion can then be utilized to create steam which is routed through a steam turbine to produce electricity [112]. The other processes of using biomass include a thermochemical version to transform biomass into other solid, gaseous, and liquid fuels that can be used to produce electricity. In the case of MSW, it can be used either in a combustion process to create heat or can be decomposed through the use of anaerobic bacteria to produce biomethane and other gases. The combined gases, now referred to as renewable natural gas, or biogas, can then be used in natural gas generators to produce electricity [113].

Another possibility of electricity production through the usage of biomass is through the process of gasification. In this process, biomass is heated between 800° and 900° and injected with oxygen or steam. Gasification produces a carbon monoxide and hydrogen rich mixture referred to as syngas. The syngas can then be utilized in gas turbines to produce electricity. Hydrogen can also be stripped from the syngas mixture to be used in fuel cells [114].

Location Availability

As biomass involves all plants, animal and human waste, the majority of the US has biomass available. However, much like sunlight, which is available everywhere, there are concentrations in the US that have higher biomass potential. This is mainly due to the variety of different biomass materials utilized and their weight per cubic meter, otherwise known as the bulk density. In this case, most agricultural crops and grasses are estimated to be 80 to 100 kg/m^3 and wood biomass is estimated to be 150-200 kg/m^3. Although not in kg/m3, FIGURE 27 shows the average tonnage by county within the US over a five-year period. This map is a good indicator of the amount of biomass that is available in locations around the US. However, the low bulk density of biomass makes it difficult to use these sources in the traditional coal power plants that are being utilized. To aid in the utilization of solid biomass products, a process known as densification, or compressing material, has been widely used throughout the US. The densification process results in the production of pellets, bales, and briquettes that can be up to 10 times as dense as the raw material [115]. Densification occurs in many different locations throughout the US that is shown in FIGURE 28. The locations of the companies that produce these condensed biomass products can also be used when determining areas where biomass sourced electricity would be viable due to the lessened transportation distances of fuel that could lead to both security threats and refueling times of the system.

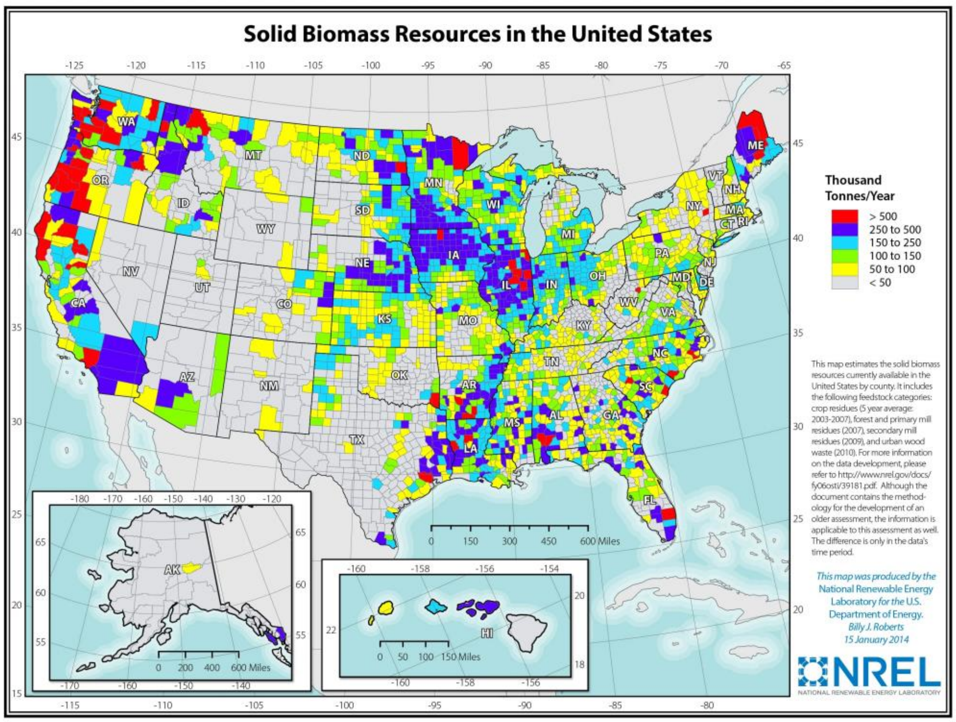


Figure 27 Solid biomass resources in the United States. Source: National Renewable Energy Laboratory [116]

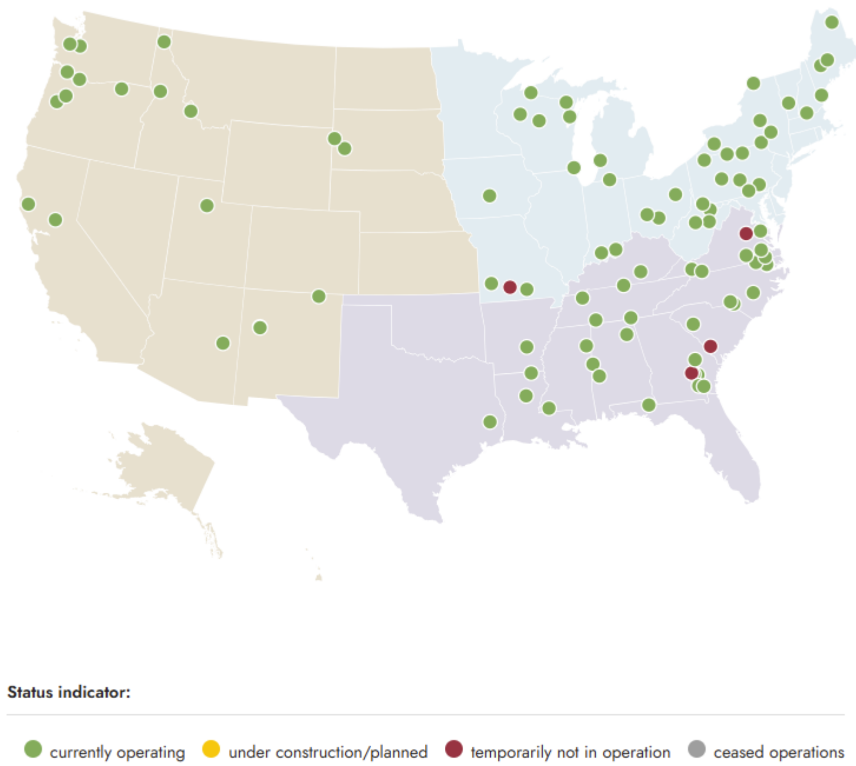


Figure 28 Locations of biomass pellets, bales and briquettes. Source: U.S. Energy Information Administration (February 2025) [117]

Security

The security of biomass-sourced electricity generation is like fossil fuel plants and nuclear power due to the capability to generate large amounts of electrical power with minimal units. With that being said, coal power plants will be discussed in this section in the expectation that biomass power plants operate in much the same way. For physical security, biomass generation plants can take up large amounts of land due to the necessity of having large stockpiles of biomass material. Although a study in 2017 showed that, for electricity production itself, coal power plants averaged 0.699 acres per MW produced, the amount of land needed to hold material has the potential to be large depending on the amount of fuel needed. In locations that do not have a large electrical demand, the potential for a smaller generation plant that can be on-base and the physical security of the plant increases [37]. Physical security at the power plant can increase as the land usage decreases but there is still some physical threats due to using fuel sources that are located off of the military installation.

The use of one of two electricity generation turbines does not rely as heavily on the communication of many turbines as seen in both solar and wind electricity generation. The main way it would differ from fossil fuel plants is that the design for a military base would not be controlled by the electrical grid and so it would not need an outside connection. Being disconnected from the grid would decrease the potential to be hacked. However, if a controller was used to control load chasing, a cyber-attack could still be possible.

Reliability

As biomass involves the use of crop residue and woody plants, the reliability of this source can be seasonal dependent in that it only grows in certain months. The crop residue is only available after the crops have been grown and harvested. This period differs between the different crops. The woody biomass, on the other hand, can be harvested year-round but with careful harvesting practices to ensure the wood sources are not used faster than they can be produced. There are storage systems that can aid in decreasing the seasonal fluctuations of biomass but there is still a threat of fuel becoming scarcer, especially after a few months of using the stored biomass. This dependability on resources around the site location can make a biomass system not as reliable, but the energy generation process itself is reliable as seen with the current electric grid.

Capability

At this point in time, countries in Europe have developed an electrical generation system that is much more reliant on biomass than in the US. Following in their footsteps, there are currently turbines that utilize the syngas and biogas that can have outputs from 2 kW up to 150 MW [118]. Besides the gas turbines, there are also steam turbines and generators that operate with an electricity output of 100 to 1500 kW [119]. As these generators are becoming more modular in nature the ability to add units for more electrical generation can be utilized to ensure the electrical demand is met.

Efficiency

Due to being used in traditional electricity generation processes like steam turbines and natural gas generators, the energy efficiency of using biomass depends on which type of energy generation system is chosen. The efficiency for steam turbines is the well-documented efficiency of 35% for producing electricity which is low compared to some of the newer technology that has been seen in the industry, but when biomass is used to replace coal the energy efficiency has been noted to drop to 20%. The main cause of the change in efficiency is the high moisture levels that are typically seen in biomass. However, on the other side of the energy efficiency spectrum is the natural gas turbines that have energy efficiencies of 60%. Natural gas generators can use the biogas produced from the anaerobic digestion process and syngas from the gasification process. As stated before, the hydrogen stripped from syngas can also be used in fuel cells which have an efficiency of 50 to 60%. Even though they have better energy efficiencies most power plants do not use biomass in natural gas generation because of the extended processing needed for creating the syngas and biogas.

Although these efficiencies look good on paper, the reality is that to use biomass as a resource involves more processing than other sources. The energy used during the process of densifying and refining biomass to be used in electricity generation does not show up in the energy efficiency in the conversion to electricity.

Constructability

The constructability of a biomass power plant is much like coal and natural gas power plants. Designing a common steam power plant around biomass involves components such as fuel storage, combustor, boiler, pumps, fans, steam turbine, generator, condenser, cooling tower, and controlling methods. The fuel storage can lead to a larger land footprint than some other systems. The suggested maximum biomass pile size is 295 feet wide by 492 feet in length taking roughly 3.3 acres for fuel storage alone. Although none of these components is unique to this system, the system is built up on site leading to longer construction times than some of the modular systems listed in this report. Being built on site also leads to longer construction times. Even though the US has not built a coal-sourced power plant since 2013 the average construction time for these steam turbine power plants can be estimated to be about 15 to 20 MW per month of construction. This information can be found looking at the construction time of the coal power plant built in 2013 which was 48 months with a capacity of 900 MW [120]. Besides this information, taking a look at other countries building steam turbine power plants shows that South Korea has built 1000 MW, 800 MW, and 500 MW coal power plants in time lengths of 55-60 months, 52 months, and 40 months respectively [121]. On the positive side, these types of power plants have been proven to have a lifetime of 40 years as seen by many coal-sourced power plants still being used in the electrical grid today.

The permitting process of biomass power plants is mainly enforced by state and local jurisdictions but can also be subject to both an Environmental Site Assessment and an air permit from the US Environmental Protection Agency. To receive the air permit, the power plant must pass requirements centered around greenhouse gas emissions.

Maintenance

The maintenance involved in a biomass system involves both reloading fuel as well as the general maintenance of equipment used. The equipment the electricity generation process utilizes is common in industry as seen in the constructability subsection. The commonality of the equipment means that no advanced training is needed to repair and maintain this system, like other energy sources discussed in this report.

Where frequent maintenance is required in this system is its dependence on being refueled. Unless a conveyer system is used on the generation site, refueling is typically done using front loaders that scoop biomass material from a pile and place it in the combustor. In a presentation concerning the combustion of woody biomass in California, studies showed that to produce 1 MWh took 1 ton of biomass [122]. With this, one can observe the amount of material needed to generate electricity with biomass products.

System Summary

Location Availability

As biomass relies on both the availability of biomass and manufacturers of dense biomass fuel sources, both locations should be used to aid in determining whether biomass can be utilized in a location. With this, it is important to consider the additional space requirements of the system due to the storage of biomass fuel products.

Security

With the security of biomass, can the generation site be located on the military installation or does it need to be located off base? Much like other sources, if the site is off base, can a reaction force quickly reach the area if needed?

For the cybersecurity of biomass, are there other control systems that can be utilized without connecting to the internet? In the process of fueling and generating electricity, how many locations are controlled by the control system that could be used to hack into the system?

Reliability

For the reliability of biomass, an evaluation of the biomass resources in the area should be conducted. With this, the main issue in reliability would be that some biomass resources, crop residue especially, is only available to be harvest at certain time periods throughout the year. This has the potential to lead to more fluctuations in available fuel than other energy sources, ultimately leading to a risk of fuel scarcity if improperly used.

Capability

In evaluating the capability of the system, since biomass specific units are becoming more available, the capacity of each unit should be addressed to ensure the system can meet the electrical demand. The type of unit should also be considered as using different types of biomass fuel can result in higher or lower electrical capabilities.

Efficiency

The efficiency of biomass can be highly dependent on the preprocessing of biomass material. This should be checked with manufacturers of the densified biomass products to ensure that they can provide products that are in the desired range of moisture content. An additional item to consider is the amount of preprocessing needed for the biomass to be used as that may not show up on the energy efficiency of the power plant itself.

Constructability

With the constructability of the system, as with other systems, the construction time of building the power plant on site rather than selecting a more manufactured system should be evaluated. This could be difficult to determine based on the US's current stance on the construction of power plants the resemble coal-fired power plants.

Maintenance

One of the main concerns for biomass energy is the refueling required. To investigate this category, the energy density provided by biomass product suppliers should be looked at to determine the quantity of times the system will need to be refueled and the time between refueling. The maintenance of this system involves a large quantity of different sections like the harvesting, densification, transportation, and the actual loading of fuel to generate electricity.

Tidal Power

History

Although some might think that tidal power is a relatively new concept, it has actually been around for at least 50 years. The age of tidal power is shown when considering that the first tidal power plant started producing energy in the mid-1960s. There are two main types of tidal power technology in use today. Tidal range technology involves building a dam along the shore that uses the tidal flow to produce energy. Tidal range technology can be further split between lagoon and barrage type based on where the dam is located. If the dam is located entirely off-shore, it is classified as a lagoon-type range because it stores the water from the tide. When the dam is constructed right along the coast, it is considered a barrage. The other tidal power technology, known as tidal stream, is newer than tidal range and is less common. Tidal stream technology is similar to wind turbines on the ocean floor and does not require the construction of the large dam found in tidal ranges. As hydrokinetic turbines are a newer technology, many units are in the development phase with a few units being in operation and under testing phases. This report will focus on the promising newer units from both the Ocean Renewable Power Company (ORPC) and Verant Power. These two sources will be used due to their extensive research and data on their units. Verdant Power has created a turbine similar to a HAWT while ORPC has created a turbine similar to the VAWT but in this case rotated on its side. The two types are shown in FIGURE 29.

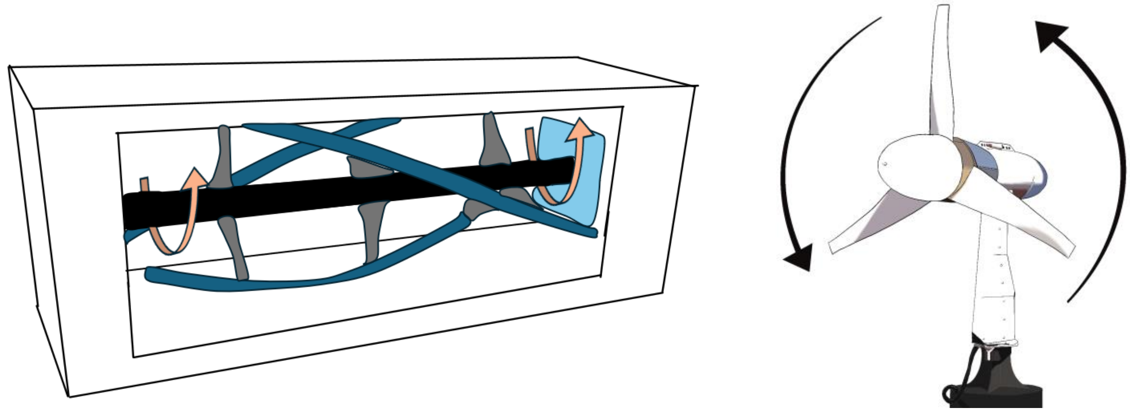


Figure 29 The different configurations of hydrokinetic sources that can be submerged. Referenced from [123] and [124]

Energy Production Process

Much like the difference between typical hydropower technology, the differences between tidal range and tidal stream technology relies on the type of energy it is harvesting. Tidal range power is similar to dams built in riverbeds in that they primarily function on potential energy caused by a differential in height as the tide ebbs of floods. Depending on the type of turbine selected, the system can generate electricity during ebb tide, flood tide, or both. In all three configurations, a sluice gate is utilized to stop water flow until the preferred height difference is reached, which is different from site to site. The total power generated by a tidal range can be calculated with the following equation:

$$P = \frac{\rho g R^2 S}{2T}$$

Where P is the power generated in Watts, ρ is the density of water being 1025 kg/m^3 for seawater, g being the gravitational acceleration, R^2 being the tidal range, S being the surface area of the tidal basin and T being the period of time as 12.4 hours as there are 2 tides per day [125].

Since tidal streams use similar technology to wind turbines, the equation for tidal ranges does not work for calculating the power. Instead, the power output used for tidal streams can be calculated using the equation:

$$P = \frac{1}{2} \times \rho \times A \times V^3 \times C_p$$

Where P is the power output in Watts, ρ is the fluid density in kg/m^3, A is the area swept by the turbine in m^2, V is the fluid velocity in m/s, and C_p is the power coefficient of the turbine [126].

Location Availability

Since this energy collection technology utilizes the tides of the oceans, the location able to use this source of energy is limited to installations that along the coast. According to the United States Geological Survey, the US has roughly 100,000 miles of coastline shown in FIGURE 30 [127]. However, the utilization of tidal energy is not restricted just to locations along the shoreline. If electrical lines are utilized to transfer electrical energy from one location to another, tidal energy can be used in areas adjacent to the coast. In this instance, the value of 400 miles was utilized as the maximum length of an electrical line. The length of 400 miles was chosen based on the consideration of the wavelength of the alternate current electricity at 60 Hertz. With this in mind, there is a maximum line distance of 750 miles where the voltage is 0. To ensure that this does not occur, 400 miles is a common value used in the field for the maximum length of a high voltage electrical line. With this in mind, Google Earth was utilized to depict a 400-mile electrical line from the coast of the US. This map is shown in FIGURE 30, where a fairly large portion of the US could utilize tidal energy.

In the development of tidal ranges, many sites are evaluated to determine the areas that have either large areas that can be encapsulated or areas that have a large rise in the height difference of tides. Looking for locations that have these factors ensure that the optimal location is chosen for peak electrical generation. When looking for areas for tidal stream technology, areas that have higher velocities of water during the tides are most preferred for their ability to produce power.

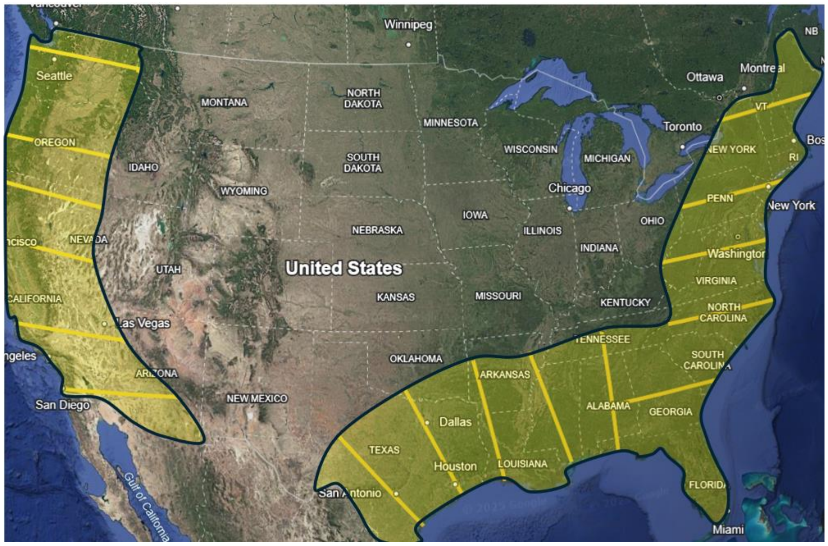


Figure 30 Areas within 400 miles of the US coastlines. Referenced from [128]

Security

For the physical security of both the tidal range and the tidal stream, the location of the system creates concerns. As the coasts are the exterior portion of the US, they are the most threatened. To secure the electrical generation site, more measures will need to be taken such as routine patrols, the installation of watchtowers, and the availability of a quick response force. Even without the threat of adversaries, systems in the water have tended to have damage occur for other reasons, primarily from ship anchors as seen in the recent incidents involving underwater cables in the Baltic Sea and Taiwan Strait [129]. However, the coastline is also more secure than the middle of the US from inside threats due to the coast securing one side of the electrical generation site. The power lines from the tidal power plant to the military facility poses some security risk but are not in as much risk due to the lack of electrical equipment that are typically seen as targets.

The cyber security of the system is dependent on the type of system selected. Since the tidal range generators work like the generators found on dams, they would be used to generate a base electrical generation and as such could have controls that are not reliant on the use of remote controls. As the connection would not need to be remote to the tidal range generator, the cyber threats against the generator would be low. On the other hand, when using hydrokinetic turbines, these systems are typically installed with the ability of remote communication like wind turbines. This remote connection is a spot where a cyber threat is more likely.

Reliability

Unlike some renewable energy sources, tidal power is reliable due to its predictability and ability to produce power throughout both the day and the night. This predictability stems from historical data as well as the whole tidal process occurring due to the moon's gravitational pull on the Earth. The tides are not as effected by variable weather conditions such as the wind and clouds that wind and solar technology are reliant on.

In terms of physical structure, the turbines utilized in tidal ranges have proven their stability. This can be seen most easily by the turbine found in the tidal range in La Rance, France. In a report, the blades used in the turbine were found to be in good condition even after being submerged in water for 70,000 hours or just around 8 years [130]. Another turbine design located in Annapolis, Canada was noted to have an availability of 98% throughout the year showing that it can be expected to be down for 2% of the year or 1 week.

As the hydrokinetic turbines have not been in operation very long, they cannot claim the same historical data as the turbines used in tidal ranges. However, the turbine created by ORPC has been shown to be functional in Alaskan winters where temperature have reached -40°C and the turbine has been iced over showing that it can relied on even in harsh conditions.

Capability

Of the existing tidal ranges in operation around the world, the power outputs vary greatly with the number of turbines and the available height difference. There are records of tidal ranges in China that produced 40 KW and up to recent tidal ranges build in the UK that can produce 320 MW through 16 turbines [130].

Even though tidal power relies on some of the same principles wind turbines, tidal power can produce a large amount of electricity. The reason for a higher energy output, even though the speed of the water is slow, is that the water in the oceans are roughly 832 times denser than air. Some units that are being developed for large power applications involve the use of 35 KW and 160 KW devices. Much like the use of wind turbines, the power output is affected be the velocity of the water the turbines are placed in with a minimum operation speed of 1 m/s. With the use of these turbines, one location is expected to produce up to 1.05 MW through the use of Verdant Power's 35 KW unit [124] and the other project using ORPC's 160 KW devices [123] has around 500 KW of energy production.

Efficiency

The technology currently used in power generation from tidal ranges is one of the most efficient systems available having an average energy efficiency of 80%. Some of this efficiency is dependent on the type of turbine utilized for power generation. The bulb turbine is the most common turbine found in most tidal ranges throughout the world due to its success in La Rance, France. This type of turbine has achieved energy efficiency values of 90%. However, due to the configuration of the turbine, it can only achieve 90% efficiency with the tide it is primarily designed for. When these turbines are used during the opposite tide, the efficiency has been seen dropping to a maximum energy efficiency of 70%. The other turbine that has been used in tidal ranges is the Straflo turbine. The energy efficiency of this turbine can range from 78 to 89%, which is still high compared to other energy sources.

Unfortunately, the hydrokinetic turbines do not have the high efficiency of the dam turbines. Since hydrokinetic turbines are similar to wind turbines, they have the same Betz limit of 59.3% as wind turbines. However, even with this maximum efficiency limit, there is still room for the improvement of today's hydrokinetic efficiency because the currently operate at around 35% [131].

Constructability

The length of time for construction can vary depending on the type of hydropower used. Tidal ranges require a large amount of construction as they require the building of a barrage to keep the water in, sluice gates, a basin area for water storage, and the turbine itself [132]. With the amount of construction, as well as engineering associated with tidal ranges, this source of energy can expect longer construction times than several other energy sources. Despite this, the turbine is expected to have a lifetime of 40 years with some tidal ranges, and even one in Swansea Bay in the United Kingdom outperforming this lifetime with the expected lifespan of 120 years.

Hydrokinetic power construction time is less than that of tidal ranges due to the ability to have hydrokinetic turbines manufactured and then placed in the water. Several companies utilize hydrokinetic turbines but have different approaches as to how they are installed. One type of hydrokinetic turbine, like a VAWT, is installed using cables that anchor it to the ocean floor [123]. Another type of hydrokinetic turbine, similar to the HAWT, is anchored to the ocean floor by a triangular frame that is able to hold and appropriately space the turbines [124]. Both technologies used for hydrokinetic turbines allow for simple and quick installation. However, from projects that have been used as tests for hydrokinetic turbines from both companies, a process of licensing has been in development. The main licenses and certifications needed for tidal stream power are a preliminary project license and a project license that are both filed to FERC. Other important site observations need to take place in the construction zone as well as the licensing of the project. These site observations involve mapping out the site to determine the best placement of the hydrokinetic turbines and environmental surveys to examine the wildlife around the area. In both tests, the presence of threatened and endangered aquatic species were identified for documentation. This documentation is required by state and national conservation departments.

Maintenance

The maintenance around tidal ranges can be difficult based on the type of turbine selected. The bulb turbine has been noted to have issues with debris that have damaged the turbine blades. This can be an issue because the configuration of the turbine blades and generator are not very accessible and as such have long and expensive maintenance times. Some of the damage to the turbine blades can be prevented using a trash rack placed in the water intake pipes. However, with the addition of a trash rack comes with more frequent cleaning to ensure it does not get plugged. A Straflo turbine allows for easy access to the turbine blades for maintenance. However, this turbine has been noted to have issues with water damaging the turbine and as such required inspections to ensure seals are watertight.

The maintenance involved with hydrokinetic turbines has primarily been performed by the companies evaluating them. Both ORPC and Verdant Power use different techniques to allow for quick repairs. ORPC has created a system that allows their turbine to be transported easily and put together on-site. To allow for quick maintenance, ORPC incorporates a foundation that is both towable and includes a remotely activated buoyancy system [133]. This allows for turbines to be brought out of the water to be repaired. Verdant Power incorporates a mounting system that can hold three turbines. This means that for routine maintenance, the foundation can be hoisted up and all three turbines can be worked on. However, one flaw in this design can be the case of one turbine needing repairs in that it would be required to be disconnected underwater or two additional turbines would need to be offline during the maintenance. To combat this, Verdant Power has manufactured multiple units allowing for quick replacements that do not rely on the manufacturing of additional units or time needed to repair the turbine.

System Summary

Location Availability

For the location for tidal power, site evaluations should take place to determine whether the location along the shore can be used for energy production. What are the expected differences in tides for the location that can make tidal ranges feasible? The other site evaluation should be the velocity of the currents to determine whether hydrokinetic turbines can be used. Can the location be within the 400 miles needed to utilize electrical lines?

Security

For the physical security of the system, since it is along the coastline, what additional measure need to be taken to ensure the system is not physically attacked? What kind of monitoring systems will be utilized to check the status of turbines?

With the monitoring system, does it rely on an internet connection of does it utilize a more secure network to avoid cyber risks?

Reliability

For the reliability of the system, the tides are considered reliable in industry. With this being the case, what measures will need to be taken for the redundancy of the system and how will they affect the design of the system?

Capability

When considering the capability of the system, with tidal power, especially hydrokinetic turbines being newer, can the electrical demand be met? How do the tides affect this capability in both tidal ranges and tidal stream technologies? Are there areas in the vicinity that could be used for future electrical generation?

Efficiency

The efficiencies of tidal power being dependent on the type of system selected, what is the efficiency of the most viable tidal power system. How does this efficiency compare to other sources and are there ways to increase it?

Constructability

The constructability of the system, like the efficiency of the system, relies heavily on the tidal system selected. If tidal ranges are selected to be used, what is the expected construction timeline of the system? If tidal streams are designed for, how long it the expected process to receive different permits in order to perform site evaluations and construction. What is the lead time of the equipment from the manufacturers?

Maintenance

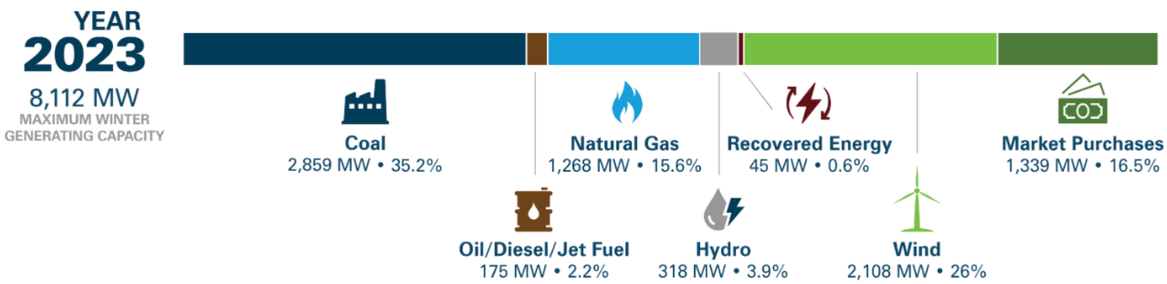
The maintenance of the system is also highly dependent on the tidal system selected. When a tidal range is designed, what is the turbine that is being designed for as this affects the difficulty of maintenance? When a tidal stream is designed for, what are some of the manufacturers’ maintenance strategies that can be utilized? In both systems, how often is the expected maintenance of the equipment?

Case Study Analysis

To demonstrate how the process of choosing an energy source for a base may be considered, Minot Air Force Base (AFB) in North Dakota was selected for evaluation. This 5000-acre military base houses both a bomber wing and a missile wing. To determine the best energy source to be used, the form in Appendix A summarizes the discussion of this section. Utilizing a form like the one supplied can simplify the process of choosing an alternative source for a base, but the following discussion should still be used in order to fill out the alternative energy source form correctly. To identify how each system is expected to compare to other systems, a point system from 1 to 5 will be utilized. The rating will be determined by how well an energy source performs compared to the national power grid. With this being the case, the number 3 will signify that there is relatively little difference when compared to the power grid. Ratings greater than 3 will indicate and quantify how much a source will perform better than the grid while a rating less than 3 will indicate and quantify how a source will perform worse than the power grid. With this in mind, any overall value that is above 24 indicates that a source is better than the power grid and should be investigated in more detail.

According to information from an Air Force report, Minot AFB relies on power being supplied from Verendrye Electric Cooperative by three 41.6 kV feeders. The base itself reduces the voltage down to a manageable voltage with one 30 MVA transformer and one 15 MVA transformer [134]. According to the report released in 2019, Minot AFB averages an electrical demand of 15 MVA throughout the year. Since there is 45 MVA with the combination of both transformers, the value used for the evaluation of this base is 45 MVA.

Upon further investigation, it can be found that Verendrye Electric Cooperative buys the majority of its energy from Basin Electric Power Cooperative which is in the Southwest Power Pool region. This is relevant information because it shows that the current power being supplied to Minot AFB is produced by a much larger energy company that generates electricity for nine different states. Although Minot AFB has generators for emergency purposes, this system is not ideal due to the reliance on different energy cooperatives to upkeep electrical lines. A look at the resource portfolio of Basin Electric shown in FIGURE 31 shows that over a third of its power generation comes from coal sourced power plants and a sixth of its power generation comes from natural gas [135]. These two sources would be the main sources of electricity that today's economy is trying to phase out. Basin Electric also produces a third of its electricity by renewable sources with wind and hydropower.



- Generating capacity chart indicates only generation owned by Basin Electric or purchased power longer than three years
- Maximum generating capacity in megawatts (MW)
- At end of year 2023, Basin Electric operated 5,217 MW of wholesale electric generating capacity and had 8,112 MW of generating capacity within its resource portfolio

Figure 31 Resource portfolio from Basin Electric Power Cooperative. [135]

Location Availability

After understanding what the current energy mix supplying Minot consists of, the next step in determining other energy sources to consider is to investigate the environment surrounding the base. This information will aid in narrowing down the options to those that have the ability to produce their rated capacity based on the resources available. To find this information, several government entities keep track of the weather data across the US and have many historical records aiding in the reliability of the information. Some of the important items that need to be considered is the wind availability and expectation, shown in FIGURE 32, the average amount of solar irradiance, seen in FIGURE 33, the sources of water for hydropower shown in FIGURE 34, the geothermal potential shown in FIGURE 35, and the climate data shown in FIGURE 36. This information can be used to determine the viability of wind power, solar power, enhanced geothermal, and hydropower.

The other energy options such as nuclear, hydrogen fuel cells, and biomass do not rely on location conditions as much as the renewable energies allowing these systems to be used in most locations. However, these energy sources will require refueling at different points in time so they do require a way to be refueled depending on the frequency of refueling needed. The frequency of refueling is important because if a source needs to be refueled often, it should have the infrastructure around it to do so. Sources that do not require frequent refueling, and as such are less dependent, do not require the infrastructure upkeep that regularly refueled sources need. In the case of Minot AFB, the roadways already exist that would allow refueling as required.

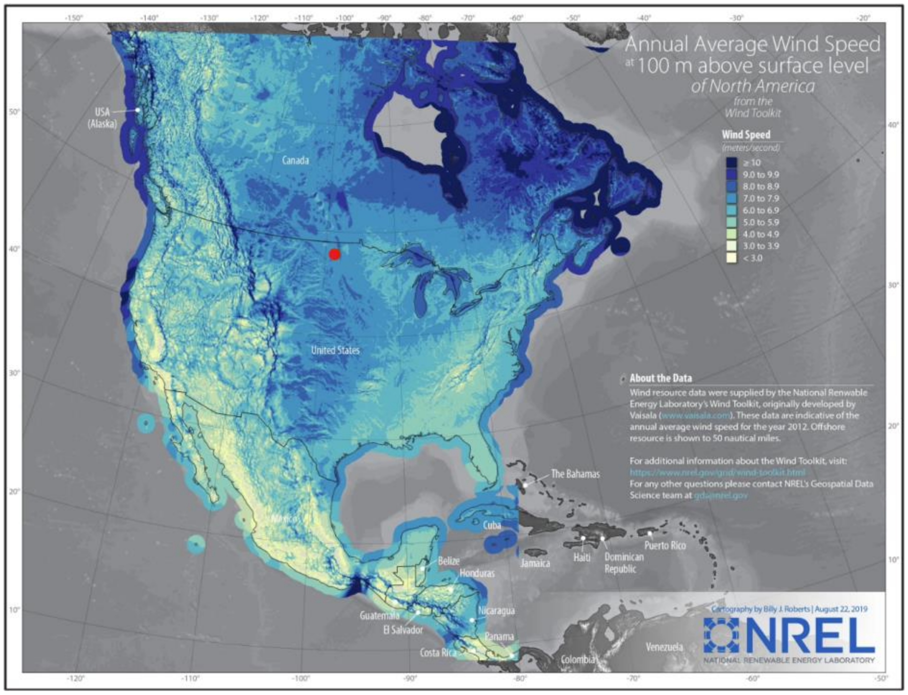


Figure 32 Map showing the average wind speed throughout the United States with Minot AFB marked by the red dot. Source: National Renewable Energy Laboratory [31]

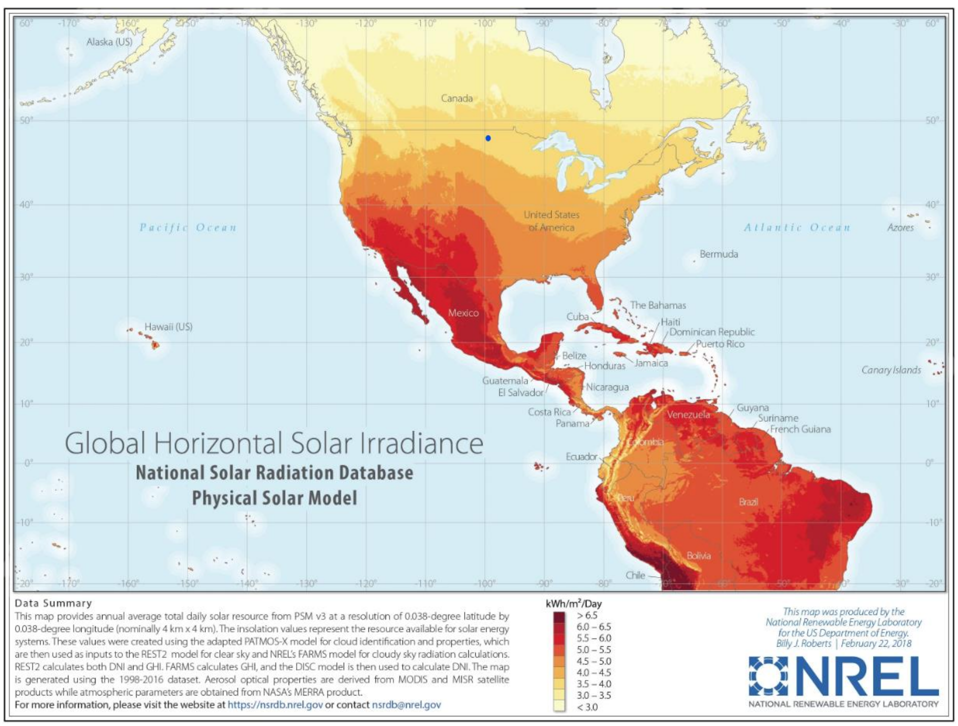


Figure 33 Map showing expected sunlight over the United States with Minot AFB marked by the blue dot. Source: National Renewable Energy Laboratory [44]

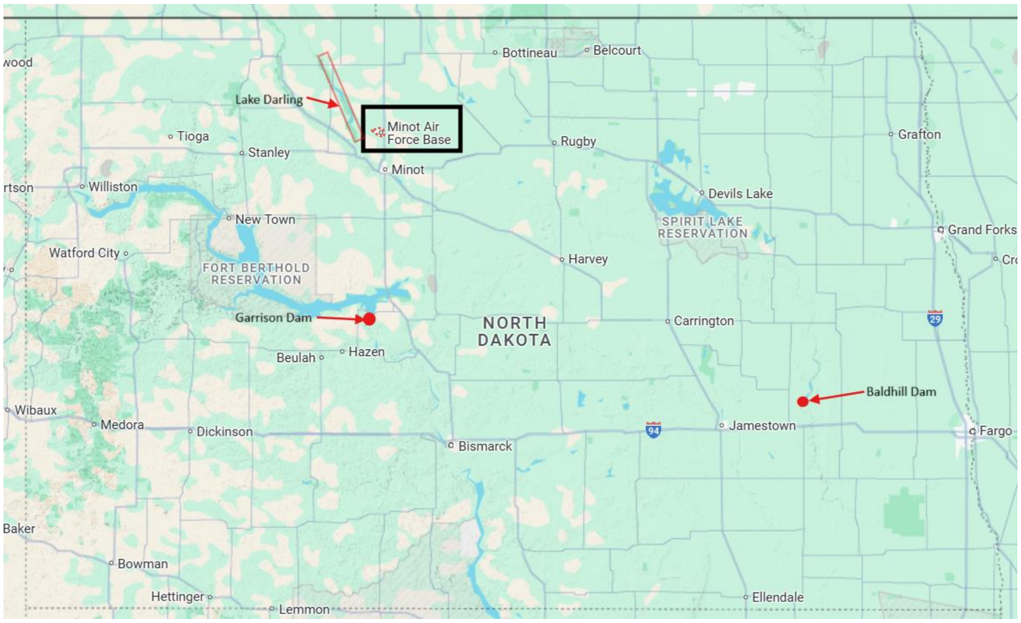


Figure 34 Map showing Minot AFB and the surrounding water sources. Referenced from [136]

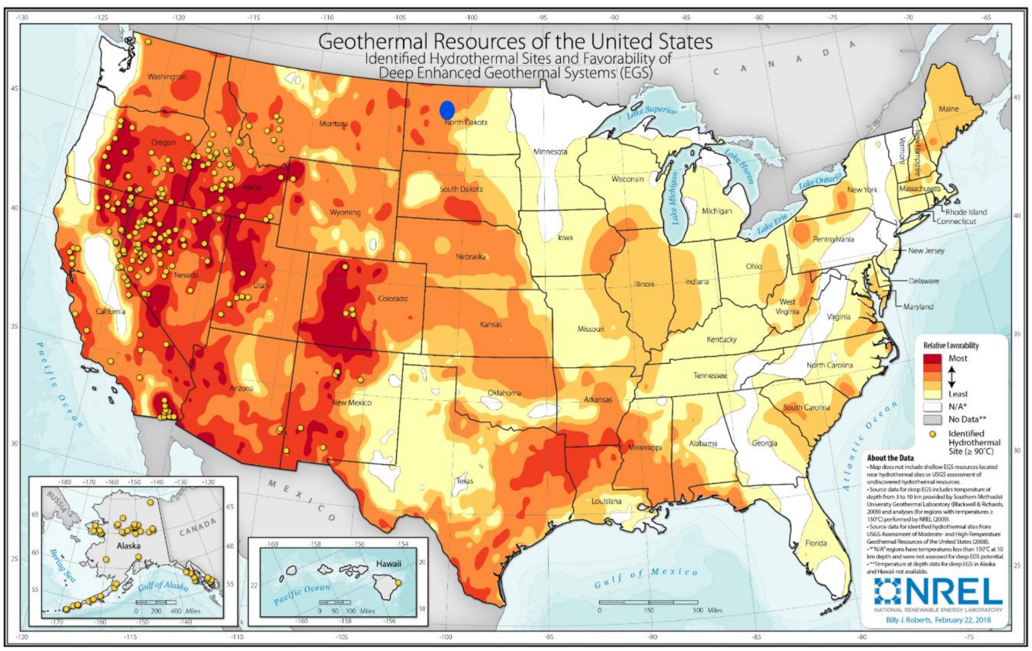


Figure 35 Map of Geothermal system potential with Minot AFB marked by the blue dot. Source: National Renewable Energy Laboratory [76]

Month	MAX TEMP (°F)	MIN TEMP (°F)	AVG TEMP (°F)	PRECIP (IN)	SNOW (IN)
Jan	23.3	4.4	13.8	0.28	9.8
Feb	27.0	7.7	17.3	0.29	5.4
Mar	39.5	19.0	29.2	0.51	6.1
Apr	55.8	31.2	43.5	1.00	4.5
May	68.9	43.3	56.1	2.73	0.7
Jun	77.5	53.6	65.6	3.73	0.0
Jul	83.8	58.5	71.2	2.50	0.0
Aug	83.7	56.4	70.1	2.08	0.0
Sep	73.1	47.1	60.1	1.57	0.1
Oct	56.8	34.3	45.6	1.15	1.2
Nov	39.7	20.6	30.2	0.56	9.2
Dec	27.2	9.3	18.3	0.31	8.1

Figure 36 Figure showing the average climate data of Minot, North Dakota from 1991-2020. Source: National Oceanic and Atmospheric Administration [137]

Wind Power

From FIGURE 32, the average wind speed around Minot AFB is around 7-9 m/s. This high average wind speed shows that wind is consistent in this location and therefore can be relied on for electrical generation. Not only can it be seen on the wind speed map, but this is also shown in the generation mix for the RTO in this area. The generation mix of the electricity provider in FIGURE 31 shows a substantial portion of energy being produced from wind powered generators. Not only does the wind speed show that wind turbines are a reliable option in this location, but the map also suggests that wind can be taken advantage of close to, or located on, the military base itself. With this potential of generating energy, wind power is rated as a **3**, indicating that it has the same potential as the current grid. This can be justified by the Basin Electric's current generation mix showing a high percentage of wind power in the area.

Solar Power

From the irradiance maps for both direct irradiance and global horizontal irradiance, the location of Minot shows less than desirable conditions indicating that the expected output from the system will not be as good from a resource management perspective. With the expected irradiance value of 3.5-4 kWh/m^2/day, solar panels will not produce their maximum output. This area is also prone to extreme weather conditions, primarily snow and ice as seen in FIGURE 36. It can be observed that the average snowfall from November to April is high, making it highly likely that snow will affect the system. The expected snow and ice for this location would increase the amount of maintenance of the system to allow it to function during the winter months. To produce power for the base, more solar panels would be needed because of the low availability of sunlight. With this less-than-ideal irradiance in mind but still available resource, solar power is rated as a **2** indicating the expectation that the system will perform worse than the current grid system.

Nuclear Power

When looking at nuclear power, it is the most promising energy source due to having the highest amount of energy output with the least number of units needed, especially when considering an SMR that could power the whole base from a single module. For redundancy purposes a second module could be designed for. Unlike some other technologies seen in this report, nuclear power is not affected by weather conditions, so it can be relied on to produce vast amounts of power during all weather conditions at Minot AFB. Due to its potential for large power output at the Minot AFB and its independence from weather conditions, it is rated as a **5** showing that it has high potential in this location.

Enhanced Geothermal

Another source of energy that can be seen through a data collection map is the enhanced geothermal system. Utilizing this map in FIGURE 35, the area around Minot AFB is identified as an area with medium potential where the heat of Earth's core is closer to the surface than surrounding areas. Like the wind speed map, the geothermal map also suggests that the available geothermal energy could be located on or near the base.

Looking at Enhanced Geothermal Systems (EGS), in particular the Closed Loop Geothermal (CLG) system, we can see from the resource map that this location has potential, meaning that the heat from the core is expected to be closer to the surface, therefore reducing the depth of drilling needed. This expected heat coming closer to the surface than in some other locations could make the CLG system worth putting in because of the close availability at Minot AFB. In fact, the proximity to base without disturbing base operations, unlike wind power, would show that this system could be located in a more desirable location than wind power. The medium potential of the location from FIGURE 35 and the more desirable location than wind power earns this system a rating of **4** because it can produce the amount of power needed and still be on the base itself.

Hydropower

Hydropower can be evaluated based on FIGURE 34. The water source closest to Minot AFB, known as Lake Darling, is a National Wildlife Refuge. Due to this body of water being part of a National Wildlife Refuge, it should not be considered as an energy generation site so that the wildlife may be preserved. The next closest source of water is the Missouri River, which when measured in Google maps, is around 65 miles in a direct route. Lake Sakakawea is the main body of water that the Missouri River flows into and was created by the Garrison Dam, which can produce 583 MW of electricity. To avoid further changes to the river flow, a hydrokinetic turbine could be evaluated. However, when looking at flow rates of streams in North Dakota by the United States Geological Survey, the only river that has enough flow rate to produce power effectively was identified as the Sheyenne River below Baldhill Dam [138]. According to the data that has been taken, the Sheyenne River has had a median flow rate of 62 ft^3/s. Baldhill Dam itself does not produce any energy, but the downstream side of it has the potential for a hydrokinetic turbine. When mapping it, Baldhill Dam is around 180 miles from Minot AFB. While the power generation site would be a long distance from Minot AFB, the flow rate allows the hydrokinetic power generation option to remain a viable option and does not disqualify the possibility of utilizing this water sourced energy. However, the longer distance does make it a less desirable option than other energy sources due to the transmission losses from the power lines and the long distance of power lines that will need to be maintained. The issue is that the availability of hydropower at the location itself is nonexistent, giving hydropower the rating of **2** due to the potential hydropower being located at a longer distance than other available resources.

Hydrogen Fuel Cells

The next source under evaluation is the hydrogen fuel cell. This source is viewed much like a portable generator in that it can be located anywhere and can meet the electrical load. This system also does not rely on the weather conditions in the production of energy so it can be expected to be used in all weather conditions like the previously discussed nuclear power. This system is rated as a **5** because it can be located on base without disturbing operations and is reliable during all weather conditions much like nuclear power.

Biomass

Another energy source considered in this report is biomass. From an availability standpoint, the main biomass source around the location is crop residue. The main issue with using biomass at this location is that it is not readily available on base and must be gathered from the surrounding countryside. This characteristic gives biomass the rating of a **3** as it, much like hydropower, has the potential for producing energy but, unlike other sources with better ratings, is farther from base and in the case of biomass, must be harvested at many different sites [139]. However, in this case, the reliance on the surrounding area is similar to the reliance on the power grid.

Tidal Power

Due to its location, being in the center of the US in reference to East and West, tidal power generation is not a viable option for Minot AFB. Although the closest of the Great Lakes, Lake Superior, is within 500 miles from the base, the NOAA has classified the Great Lakes as non-tidal bodies of water due to their minor change in height due to tides [140].

Viewing the resources around the location also enables several power generation sources to be identified as viable options that should be considered in the choices. The final resource to be evaluated at Minot AFB is the use of tidal power. As discussed previously, this location and the surrounding bodies of water are not expected to have any potential energy production and as such is rated as **1** for location availability because it has less potential than all of the other sources.

Table 6 A summary of location availability ratings for Minot AFB.

Energy Source	Location Availability Rating
Wind Power	3
Solar Power	2
Nuclear Power	5
Enhanced Geothermal	4
Hydropower	2
Hydrogen Fuel Cell	5
Biomass	3
Tidal Power	1

As seen in TABLE 6, the systems that are expected to perform better than the power grid are nuclear power, EGS, and hydrogen fuel cells. The systems expected to perform worse than the power grid are solar power, hydropower, and tidal power.

Security

In terms of security, Minot AFB, like any other military base, needs to be secure against all threats. Currently the base is connected to the electrical grid. This connection can lead to both physical threats by attacks against physical infrastructure and cyber threats through the hacking into SCADA. As these threats are caused by the interconnectedness of the grid, creating a microgrid for the installation can greatly enhance both physical security and cybersecurity. As energy sources are being selected though, it is important to note that some systems can be more secure than others. As discussed in the methodology section, the security criterion will be multiplied by a factor of 2 to weight this category more than others. A rating of less than 3 will disqualify an energy source from being selected as it indicates a greater security concern.

Wind Power

As wind power should not be located on military installations due to the frequencies emitted by the turbines that can mess with telecommunication equipment and the obstacles that they can become to both helicopters and airplanes, a wind farm will need to be located off base. Aerial views of the area, shown in FIGURE 37, surrounding the base show that the area is mainly agricultural. With this being the case, it can be assumed that a wind farm can be located within the allowed distance of five miles from the base. This would allow for a quick response force to confront any physical threats quickly even if the wind farm is not able to be secured.

The downside of using wind energy is the turbines' reliance on wind forecasts and sensors to control the turbine blades to maximize power output. Both the forecasts and the sensors create gateways that decrease the ability to be secure from cyber-attacks. Overall, wind energy can be rated as a **4** because it is physically more secure than the grid even if cybersecurity is the same as the current grid.

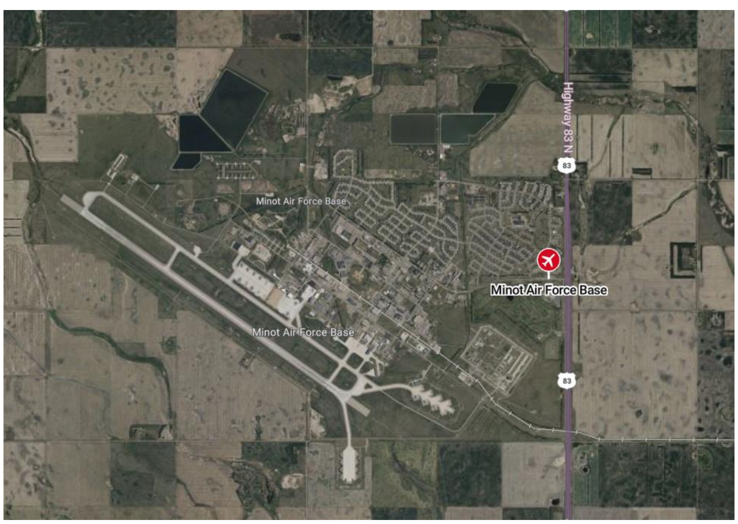


Figure 37 Aerial view of Minot AFB. [141]

Solar Power

Solar power, unlike wind energy, can be located on base due to its low profile. However, even though the system can be located on the base, due to the number of buildings located on the

base the use of a CSP system would likely be located outside of the base perimeter while an SPV system could be located on or off the base. Even with the CSP system located outside of the base, solar energy can still be physically protected more than the current electrical grid.
As discussed in this report, solar energy can also be hacked through the inverter and data acquisition sensors and as such is not that much of an improvement from the current grid's cybersecurity. With this being stated, the solar energy system can also be rated as a **4** due to its improvement in physical security.

Nuclear Power

As both SMRs and MRs are relatively small in nature, the possibility of being located on the base is likely. The NuScale SMR is predicted to only take 0.16 acres. Even though nuclear energy has a history of catastrophic events, both Air Force wings located at Minot AFB deal with nuclear weapons and as such it can be assumed that a high level of safety measures are already present at the base.

The cybersecurity of nuclear energy is also very protected as both SMRs and MRs have become more reliant on passive cooling technologies rather than automated controls. As these systems have been improved to adjust electrical output to the demand, these systems could have a few points that could be hacked but it would be less of a risk than both the electrical grid and wind and solar energy. Since both physical security and the cybersecurity of nuclear energy can be seen as better than the electrical grid the security rating can be **5**.

Enhanced Geothermal

The physical security of EGS and CLG systems are dependent on the location of the inlet well, production well, and electricity generation plant. As systems have been developed to have the same inlet and production well, therefore reducing plant footprint, they can be more easily secured.

Since EGS and CLG systems produce constant energy from the Earth they do not necessarily have to be connected to a remote-control system. In fact, as seen previously, some manufacturers have already developed systems that do not require the control connections that create cybersecurity risks. The independence of this system greatly enhances the electrical security from both physical and cyber threats and, as such, can be rated as a **5** indicating it is the most secure energy source in this report.

Hydropower

Due to the location availability of hydropower this system would require vast amounts of infrastructure in the form of electrical lines spanning 180 miles that could possibly create physical risks to the system. As such it can be determined that physical security would not improve from the current grid.

Hydropower also utilizes control mechanisms that are connected to the internet and as such is not better than the current electrical grid. With the long-distance electrical line, more smart devices used to detect faults could potentially be added to the system but would allow for more gateways in the cybersecurity of the system. Due to the lack of improvements in reference to the power grid, the security category is rated as **3**.

Hydrogen Fuel Cells

As fuel cells also can have a small land footprint, this system could be located inside the base perimeter allowing for high physical security. Even if smaller units are utilized to disperse power generation, they could still be located on base. As seen in other security ratings contained in this report, the ability to be located on base increases the physical security of the system.

The cybersecurity of hydrogen fuel cells, like most systems, can be compromised in the control scheme of the system. Additionally, if the fuel cell is connected to the natural gas line at the base, then it is connected to a national interconnected line that can also be hacked. However, if a hydrogen storage system is utilized, the interconnected natural gas line can be avoided. When reviewing the security of this system, the rating is a **4** as the physical security is better, besides in the case of utilizing natural gas pipelines, but the cybersecurity is the same as the current grid.

Biomass

Biomass systems require large amount of land area for the storage of biomass fuel but they are still smaller in footprint than wind and solar energies. Even though they are smaller, the power plant could be located outside of the base perimeter. As seen in previous energy sources, due to the surrounding area of Minot AFB being largely empty, the location of the biomass electricity generation plant could be close enough to the base to still be considered as better secured than the electrical grid.

The cybersecurity of biomass systems, like many others, is affected by the use of controllers to aid in the ability to chase the electrical demand. This control scheme, although unlikely, could allow a hacker to gain control of the system. Much like other systems, the improved physical security but lack of improvement on the cybersecurity front leaves the biomass system with a rating of **4**.

Tidal Power

For this location, the use of tidal power is not very relevant due to the location availability. If a system was designed, it would require very long electrical lines that would rely on smart devices that could be hacked. With the long-distance electrical lines and smart devices, this system is comparable to the national power grid and is rated as a **3**.

Table 7 A summary of security ratings for Minot AFB.

Energy Source	Security Rating
Wind Power	4
Solar Power	4
Nuclear Power	5
Enhanced Geothermal	5
Hydropower	3
Hydrogen Fuel Cell	4
Biomass	4
Tidal Power	3

As seen in TABLE 7, the most secure systems were found to be nuclear power and EGS with their ability to be located both on a military base and have a simplified control scheme that decreases the potential for cyber threats. Hydropower and tidal power were identified as having the same security rating as the national power grid with the long powerlines and the cyber threats they involve.

Reliability

Wind Power

The reliability of wind power in this location, as seen on the wind map used in the location availability category, has been shown to have an average speed in the desirable range for wind turbines. As this is an average, it can be assumed that the wind speed ranges from wind speeds below and above this value. A look at the weather forecast for Minot AFB, shown in FIGURE 38, confirms this assumption. However, with the usage of wind, which can be rather variable, the reliability of wind energy cannot be truly relied on to fulfill the electrical load. In this case, BESS can be used to further improve the reliability of this system. With the expectation that Minot AFB typically has a wind speed suitable for wind energy generation with the backup of a BESS, the reliability of wind energy is rated as a **4** as it is highly reliable. It is not rated as a 5 due to the chance that wind might not generate the electrical demand or be sufficient enough to charge the BESS for extended periods of time.

Detailed Forecast

Today	Patchy fog before 10am. Otherwise, mostly cloudy, with a high near 40. Light north wind increasing to 9 to 14 mph in the morning. Winds could gust as high as 22 mph.
Tonight	A 50 percent chance of snow, mainly after midnight. Mostly cloudy, with a low around 25. North wind around 14 mph, with gusts as high as 24 mph. New snow accumulation of less than a half inch possible.
Tuesday	A 40 percent chance of snow before noon. Mostly cloudy, with a steady temperature around 27. North wind 14 to 18 mph, with gusts as high as 28 mph. New snow accumulation of less than a half inch possible.
Tuesday Night	Mostly cloudy, with a low around 19. North wind 8 to 16 mph, with gusts as high as 26 mph.
Wednesday	Mostly sunny, with a high near 37. West wind 6 to 8 mph.
Wednesday Night	Partly cloudy, with a low around 21. West wind 6 to 9 mph.
Thursday	Mostly sunny, with a high near 36. Northwest wind 8 to 10 mph.
Thursday Night	Mostly clear, with a low around 20. Northwest wind 6 to 9 mph becoming west in the evening.
Friday	Mostly sunny, with a high near 41. Northwest wind 9 to 11 mph, with gusts as high as 22 mph.
Friday Night	Partly cloudy, with a low around 25. West wind 8 to 11 mph, with gusts as high as 21 mph.
Saturday	Mostly sunny, with a high near 48. West wind 11 to 16 mph, with gusts as high as 28 mph.
Saturday Night	Partly cloudy, with a low around 29. West wind 10 to 13 mph, with gusts as high as 20 mph.
Sunday	Mostly sunny, with a high near 52. West wind 9 to 15 mph, with gusts as high as 24 mph.

Figure 38 The weather forecast for Minot AFB. (Week of March 3, 2025) [142]

Solar Power

Using the same rationale as wind energy and by looking at the forecast in FIGURE 38, the reliability of solar power is not as reliable as wind energy because it has less desirable conditions to start with but also is shown that solar energy cannot be counted on even during the day. Even with the usage of a BESS, a solar power system is not expected to be reliable because it could be highly likely that the BESS would not be fully charged throughout the day. Due to this observance, the reliability of solar power is rated as a **2** for Minot AFB.

Nuclear Power

As nuclear power does not rely on the inconsistent weather conditions that renewable energies do, it is generally more reliable than renewable energies. The downside of nuclear energy comes from the lack of redundancy that can be in these systems. Minot AFB does not have enough electrical demand to require multiple SMRs needed to increase system redundancy but could have redundancy if MRs are designed for. However, with this being the case, a secondary SMR module could be designed for to aid in the redundancy of the system. As nuclear power can be seen as a reliable, constant source and can have increased redundancy by being modular it is rated as a **5**. Even with a decreased response time to fluctuating energy demands, the power source can remain in constant operation.

Enhanced Geothermal

EGS and CLG systems also do not rely on weather conditions and so they can be classified as reliable systems. CLG systems can rely on numerous different lateral lines to harvest Earth’s heat, allowing for built in redundancy in that aspect. Where EGS and CLG systems can lack redundancy is the actual electricity generation equipment. If this is the case, redundant energy generation equipment can be added to the system so that the system is more dependable. For the built-in redundancy of multiple lines and the ability to add redundant equipment, this system is rated as a **5**.

Hydropower

Hydropower is less dependent on weather conditions but can be heavily affected by the seasonal conditions. When considering the seasonal conditions in North Dakota it was found that precipitation ranged from less than an inch in the winter to around four inches [143]. This shows the variation in expected seasonal precipitation. With the seasonal conditions being very diverse as well as winter temperatures often below freezing temperatures, hydropower systems cannot be relied on in this location for a third of the year. This lack of reliability correlates to a rating of **1** as it is worse than the electrical grid and other energy sources.

Hydrogen Fuel Cells

Hydrogen fuel cells do not rely on weather patterns and as such can always be counted on for electricity production. In fact, this reliability has shown up in the many reports conducted and in natural disasters that have occurred. Fuel cells also come in a variety of sizes that allow for systems to be designed for increased redundancy. Where these systems have the potential to be unreliable is if they do not have the fuel required to produce energy. However, if they are connected to the natural gas pipeline, assumed to be reliable in this report, the fuel cell is expected to have the high reliability seen in other reports. Due to their high reliability in all circumstances and their redundancy, hydrogen fuel cells receive a rating of **5** in this category.

Biomass

The biomass sourced electricity generation plants don't rely as much on weather patterns but instead rely heavily on the environment to grow plants. In this case, the biomass surrounding Minot AFB is mainly agricultural crops which are not as ideal as woody biomass. Crop residue is limited in the seasons in which it can be harvested and as such cannot be relied on throughout the whole year without receiving biomass products from other locations in the US. As they cannot be relied on for the whole year, biomass systems have a rating of **2** in this category. They are still expected to be more reliable than hydropower as the biomass products can be stored.

Tidal Power

In locations where tidal power is more available, the reliability of this system can be higher than some renewable energies due to its predictable 24-hour cycle. However, since tidal power is such a long distance from Minot AFB, the reliability of this system suffers from the potential for faults to occur on the line as the length increases. However, since tidal power does not have as much potential to freeze and does not vary like hydropower does during dry seasons, the tidal power can be rated as **3** in this category as it is similar to the national power grid.

Table 8 A summary of reliability ratings for Minot AFB.

Energy Source	Reliability Rating
Wind Power	4
Solar Power	2
Nuclear Power	5
Enhanced Geothermal	5
Hydropower	1
Hydrogen Fuel Cell	5
Biomass	2
Tidal Power	3

TABLE 8 shows that hydropower in this location cannot be relied upon due to both the climate conditions and the seasonal variation in precipitation. Nuclear power, EGS, and hydrogen fuel cells are expected to be the most reliable source as they can have built-in redundancy, rely on fuel sources assumed to be dependable, and can remain in operation during weather fluctuations.

Capability

Wind Power

As wind power is modular, as many other sources in this report, the ability to supply the electrical demand can be accomplished through the utilization of additional wind turbines. In this case, to meet the 45 MW capacity that Minot AFB has could involve (8) six MW turbines, (15) three MW turbines, or (23) two MW units from GE. The (8) turbines would be capable of producing more energy than the other two options so it would have some built in redundancy. The estimated land area to meet 45 MW of electrical demand, using the 1 MW per 60 acres mentioned earlier in this report, is around 2,700 acres. With the required amount of wind turbines to meet the electrical demand, this system can produce an excess of 3 MW which causes this system to be rated as a **4** in this category.

Solar Power

Utilizing the expected land capability of solar panels, the use of an SPV system would need roughly 355 acres to meet the electrical capacity of the base. The CSP system would be estimated to need 450 acres to fulfill the electrical capacity of the base. Both take up a rather large portion of land from the base or surrounding the base but not as much as wind energy would require. However, the capacity of the base can be fulfilled if enough solar irradiance is available, allowing the system to be rated as **3** because it fulfills the load but will need more units to exceed the electrical demand.

Nuclear Power

As touched on in the reliability rating, nuclear energy has a large energy capacity with the NuScale SMR producing 77 MW and Westinghouse's proposed MR eVinci producing 5 MW. With these capacities it would take only (1) NuScale module or (9) eVinci's to fulfill Minot AFB's electrical capacity. The reliability section also discussed the use of additional equipment to make the system more redundant. This can be done using an N+1 arrangement in which an extra module is designed and constructed within the system specifically for redundancy, ensuring the energy demand can be met even if 1 module is malfunctioning. Due to the process of nuclear fission, these energy sources can produce a lot of electrical energy with relatively little land usage with NuScale's SMR predicted to take 0.16 acres. This large power output exceeds the electrical demand with a minimal number of modules in the case of SMRs rates nuclear power as a **5** in this category.

Enhanced Geothermal

EGS and CLG systems, on the other hand, have only been shown to produce roughly 10 MW per project in both models and pilot programs. This observation suggests that either more laterals will need to be drilled and tests performed or there needs to be five different EGS or CLG systems to produce the electrical capacity. The use of multiple EGS or CLG systems will eventually meet the electrical demand. As this system is expected to be capable of meeting electrical demand through using multiple wells, it is rated as a **3**. It is not rated higher because, like other systems, to increase generation past the electrical demand would require additional wells or loops to be constructed.

Hydropower

Hydropower energy production has a varying electrical output based on the type of system selected. However, the most common electrical output from dams is under 10 MW but there is a few over 10 MW. Hydrokinetic systems have smaller electrical output with ranges from 25 to 50 kW. To fulfill the electrical capacity of Minot AFB, at least (900) fifty kW hydrokinetic turbines would need to be used. This is important to note because it will require a large portion of the river to be utilized. Despite the large portion of the river used for electrical generation, the electrical demand for Minot AFB can be achieved by using hydropower earning this system a **3**. As seen in other systems, the units needed supply the base electrical demand causing this system to be equal to the power grid.

Hydrogen Fuel Cells

Hydrogen fuel cells operate with a variety of different electrical capacities as well. However, unlike hydrokinetic turbines, some hydrogen cells can produce power in the MW values. Using FuelCell Energy's 3 MW system would require the use of (15) units. Using the dimensions found in the specifications, it was determined that these (15) units would only take around 1.5 acres of land. Much like other systems, the required amount of units would only meet the electrical demand without excess. This causes this system to be rated as a **3** in this category.

Biomass

Since biomass systems are currently being developed to be more modular in nature, their electrical energy generation has been scaled down, but the gas turbines are still capable of supporting 150 MW loads. Steam turbines and generators have capacity from 500 to 1500 kW. In the design of the electrical generation system, Minot AFB's capacity could be fulfilled by (1) gas turbine or by (30) 1500 kW steam turbines. Due to the ability of biomass systems to meet the electrical capacity of the system and, utilizing a gas turbine, produce an excess of electricity, this system is rated a **5** in capability.

Tidal Power

Tidal power is much like river hydropower systems where the use of dams in tidal ranges have many different electrical outputs and as such can fulfill the capacity of Minot AFB. Like hydrokinetic turbines, tidal stream technology is also limited so far to being in the kW range. Using ORPC's 160 kW turbines would result in the usage of 282 turbines. The ability to produce the electrical capacity of Minot AFB without any extra electrical energy causes tidal power to be rated as a **3**.

Table 9 A summary of capability ratings for Minot AFB.

Energy Source	Capability Rating
Wind Power	4
Solar Power	3
Nuclear Power	5
Enhanced Geothermal	3
Hydropower	3
Hydrogen Fuel Cell	3
Biomass	5
Tidal Power	3

TABLE 9 shows that, with the technology used today, the electrical demand can be met by all of the energy sources. This shows the advantage of using modular systems has in terms of meeting electrical demand. Where some energy sources excel more than others is the electrical output that each unit of the energy source typically produces.

Efficiency

Since the efficiency metric will use the power grid as a reference, a combined efficiency for the total generation of the power grid needs to be calculated. Using the data from TABLE 10, the net efficiency considering the weight of load percentages was calculated to be 48%. This was calculated using the equation:

$$\eta_{combined} = \sum(\text{Weight} * \eta_{Source})$$

Where $\eta_{combined}$ is the combined efficiency, weight is the percentage of electrical load, and η_{Source} is the energy efficiency of each energy source.

Table 10 Summarization of percentage of electrical production for major energy sources and their energy efficiencies.

Energy Source	Percentage of Electrical Production	Energy Efficiency
Natural Gas	37%	55%-60%
Coal	18%	32-36%
Nuclear	18%	36%
Wind	9%	40-50%
Solar	9%	20%
Hydro	9%	90%

Wind Power

As discussed in this report, the energy efficiency of the system is 40-50% with the maximum efficiency of 59.3% because the system relies on kinetic energy to drive the blades. Even though wind turbines have been increasing in energy efficiency, they are still operating at an efficiency that is similar to the national power grid. Since the efficiency of wind energy is similar to the overall efficiency of the electrical grid causing this system to be rated as a **3**.

Solar Power

Solar power energy has increased in the past few years and because of the introduction of different technologies has an efficiency of 45% for top-of-the-line SPV systems. However, some of the solar panels used due to their lower first costs only have efficiencies of around 15%. Around the same efficiency can be found in CSP systems with efficiencies being close to an average of 35% for well-maintained systems. As the energy efficiency of solar panels varies based on the cost and the majority of panel technologies being under 35%, solar power was rated as **2** in this category as it is worse than the combined efficiency of the power grid. This system efficiency is also expected to decrease in this location due to the high possibility of snow in the area.

Nuclear Power

Nuclear power has been long recognized with an efficiency of 35%. However, with newer technologies, efficiency is expected to rise to around 45% with just electricity production. With the ability to reclaim heat, energy efficiency can be boosted to 80% although this is not considered for this report. As the newer nuclear sources such as the SMR and MR are expected to increase have an efficiency of 45% this system was rated as **3** as it is similar to the power grid's efficiency.

Enhanced Geothermal

Surprisingly, EGS and CLG systems have very low efficiencies due to using the ORC to generate electricity. Using this process, energy efficiency of these systems can have an average of 15%. With new technology and more research and development, energy efficiency will hopefully rise to a more acceptable level but as of yet these systems are rated a **1** being significantly less efficient than the power grid.

Hydropower

Hydropower systems are known for their energy efficiency levels of close to 90% for the different types of turbines used in dams. The energy efficiency of hydrokinetic turbines do not follow in this characteristic but instead have the same energy efficiency as wind turbines of 59.3%. As the hydrokinetic turbines would be most likely to be used for this location, the value of 59.3% will be used in this category so hydropower is rated as a **4**. With this being the case, a further study would need to be conducted to determine the energy loss on transmission lines that would decrease the total energy efficiency of this system.

Hydrogen Fuel Cells

Hydrogen fuel cells also benefit from high efficiency ratings as they do not lose energy due to mechanical losses. These efficiencies have been reported between 50 to 60% while only producing electricity. With a system that reclaims heat, the energy efficiency can be up to 95%, showing that other energy losses when producing energy are lost as heat. As these systems have one of the highest efficiencies they are rated as **4**.

Biomass

Due to the high moisture content typically found in solid biomass products, the energy efficiency associated with power plants that use biomass drops from 35 to 20%. By using biomass products in the form of gas in hydrogen fuel cells and natural gas generators, the efficiency can be up to 60%. As either energy production could be used for Minot AFB, the higher efficiency of 60% can be used to rate biomass energy as a **4**.

Tidal Power

Tidal power, like hydropower systems, generally have high efficiencies if they are based on tidal ranges. The turbines can reach efficiencies of up to 90%. Like hydropower systems as well, the turbines used in tidal streams that utilize kinetic energy have a maximum efficiency of 59.3%. These hydrokinetic systems currently have an efficiency of 35%. As these systems have both high and low energy efficiencies the higher efficiency can be used to get a rating of **5** in this category.

Table 11 A summary of efficiency ratings for Minot AFB.

Energy Source	Efficiency Rating
Wind Power	3
Solar Power	2
Nuclear Power	3
Enhanced Geothermal	1
Hydropower	4
Hydrogen Fuel Cell	4
Biomass	4
Tidal Power	5

TABLE 11 shows that the energy efficiency values in energy production is variable based on the energy source and the technology used to harvest energy. For the probable technologies for this location, EGS were identified as having the worst energy efficiency while tidal ranges were identified as having the best energy efficiency with an overwhelming efficiency of 90%.

Constructability

For this category, since the power grid already exists and would only need to be maintained, the maximum value of 3 was used. This is because any system that will be designed for will require construction that the power grid does not need. The target lifespan, as discussed in the methodology section, was identified to be 20 years.

Wind Power

As wind energy has continued to become more available for public use, the design of wind farms has become more optimized so that the wake of each turbine does not affect the others. The process of constructing wind farms has been made easier due to the ability to manufacture wind turbines off site and ship them to the location. Once placed wind turbines have a life expectancy of 20 years. The research and development of wind turbines has produced results in the turbines to make them strong enough to endure high wind speeds but still light enough to capture acceptable energy efficiencies. The ability of this system to be developed quickly with the target lifespan gives wind turbines a rating of **3**.

Solar Power

The construction of solar powered electricity generation can include the installation of many solar panels in SPV systems and the installation of many heliostats in CSP systems. For SPV systems, equipment like disconnects, switches, and transformers are needed while CSP systems require additional equipment like the central receiver, thermal storage equipment, steam turbines and a generator. Both systems meet the desired lifespan with SPV systems having a lifespan from 20 to 40 years and CSP systems having a lifespan of 30 years. The process of construction for these systems with the lifespan more than the target amount earns solar power a rating of **3** in this category.

Nuclear Power

To help nuclear power compare to other renewable such as wind and solar, the newer SMRs and MRs have been designed to be modular, shippable, and most importantly manufactured. The manufacturing process can make nuclear power more available by having units ready to go as soon as the project permits are approved. The manufacturing of SMRs in particular can be seen by NuScale’s claim to be able to construct a plant in 3 years rather than the generally expected construction time of 5 to 10 years. The manufacturing process also allows for quality control of units to be conducted to help ensure the public safety. The US has seen many nuclear power plants last for 30 to 40 years and the new SMRs and MRs are expected to perform to this life expectancy. Even with the decrease in construction time, the longer construction process of nuclear power with a similar lifespan to other systems, this system is rated as **2** in this category.

Enhanced Geothermal

Although EGS and CLG systems might not look large on the surface, both systems require long lengths of drilling to be completed for the system to be functional. The drilling can take a large portion of the construction time as drills typically have a maximum speed of 40 to 50 feet per hour. Besides drilling, these systems also include heat exchangers, pumps and steam turbines. However, once built EGS and CLG systems have a life expectancy of around 30 years. As the construction process can be uncertain due to the speed of the drill bit and the unknown rock material coupled with the low capability of this system it can be rated as **2** for this location.

Hydropower

The construction of hydropower is very dependent on the system chosen. If conventional hydropower is designed for, the construction process can take from 5 to 8 years. Whereas with hydrokinetic turbines, the construction process involves some site observations under a preliminary permit followed by the rapid deployment of manufactured turbines once the construction permit is approved. For Minot AFB, only hydrokinetic energy would be relevant due to the location availability. With this system, the rapid deployment of turbines makes it an option but due to the long electrical lines that would need to be installed to Minot AFB, it receives a rating of **2**.

Hydrogen Fuel Cells

The construction process of fuel cells, like most other systems in the market currently, allow for quick manufacturing time. This system, like many others, has been designed to be modular to allow for greater flexibility of electrical loads to be designed for. The life expectancy of fuel cells is currently 20 years, but they have not been truly tested in their life expectancy yet. As fuel cells can be developed quickly through manufacturing and have the target lifespan of 20 years, fuel cells can be rated as **3** for this category.

Biomass

As solid biomass is used for electricity generation through a steam turbine with combustion, the construction of this site also needs more space around the steam turbine and combustor for the storage of biomass products. The processes that use biomass are both common, being the natural gas generator and the coal power plant. However, the construction of coal power plants has stopped and systems like it have not been constructed for biomass use. A typical power plant construction takes around 4 years to complete and can remain in operation for 40 years. As these systems have a lifespan of 40 years but require several years of construction, biomass power is rated as a **2** in this category.

Tidal Power

The construction of tidal power is similar to hydropower in that the two system types available have different construction times. The design of tidal ranges can take longer to construct but they can reach lifespans of 40 to 120 years. Tidal streams, like river hydrokinetic turbines, can be constructed quickly due to the manufacturing of turbines but it still requires site observations and preliminary licenses. Additionally, with both systems, national and state conservation departments can require documentation to ensure threatened and endangered species are not harmed in the electrical generation process meaning that even more observations need to be completed when the system are installed. This system could be a good use of long construction periods with a long lifetime but for this location, in addition to the electrical generation plant comes the installation of the electrical lines to get to Minot AFB. As this idea is not feasible due to the large amount of construction involved with the long electrical lines and the power generation site, especially when using tidal ranges, it is rated as **1**.

Table 12 A summary of constructability ratings for Minot AFB.

Energy Source	Constructability Rating
Wind Power	3
Solar Power	3
Nuclear Power	2
Enhanced Geothermal	2
Hydropower	2
Hydrogen Fuel Cell	3
Biomass	2
Tidal Power	1

TABLE 12 shows that the construction of these energy systems will require more construction than the power grid. However, there are several energy sources that are able to be constructed in a timely manner with the desired lifespan that would make them comparable to the national power grid. This table also shows that some of the energy sources have longer construction times due to either a more unique process of permitting or a longer construction period due to on-site construction.

Maintenance

Wind Power

In the 20-year lifespan, wind turbines need to be inspected at least once every year to ensure all of the connection points are tight and there is no wear and tear that could ultimately cause the wind turbine to malfunction. Besides the inspections, some expected maintenance includes replacing edge tape every 2 to 4 years and a bearing or blade every 5 to 10 years. Wind farms are dominant in areas close to Minot AFB so there is assumed to be crews that can aid in the maintenance of wind turbines. With the expected maintenance of this system over the shorter lifespan gives wind energy a rating of **3**.

Solar Power

The main challenges facing both SPV and CSP systems are the ability to keep the solar panels and heliostats clean. This is important because it can directly impact the amount of power produced by the solar plant by affecting energy efficiency. It is important to consider the environment when looking as the maintenance of both of these systems. Besides not having the desired amount of solar irradiance, North Dakota is also known for it snow throughout the winter months. The snow would be a direct cause for more maintenance than is originally planned for solar systems located in more favorable climates. As the climate at Minot AFB would require more maintenance of the system, the system is rated as a **2**.

Nuclear Power

The operation and maintenance in SMRs and MRs is expected to be safer than conventional nuclear power plants. This comes from the development of systems with passive safety measures that can ensure the plant can be shut down in an emergency. Some advantages of the SMRs and MRs are the extended refueling periods that can range from 7 years to 30 years. This makes nuclear power more convenient to use due to the elimination of needing to refuel the system frequently. One concern for maintenance that is negligible at Minot AFB is the technical skill required to maintain a nuclear power plant. This can be neglected due to the handling of nuclear material on the base by both the bomber and missile wings that reside at Minot AFB. As the maintenance of nuclear energy can be performed by personnel on base and has long time periods between refueling, this system is rated as a **4**.

Enhanced Geothermal

The maintenance associated with EGS and CLG systems can be expected to be very minimal. Since most of the system piping is underground, the only way to tell that fluid is being lost is through the amount of makeup water needed during operation. Even so, in most models, any pieces of the system below ground are assumed to not require maintenance. This leaves just the surface equipment which is just the steam turbine and heat exchange with the possibility of pumps. In CLG systems, the equipment does not have to be cleaned regularly either due to the HTF being water and not being able to pick up rocks and minerals the EGS can pick up in the thermal reservoir. EGS and CLG systems requires some of the least amount of maintenance due to most of the system being located underground and the equipment that does need maintained being common in industry, this system is rated as a **5**.

Hydropower

The maintenance of hydropower is based on what hydropower system is designed. As dams affect more of the environment downstream, they require more inspections and maintenance in the form of structural support to ensure the dam does not fail. Hydrokinetic turbines do not need to be inspected for structural damage but should be checked for debris that can get stuck in the turbine blades. As these systems do not require constant maintenance and are located 180 miles from Minot, they are rated as a **2** because of the long distance of electrical lines needed to be maintained.

Hydrogen Fuel Cells

Since fuel cells do not have any moving parts, they do not need to be maintained as often as other systems like turbines and generators. However, the system still needs to be checked due to the electrochemical process used to make electricity. The other part of maintenance that fuel cells require is refueling if they are not connected to a natural gas line. In most cases for emergency power, 72 hours' worth of hydrogen is stored in a hydrogen storage tank. To circumvent the process of refueling, hydrogen fuel cells can also be connected to the natural gas lines. Since hydrogen fuel cells do not require as much maintenance as other system due to the electrochemical process, this system is rated as a **5**.

Biomass

The main downside of biomass is the refueling and the preprocessing that is needed to use it as a viable alternative energy source. Biomass by itself is not very energy dense and so the densification process must take place before being used. If the biomass is not densified, it could also be used as biogas or syngas. The whole process can take time and is best performed by manufacturers of biomass products that already have processes in place. Having others perform the densification or gasification process still requires transport to and from the energy generation site leading to supply coordination that other systems in this report do not have to deal with. Biomass energy requires a large amount of maintenance, in the form of refueling, to keep the system operational and also requires the coordination of supply routes that are not as necessary to other sources. Due to the large amount of maintenance needed in the form of processing fuel and refueling biomass energy receives a rating of **2**.

Tidal Power

The ease of maintenance for tidal ranges was found to mainly involve the cleaning of the turbine from trash, silt, and some tree limbs. This occurs as the tide ebbs and flows, carrying with it items that can cause damage to the turbines. To protect the turbines, trash racks can be utilized but then the trach racks will need to be cleaned more frequently. Tidal stream technology on the other hand does not have to worry about the driftwood as they are on the bottom of the ocean floor. Since they are located on the bottom, systems have been developed to allow for either multiple turbines to be hoisted up for maintenance or individual turbines have buoyancy devices to float up for maintenance. Even though the maintenance for tidal power is becoming more time efficient in tidal streams due to the design of equipment this system is rated as a **1**. This low maintenance rating is largely in part to the long electrical lines that would be utilized to generate power for Minot AFB.

Table 13 A summary of maintenance ratings for Minot AFB.

Energy Source	Maintenance Rating
Wind Power	3
Solar Power	2
Nuclear Power	4
Enhanced Geothermal	5
Hydropower	2
Hydrogen Fuel Cell	5
Biomass	2
Tidal Power	1

TABLE 13 identifies EGS and hydrogen fuel cells as being the best in maintenance as these types of systems have a large portion of the energy generation process that does not require as much maintenance. The table also shows that the systems that require frequent refueling, a lot of processing, and incorporate long electrical lines are undesirable in terms of maintenance.

Overall Rating

The overall ratings that can be used to determine the best energy source to use at Minot AFB is shown below in TABLE 14.

Table 14 The overall ratings for energy sources at Minot AFB.

Energy Source	Overall Rating
Wind Power	28
Solar Power	22
Nuclear Power	34
Enhanced Geothermal	30
Hydropower	20
Hydrogen Fuel Cell	33
Biomass	26
Tidal Power	20

Recommendations

Upon reviewing the information and proceeding through the rating process developed in this report, an appropriate alternative energy source for Minot AFB in North Dakota is nuclear power. As mentioned previously in this report, the national power grid will serve as the backup power in case of system failure. Nuclear power is an appropriate alternative energy source considering that it is a highly reliable system that does not depend on weather conditions. The factory manufacturing process that nuclear module manufacturers have developed help these systems be easily designed as well as decreasing construction time like in the case of NuScale. The other options that are better than the national power grid are hydrogen fuel cells, EGS, wind power, and biomass.

Following the process outlined in this report, nuclear power, hydrogen fuel cells, EGS, wind energy, and biomass might be investigated further if extenuating circumstances such as cost come into play. This report identifies nuclear power as being the best option considering the criteria of location availability, security, reliability, capability, efficiency, constructability, and maintenance. Hydrogen fuel cells, EGS, wind energy, and biomass were identified with an average higher rating than the power grid in this report as well. The next step for the process would be to perform a life cycle cost analysis of these systems to determine which one makes the most economical sense. To do this a budget for the project would need to be determined.

Another step would be to investigate the equipment that manufacturers have available for construction as well as experts in designing the system identified as the best option after the life cycle cost analysis. This report identified energy sources that are being utilized currently or are on the threshold of becoming readily available that military facilities can look into.

As this report suggests, the current electrical conditions are a threat to national security that should raise concern for the military. The projects already under construction show that alternative energy sources are being designed at military facilities. This report shows several factors that should be considered when determining alternative energy sources. Once systems are identified as being viable options, other steps such as a life cycle cost analysis and available equipment should further narrow down energy sources to the most preferred energy source.

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Appendix A - Alternative Energy Selection Form

Alternative Energy Source Selection Form

This form is to evaluate alternative energy sources to be utilized at facilities. To fill out this form refer to the page attached with "Instructions to filling out the Alternative Energy Source Selection Form."

1. Project Information - Fill out the following project information

Installation Name: Minot Air Force Base

Address: 220 Peacekeeper PL
Minot AFB, ND 58704

Facility Manager:

Project Coordinator: Drew Holliday

2. Current Conditions - Fill out the following current conditions to aid in project evaluation

Energy Provider: Verendrye Electric Cooperative

Base Energy Capacity: (1) 30 MVA XFMR + (1) 15 MVA XFMR = 45 MVA XFMR

3. Location Resources - Investigate the following location details to aid in energy source evaluation

Average Wind Speed: 7-7.9 m/s

Average Solar Irradiance: 3.5-4.0 kWh/m2/day

Climate Data: Cold in the winter and spring, Hot summers, chilly fall, average rainfall from spring until fall is abotu 3" per month

Geographical Data: A few lakes and rivers but no major rivers, mainly flat agricultural land

4a. Project Evaluation - In this section, list the possible energy sources that will be evaluated for this project

Energy Sources Considered: Wind, Solar, Nuclear, Enhanced Geothermal, Hydropower, Hydrogen Fuel Cells, Biomass, Tidal Power

4b. Location Ratings - The location rating is based on the availability of surrounding resources and their effect on how much power can be produced as well as infrastructure required to carry electricity to location.

Energy Sources:	1	2	3	4	5
Wind	○	○	●	○	○
Solar	○	●	○	○	○
Enhanced Geothermal	○	○	○	●	○
Hydropower	○	●	○	○	○
Nuclear	○	○	○	○	●
Fuel Cell	○	○	○	○	●
Tidal Power	●	○	○	○	○
Biomass	○	○	●	○	○
	○	○	○	○	○

4c. Security Ratings - The security rating is determined based on the physical and cyber threats that will exist. This section includes the security of the infrastructure and the controls necessary for the system to function.

Energy Sources:	1	2	3	4	5
Wind	○	○	○	●	○
Solar	○	○	○	●	○
Enhanced Geothermal	○	○	○	○	●
Hydropower	○	○	●	○	○
Nuclear	○	○	○	○	●
Fuel Cell	○	○	○	●	○
Tidal Power	○	○	●	○	○
Biomass	○	○	○	●	○
	○	○	○	○	○

4d. Reliability Ratings - The reliability rating is based on the capability of producing a steady source of energy and the infrastructure required to produce a steady flow of electricity.

Energy Sources:	1	2	3	4	5
Wind	○	○	○	●	○
Solar	○	●	○	○	○
Enhanced Geothermal	○	○	○	○	●
Hydropower	●	○	○	○	○
Nuclear	○	○	○	○	●
Fuel Cell	○	○	○	○	●
Tidal Power	○	○	●	○	○
Biomass	○	●	○	○	○
	○	○	○	○	○

4e. Capability Ratings - The capability rating is based on the system's ability to produce the full electrical load of the project location. This section also addressed the amount of units that will be required.

Energy Sources:	1	2	3	4	5
Wind	○	○	○	●	○
Solar	○	○	●	○	○
Enhanced Geothermal	○	○	●	○	○
Hydropower	○	○	●	○	○
Nuclear	○	○	○	○	●
Fuel Cell	○	○	●	○	○
Tidal Power	○	○	●	○	○
Biomass	○	○	○	○	●
	○	○	○	○	○

Alternative Energy Source Selection Form

4f. Efficiency Ratings - The efficiency rating is to determine the effective use of resources. The location of the project may affect the efficiency ratings of some systems.

Energy Sources:	1	2	3	4	5
Wind	○	○	●	○	○
Solar	○	●	○	○	○
Enhanced Geothermal	●	○	○	○	○
Hydropower	○	○	○	●	○
Nuclear	○	○	●	○	○
Fuel Cell	○	○	○	●	○
Tidal Power	○	○	○	○	●
Biomass	○	○	○	●	○
	○	○	○	○	○

4g. Constructability Ratings - The constructibility rating involves the amount of construction, expected timeline of construction, and the life expectancy of the system.

Energy Sources:	1	2	3	4	5
Wind	○	○	●	○	○
Solar	○	○	●	○	○
Enhanced Geothermal	○	●	○	○	○
Hydropower	○	●	○	○	○
Nuclear	○	●	○	○	○
Fuel Cell	○	○	●	○	○
Tidal Power	●	○	○	○	○
Biomass	○	●	○	○	○
	○	○	○	○	○

4h. Maintenance Ratings - The maintenance rating is based on the amount and frequency of interactions with the system. Interactions include repairs, refueling, and general upkeep.

Energy Sources:	1	2	3	4	5
Wind	○	○	●	○	○
Solar	○	●	○	○	○
Enhanced Geothermal	○	○	○	○	●
Hydropower	○	●	○	○	○
Nuclear	○	○	○	●	○
Fuel Cell	○	○	○	○	●
Tidal Power	●	○	○	○	○
Biomass	○	●	○	○	○
	○	○	○	○	○

4i. Overall Ratings - This section is to summarize the ratings of each source. In the column, add the ratings with a factor of 2 being applied to security, of each section to get the overall rating of the system.

Energy Sources:	
Wind	28
Solar	22
Enhanced Geothermal	30
Hydropower	20
Nuclear	34
Fuel Cell	33
Tidal Power	20
Biomass	26

5. Additional Comments - This section is to address any comments related to the systems evaluated.

6. Energy Source Recommendations - This section is to identify the systems that are recommended to be investigated as alternative energy sources for the identified project. If tied, preference is given to the most secure system.

Highest Rated/Recommended Source: Nuclear

Other Viable Sources: Hydrogen Fuel Cell, Enhanced Geothermal

Wind, Biomass

7. Signature Section - This section is used for authentication and includes project personnel, facility personnel, and the installation commander.

Project Coordinator:

Facility Manager:

Project Supervisor:

Installation Commander:

Instructions to filling out the Alternative Energy Source Selection Form

Section 1 - Project Information

Installation Name - Fill in the blank with common name of the installation the alternate energy sources will be evaluated for.

Address - Fill in the blank with the main address associated with the installation the alternate energy sources will be evaluated for. If multiple addresses, use the address of the installation's maintenance building.

Facility Manager - Fill in the blank with the person in charge of the facility maintenance and/or utilities.

Project Coordinator - Fill in the blank with the person conducting the project.

Section 2 - Current Conditions

Electric Provider - Fill in the blank with the main energy provider supplying electricity to the base. If the base is supplied by multiple providers, list all of them.

Base Electrical Capacity - Fill in the blank with the base design for electricity capacity. This can be the sum of the size of the transformers supplying the base with electricity. If the project is only to supply part of the base electrical capacity, denote the desired electrical generation by "Generating XXX MW of Total of XXX MW."

Section 3 - Location Resources

Average Wind Speed - Fill in the blank with the average wind speed of the project location. The average wind speed can be obtained by local wind speed data or through the National Renewable Energy Laboratory.

Average Solar Irradiance - Fill in the blank with the average solar irradiance of the location. The average solar irradiance can be optained through local solar irradiance data or through the National Renewable Energy Laboratory.

Climate Data - Fill in the blank with the climate data of the project location. Climate data should include: average precipitation, average snowfall, the climate in terms of expected temperature conditions. Some sources to obtain this data is local weather stations, governmental historical climate agencies, and 3rd party climate assessors such as ASHRAE.

Geological Data - Fill in the blank with the geological data of the project location. Geological data should include: water sources in the surrounding area, evaluation of travel routes, expected vegetation, and existing landforms such as hills, plateaus, and mountains.

Section 4a - Project Evaluation

Energy Sources Considered - Fill in the blank with energy sources that will be included in the evaluation. Common sources include but are not limited to: Wind, Solar, Enhanced Geothermal, Hydropower, Nuclear, Fuel Cells, and Tidal Power.

Section 4b - Location Ratings

In this section the location resources gathered in Section 3 will be used to determine the energy sources that will generate electricity (in the ratings designated as perform) well in the area with respect to the current electrical grid and other sources. The ratings in respect to the current electrical grid are as follows: 1-will perform very poorly and worse than the grid, 2-will perform worse than the grid but has more potential than rating 1, 3-will perform at the same level of the grid, 4-will perform slightly better than the grid, 5-will perform much better than the current grid and better than any other source.

Section 4c - Security Ratings

In this section the security of a system will be rated in respect to the current grid. Security measurements are based on the threat level of physical attacks and cyber attacks meant to bring the system offline. The ratings in respect to the current electrical grid are as follows: 1-will have high amount of threats and will be more susceptible to being brought offline than the grid and other sources, 2-will have high amount of threats and will be more susceptible to being brought offline than the grid but will be easier to protect than rating 1, 3-will have the same threat level and protection measures as the grid, 4-will have less threats and will require less protection than the grid, 5-will have much less threats and will require less protection than the grid and other sources.

Section 4d - Reliability Ratings

In this section the reliability of the system will be rated in respect to the current electrical grid. Reliability is how susceptible the system is to being affected by weather conditions and the ability to repair a system to produce full capacity in the case of failure. The ratings in respect to the current electrical grid are as follows: 1-will be in more risk of becoming offline in adverse weather conditions than the grid and other sources, 2-will be in more risk of becoming offline than the current grid but will be in less risk than rating 1, 3-will be in the same amount of risk as the grid, 4-will be more dependable than the current grid in adverse weather conditions, 5-will be more dependable than the grid and other sources in adverse weather conditions.

* For the instructions in filling out Section 4e through Section 7 see the next page.

Instructions to filling out the Alternative Energy Source Selection Form

Section 4e - Capability Ratings

In this section the capability of the system will be rated. The capability of the system includes how many units will be needed to meet the project electrical capacity and their ability to meet the demand at all times. The ratings are as follows: 1-will require many units and land area in order to meet the electrical demand, 2-will require a large amount of units and land area to meet the electrical demand but will require less than rating 1, 3-will adequately meet the electrical demand without the usage of many units or land area, 4-will have the capacity for generating more electricity than needed allowing for electricity to be stored or used in emergency for the surrounding area, 5-will have the capacity for generating more electricity than needed and more than any other sources allowing for electricity to be stored or used in emergency for the surrounding area.

Section 4f - Efficiency Ratings

In this section the efficiency of the system will be rated in respect to the current electrical grid and other sources. The efficiency of the system is the percentage of total energy that can be converted into electrical energy from another energy medium. The ratings in respect to the current grid are as follows: 1-will have very poor efficiency when compared to the grid and other sources, 2-will have a lower efficiency than the current grid but will be more efficient than rating 1, 3-will have an efficiency that is similar to the current grid, 4-will have an efficiency better than the current grid, 5-will have an efficiency better than the current grid and other sources.

Section 4g - Constructibility Ratings

In this section the constructibility is in respect to the other sources. The constructibility includes the amount of construction, the expected timeline of construction to get the system online, and the life expectancy of the system. The ratings are as follows: 1-will require a longer time and have a shorter life expectancy than the other sources, 2-will require a longer time and/or have a shorter life expectancy than other sources but is constructed faster and/or lasts longer than rating 1, 3-is able to be constructed in a short amount of time and/or has a mediocre lifespan when compared to other sources, 4-will be able to brought online in a very short amount of time and/or will last longer than most of the other sources, 5-will be able to be constructed in a very short amount of time with a very long lifespan when compared to the other sources.

Section 4h - Maintenance Ratings

In this section the maintenance of the system will be rated in respect to the grid and other sources. Maintenance includes the frequency of general upkeep, refueling, and average time of repairs. The ratings are as follows: 1-will require very frequent upkeep/refueling and/or has a long expected time for repairs with the possibility of hindering the mission of the project location, 2-will require frequent upkeep/refueling and/or has a long expected time for repairs but requires less maintenance and/or has faster repair times that rating 1, 3-will require some upkeep/refueling and has a reasonable amount of time for repairs that will not hinder the mission, 4-will require very little upkeep/refueling and/or repairs can be performed in a short amount of time, 5-will require minimal amount of upkeep/refueling and/or repairs are expected to be performed very quickly.

Section 4i - Overall Ratings

In this section the sum of the ratings will be calculated and shown. The overall rating of a source should correlates with the recommendation. In effect, the source with the least overall rating is the least recommended/viable option for the project location while the highest overall rating should be the most recommended/viable option for the project location.

Section 5 - Additional Comments

This section provides a way to voice any concerns or comments about the different energy sources that would influence the recommendations for energy source selection.

Section 6 - Energy Source Selections

Highest Rated/Recommended Source - Fill in the blank with the highest rated or the most recommended source if different than highest rated. Denote if not using the highest rated by "Recommended - XXXX" otherwise, list the energy source.

Other Viable Sources - Fill in the blanks if there are other options that are rated to be better than the current grid. A rating that would indicate that a source is better than the current grid would be a rating higher than 21.

Section 7 - Signature Section

Project Coordinator - Fill out the blank with the person conducting the project's rank and name. Have the project coordinator sign the form.

Project Supervisor - If applicable, fill out the blank with the project supervisor's rank and name and have the project supervisor sign the form.

Facility Manager - Fill out the blank with the facility manager's rank and name. Have the facility manager sign the form.

Installation Commander - If applicable, fill out the blank with the installation commander's rank and name and have the installation commander sign the form.

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Good luck and take care!

Thank you, Dana Hager

Dana Hager
Manager, Communications
Basin Electric Power Cooperative
Member & External Relations
1717 E Interstate Avenue | Bismarck, ND 58503
Direct: (701) 557-5344
dhager@bepc.com | basinelectric.com

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Barbara Murphy
Manager, Sales and Marketing
National Academies Press
500 5th Street, Keck 351
Washington, DC 20001
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Jordan Foster | Senior Communications Strategist | jfoster@spp.org | Office: 501-614-3370
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