# Evaluation of Renewable Energy Technologies and Their Potential for Technical Integration and Cost-effective Use within the U.S. Energy Sector

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## Abstract

Energy demands, environmental impacts of energy conversion, and the depletion of fossil fuels are constant topics of discussion in the energy industry. Renewable energy technologies have been proposed for many years to address these concerns. However, the transformation from traditional methods of power generation, usually based on fossil fuels, to power generation based on renewable resources presents many challenges associated with emerging, or less established, technologies. This paper examines the role of renewable energy in the U.S. and its potential to meet current and future energy needs in a way that is technically and economically sound. Renewable energy technologies, ranging from well-developed and established to new and emerging technologies, are presented in terms of their technical potential, current state of the technology, potential for further growth, and economic potential. While renewable energy sources are abundant across the U.S., issues of dispatchability, variability, scalability, energy storage, geographic limitations, and investment costs are critical in determining future progress. The analysis in this paper can be used to guide the integration of renewable energy systems toward becoming a larger share of energy production.

*Keywords:*
renewable energy, power generation, electrical grid, emerging energy systems, system integration

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## 1. Introduction

Renewable energy technologies have emerged as fast-growing alternative energy sources to provide sustainable power generation for the future. While renewables are described as 'alternative,' some technologies are poised to compete with traditional power generation sources and to meet the energy demands of buildings, cities, and regions in the United States. The introduction of renewable energy systems to existing electrical grids occurs at

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the same time as the rapid depletion of fossil fuels that are commonly fueling the traditional power generation sources. Additionally, greenhouse gas emissions from burning fossil fuels also create environmental concerns such as ozone layer depletion, acid rain, and global climate change [1]. Renewable energy systems are energy systems that generate electricity from renewable resources such as bio energy, geothermal energy, hydro energy, ocean energy, wind energy, and solar energy. The use of renewable energy systems has the potential to replace traditional methods of generating power from burning fossil fuels [2, 3, 4]. Countries with limited fossil fuel resources have more energy security since renewable energy resources can be substituted as replacements for fossil fuels. Furthermore, air pollution reductions can be achieved since power generation from renewable energy resources release less greenhouse gases. Renewable energy systems can also contribute toward energy price stability and affordability [5]. The implementation of renewable energy systems into existing electrical grids is becoming a natural next step to meet the energy demand for the future and to protect the environment.

Energy demand worldwide has increased significantly in recent decades. Developed countries require a stable supply of energy for daily operations while developing countries rely on the energy supply for economic development. The total world primary energy consumption was around 160,310 million MWh (547 quad BTU) in 2014 [6]. Furthermore, this number had been projected to be increased to 240,318 million MWh (820 quad BTU) in 2040 [7]. The technical global potential of renewable energy is approximately more than 18 times compared to the current world primary energy consumption [1]. The current contribution of renewable energy technologies toward the world primary energy consumption was about 22% [1]. The share of renewable energy in energy consumption varies across countries and regions, which depends on available resources, development of technologies, and government policies.

In the U.S., the total primary energy production in 2016 was 24,618 (84 quad BTU) while renewable energy production was 2931 million MWh (10 quad BTU), which was equivalent to 12% of the total primary energy production [8]. Among different renewable energy technologies, biomass energy, hydroelectric energy, wind energy, solar energy, and geothermal energy are contributing the most in terms of primary energy production by source [8]. Furthermore, solar energy and wind energy are the fastest growing renewable energy technologies. The primary energy production of solar energy has increased from less than 17.6 million MWh (0.06 quad BTU) in 1990 to 176 million MWh (0.6 quad BTU) in 2016 [8]. Similarly, wind energy has rapidly increased from less than 8.8 million MWh (0.03 quad BTU) in 1990 to 615 million MWh (2.1 quad BTU) in 2016 [8]. Biomass energy has almost doubled the primary energy production from 791 million MWh (2.7 quad BTU) in 1990 to 1377 million MWh (4.7 quad BTU) in 2016 [8]. On the contrary, hydroelectric energy and geothermal energy production have been steady due to the maturity of these technologies.

Renewable energy research has generated interest and excitement around the scientific community. Review articles on different aspects of renewable energy technologies show recent development and advancement [9, 10, 11, 12, 13]. Besides focusing on improving the existing technologies for better implementation, research interests in new areas of renewable energy have also sparked. Ocean energy research in recent years has shown the potential of power generation from wave energy, tidal energy, current energy, and osmotic energy [10, 14, 15, 16, 17]. Furthermore, urban wind power generation is another promising research area for dense urban areas [18, 19, 20]. The use of urban wind energy can integrate wind power generation with city planning. Additionally, this integration reduces the dependence of wind energy large area of land for wind farms. Within solar energy research, organic solar cell research has emerged as an alternative to silicon-based solar cells [21, 22]. These forward-thinking research has pushed the boundary of renewable energy into exploring new possibilities.

In this paper, the current state of energy usage in the U.S. is presented in the context of fossil fuels, nuclear energy, and renewable energy. Furthermore, the opportunity for renewable energy to increase its presence for the share of primary energy consumption in the U.S. is investigated. Different types of developed and emerging renewable energy technologies are reviewed in terms of their development and limitations. Some of the challenges for transformation toward renewable energy are grid reliability, energy storage, system cost, and system lifetime. Careful considerations of these issues are necessary to ensure the success of integrating emerging renewable energy systems into the existing electrical grids.

## 2. Primary energy consumption and renewable energy conversion

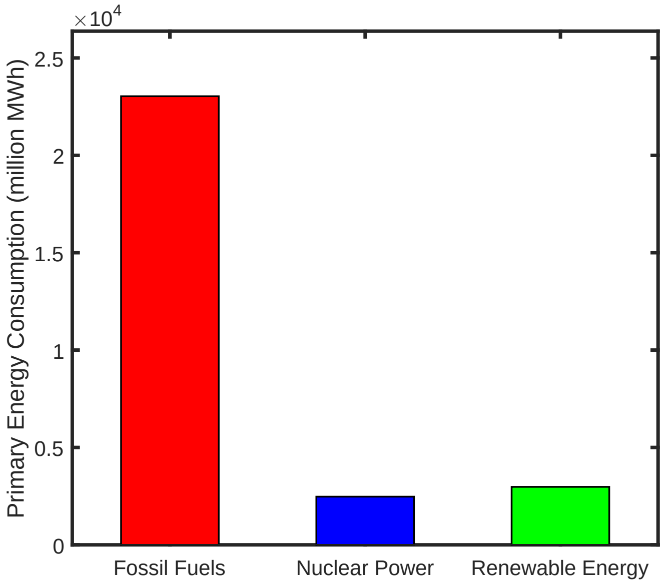


Figure 1: Primary energy consumption by source in 2016 [8].

The U.S. is one the the world's largest consumers of primary energy. The primary energy consumption in the U.S. is shared between commercial, industrial, residential, and transportation sector. In 2016, the U.S. primary energy consumption was 28,545 million MWh (97.4 quad BTU) [8]. Figure 1 illustrates the percentage of the primary energy consumption from fossil fuels, nuclear power, and renewable energy. Renewable energy has become a significant and fast-growing sector in the primary energy consumption in the U.S., which is currently dominated by fossil fuels. Fossil fuels registered 23,035 million MWh (78.6 quad BTU) out of 28,545 million MWh (97.4 quad BTU) total primary energy consumption in 2016. The use of fossil fuels peaked in 2007 at 25,175 million MWh (85.9 quad BTU) [8]. This number has been slightly decreased over the last few years. Furthermore, nuclear energy contributed 2462 million MWh (8.4 quad BTU) in 2016 to the total primary energy consumption [8]. Nuclear energy has consistently contributed about 2345 million MWh (8 quad BTU) since 2000. The primary energy consumption by renewable energy was 2989 million MWh (10.2 quad BTU), which was about 10.5% of total primary energy consumption in the U.S. in 2016 [8]. The percentage of each renewable energy technology is shown in Fig. 2. This figure accounts for energy usage as the whole mix in different sectors. The renewable energy share in the total primary energy consumption has steadily increased year over year. The primary energy consumption from renewable energy was 1758 million MWh (6.0 quad BTU) in 1990, whereas this number increased to 2989 million MWh (10.2 quad BTU) in 2016. While the total primary energy consumption in the U.S. has also been fairly constant since 2000, the share of renewable energy still manages to increase every year.

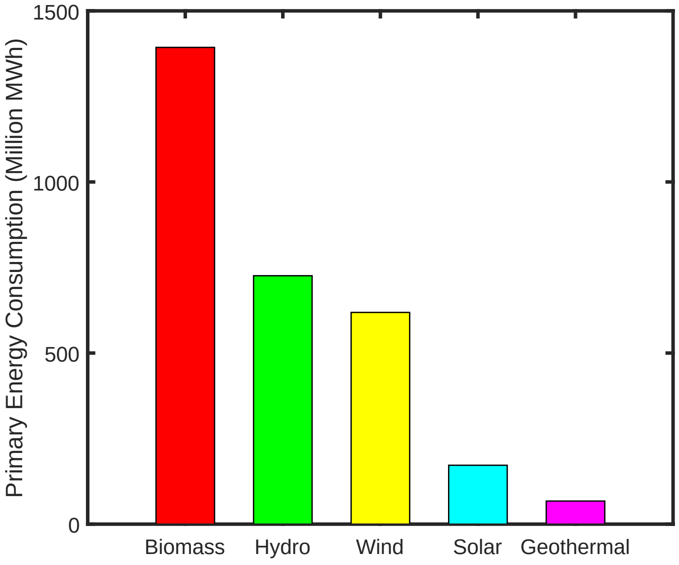


Figure 2: Primary energy consumption within renewable energy in 2016 [8].

Electricity generation is an important part of renewable energy technologies. The total net electricity generation from renewable energy in all sectors in the U.S. in 2016 was 609 million MWh [8]. During the same year, the total net electricity generation from all sources was 4079 million MWh [8]. As a result, about 15% of the electricity generation in the U.S. in 2015 came from renewable energy. As seen in Fig. 3, electricity generation from renewable energy has gradually increased over the last decade. The introduction of electricity generation from renewable energy to the electrical grid is a challenge. A large number of power injection from renewable energy can cause voltage fluctuation, which reduces the stability of the networks [23, 24, 25]. The grid infrastructure in the U.S. is complex and involves many system owners and operators. The North American Electric Reliability Corporation (NERC) is a non-profit corporation "whose mission is to assure the reliability and security of the bulk power system in North America" [26]. As seen in Fig. 4, there are eight Regional Entities for which NERC has the authority to monitor and enforce compliance [26].

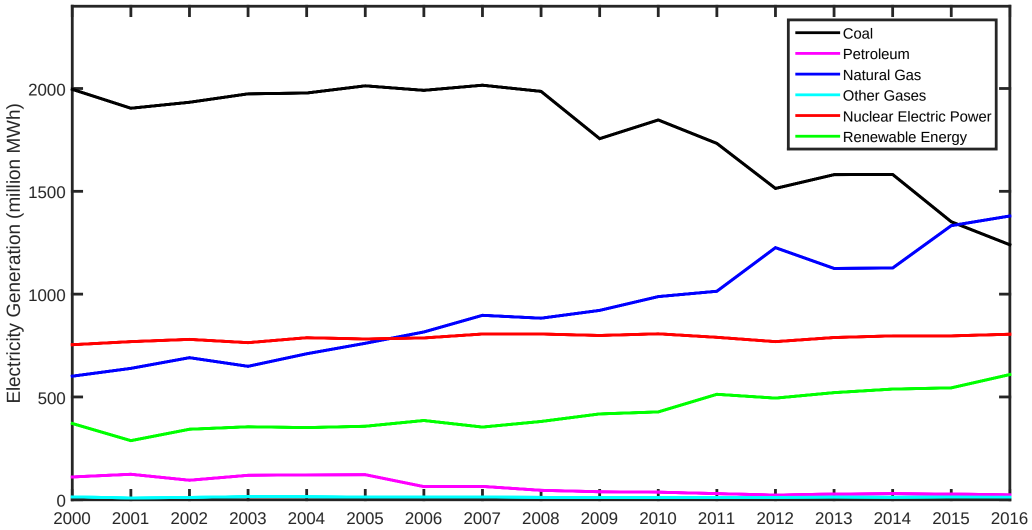


Figure 3: Electricity generation in the U.S. [8].

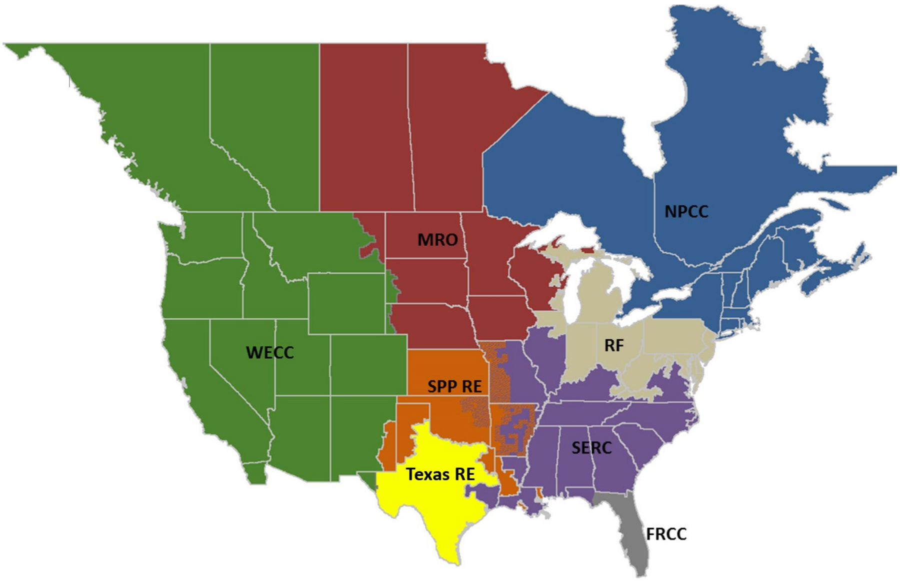


Figure 4: Regional entities in NERC [26].

Renewable energy consumption targets have been introduced in the U.S. in different levels. The main purposes are to increase the presence of renewable energy in power generation and reduce the energy dependence on fossil fuels. The U.S. government targets to achieve 30% of electricity consumed by the federal government agencies from renewable energy by 2025 [27]. The current renewable electricity consumption by the U.S. government is 8.76% in 2014 [27]. U.S. states and territories also adopt renewable portfolio standards (RPS) to increase the use of renewable electricity, even though the renewable energy targets vary for different states. The state RPS policies significantly contribute toward the growth of renewable energy in the U.S. [28]. As of 2016, 29 states, Washington D.C., and 3 territories have set renewable energy goals. Besides the states with renewable energy goals, there are 8 U.S. states and one territory with voluntary renewable energy goals. The rest of the U.S. states and territories do not have renewable energy targets [29]. Figure 5 details all U.S. states and territories with and without renewable energy targets [29].

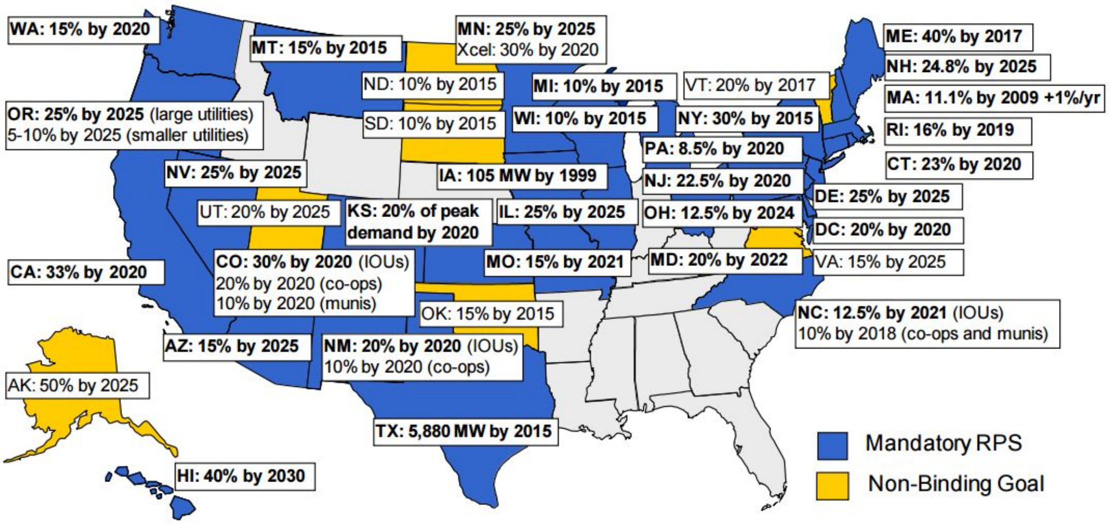


Figure 5: U.S. states and territories renewable energy targets [28].

U.S. cities also have their own renewable energy targets. Several cities around the U.S. have recently reported that they achieved 100% clean electricity to power their cities [30] (see Table 1). These grid-connected cities receive their energy from nearby renewable energy power plants. Furthermore, the energy consumptions that from these cities are equal to the energy productions from renewable energy during the same period. As of 2016, there are three cities in the U.S. that claim to have reached 100% clean energy: Burlington, VT; Aspen, CO; and Greensburg, KS. Burlington, Vermont was one of the first cities to reach 100% clean energy [30]. The city, with a population of 42,282, reached 100% renewable electricity in 2014. The breakdown of renewable energy sources is as follows: 30% biomass, 50% hydropower, and the rest from wind, solar, and landfill methane. In the case of Aspen, Colorado, 100% renewable electricity achieved in 2015, consisted of 50% of wind energy, 45% of hydro energy, and 5% from solar energy [30]. Cities around the U.S. have also their renewable energy targets for the near future. For example, San Diego, California has set the target for 100% renewable electricity by 2035. The current status was 33% in 2014. Other cities in California have also set renewable energy targets, such as San Jose 100% renewable electricity by 2022 and San Francisco 100% renewable electricity by 2030 [30].

Table 1: U.S. cities with 100% renewable electricity target.

| City | Target Year |
|---|---|
| Greensburg, KS | 2013 (achieved) |
| Burlington, VT | 2014 (achieved) |
| Aspen, CO | 2015 (achieved) |
| Georgetown, TX | 2017 |
| East Hampton, NY | 2020 |
| Grand Rapids, MI | 2020 |
| San Jose, CA | 2022 |
| San Francisco, CA | 2030 |
| Rochester, MN | 2031 |
| San Diego, CA | 2035 |

## 3. Descriptions of developed and emerging renewable energy technologies

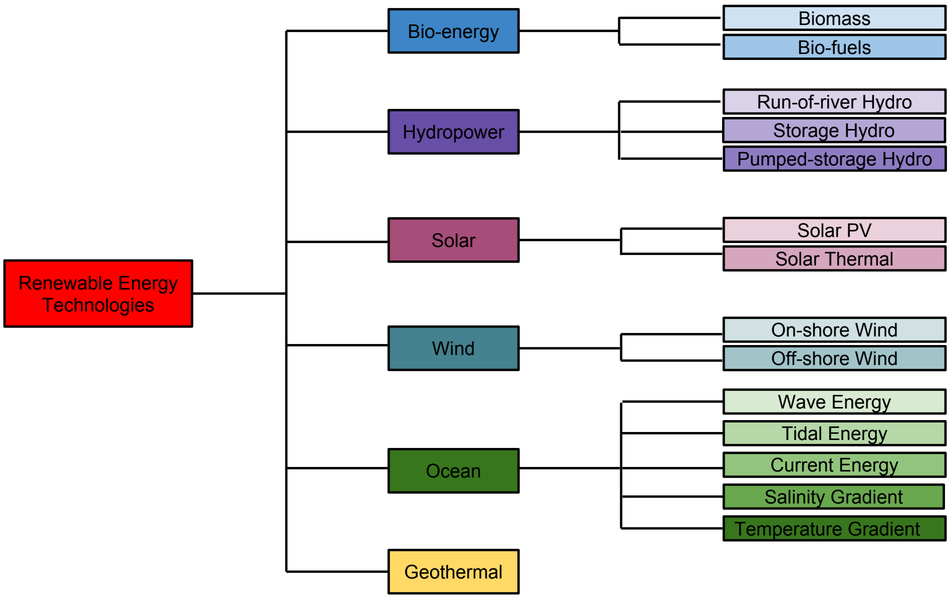


Figure 6: Different renewable energy technologies.

### *3.1. Hydro energy*

Hydro energy is one of the most widely implemented forms of renewable energy power generation. Hydro energy is currently one of the largest shares of power generation among different renewable energy technologies. The primary energy consumption from hydroelectric power was 703 million MWh (2.4 quad BTU) in 2016, which was only less than that of biomass primary energy consumption [8]. Hydro energy technology is well-developed and commercialized [11, 31, 32]. Hydro energy can be broken down into three types: run-of-river hydro energy, storage hydro energy, and pumped-storage hydro energy [1] (see Fig. 6).

Run-of-river hydro energy plants utilize the flow of the rivers to generate electricity. The flow of water in the river is run through a hydroturbine to generate electricity. This type of hydro energy power plant generally provides base load with some small flexibilities due to the demand and conditions of the flow [33].

Storage hydro energy plants store water in big reservoirs such as dams. Electrical energy is converted from gravitational energy when the water falls from a higher altitude [3]. Storage hydro energy can provide base load and additional electricity on demand. The benefit of storage hydro energy is the ability to be on and off at short notice [33]. As a result, storage hydro energy can be very flexible for generating electricity.

Pumped-storage hydro energy plants use the surplus energy during generation to convey water from a lower altitude to a higher altitude reservoir, which can be used later for high electricity demand situations. By moving to a high altitude reservoir, the water has a higher potential energy, which can translate to a higher electrical energy after generation.

### *3.2. Bio-energy*

Bio-energy is a type of renewable energy that utilizes biomass to generate electricity. The origin of bio-energy came from the use of burning wood as an energy source for cooking and heating. Nowadays, the sources for bio-energy can come from woody plants, food crops, agriculture or forestry residues, oil-rich algae, and the organic component of municipal and industrial wastes [34]. Biomass has potential to be a substitute for fossil fuels since biomass can be utilized for fuels and power generation. Biomass can be burned directly to generate electricity, or they can be converted into more efficient liquid or gaseous fuels, that then will be burned to generate electricity. As mentioned above, biomass had the highest primary energy consumption at 1377 million MWh (4.7 quad BTU) in 2016, which was about 50% of the total primary energy consumption from renewable energy in the U.S. [8]. Bio-energy research in recent years have seen the system integration of bio-energy with other renewable energy technologies, especially solar energy [35, 36, 37, 38]. This synergy allows solar energy to be converted and stored into chemical fuel, which can be used later [38].

### *3.3. Ocean energy*

Ocean energy consists of different forms: tidal energy, wave energy, current energy, temperature gradient energy, and salinity gradient energy. Among different types of ocean energy, wave energy is the most popular [1]. In wave energy, kinetic energy from waves is captured to generate electrical power through wave energy converters. Similarly, kinetic energy from tidal energy and current energy are converted to electrical energy from tides and current, respectively. Temperature gradient energy takes advantage of the difference in temperature between the ocean surface and the deep water.

Another form of ocean energy is salinity gradient energy, which is often referred as osmotic energy. There are two methods to convert osmotic energy into electrical energy: reverse electrodialysis (RED) and pressure retarded osmosis (PRO) (see Fig. 6). Osmosis energy technology is suitable for locations with fresh water and ocean water sources nearby [17]. The applications of osmotic energy can also be at locations with natural salty lakes.

PRO operates based on the principle of energy recovery from mixing water with salinity gradients [9, 15, 17]. The difference in salt concentrations of the two solutions (fresh water and ocean water) creates an osmotic pressure difference, which tends to draw the fresh water from its reservoir to the ocean water reservoir [39, 40]. Semi-permeable membranes are used to allow the direction of flow from the fresh water to the ocean water, while preventing the flow from the opposite direction. Electrical power can be generated from the permeate solution.

RED is another emerging membrane-based salinity gradient energy. RED utilizes selective ion exchange membranes to for the transport of cations and anions of mixing fresh water and ocean water [41, 42, 43]. There are two types of selective ion exchange membranes: anion exchange membranes and cation exchange membranes. They are alternatively placed between spacers in a membrane stack to create low concentration and high concentration compartments [44]. As a result, there is a chemical potential difference in the membrane stack. Ions will be transported from the high concentration compartment to the low concentration compartment.

The key parameter in osmotic energy is the performance of membranes. In osmotic energy, semi-permeable membranes and ion-exchange membranes are used in PRO and RED, respectively. Membrane research has centered during the development of osmotic energy. Desired properties for membranes in PRO are to be physically strong to withstand high pressure, to allow fresh water to permeate while preventing salt from entering, and to be economically cheap [39, 40]. In RED, the characteristics for good performing membranes are also the durability of the membranes, with additions of thermal, chemical, and transport-related properties. Particularly, ionic resistance and permselectivity are the most important properties [41].

### *3.4. Geothermal energy*

Geothermal energy plants utilize steam and hot water from below the Earth's surface for energy conversion. Hot steam can be run through steam turbines to generate power. Alternatively, hot water can be used to evaporate a more efficient fluid, and then run that fluid through turbines [3]. The use of geothermal energy plants can supply electricity base load and peaks with flexibility due to the ability for controlling the amount of steam and hot water. Additionally, geothermal energy does not depend on weather conditions, which is another characteristics for the dispatchability of geothermal energy. The primary energy consumption of geothermal energy in 2016 was 58.6 (0.2 quad BTU) [8].

Besides the traditional use of geothermal energy, combined geothermal and osmotic energy concepts are also emerged for near future implementation. As opposed to using ocean water (3.5% NaCl), geothermal water sources are often found to have high salinity ($>$ 10% NaCl) [45]. This high salinity solution can be used as a substitute for the lower salinity ocean water. As a result, the power density from osmotic energy can be increased. The addition of osmotic power generation to geothermal wells does not take away any geothermal potential. It is rather an add-on system, that captures the osmotic energy and increases the overall efficiency of the system.

### *3.5. Solar energy*

Solar energy is one of the most popular and fast-growing renewable technologies. The scope of solar energy research interests is extremely broad. The content in this section addresses some of the important highlights while more completed overviews of the technology can be found elsewhere [13, 46]. Solar energy in power generation can be categorized into solar photovoltaics (PV) and concentrating solar power (see Fig. 6). Solar PV directly converts sunlight into electricity based on the principle of photovoltaic effect. On the other hand, concentrating solar power uses mirrors and/or lenses to concentrate sunlight to a small area. The concentrated sunlight is used as a heating source for steam engines.

Research on PV solar cell for power generation has been rapidly grown in popularity. The main focus of solar PV research in the last few decades is to improve the efficiency of solar cells. Semiconducting materials are the center focus of research. In particular, crystalline silicon has been implemented in making solar cells. The use of crystalline silicon for making solar cells can be expensive due to the cost of extracting and manufacturing [21, 47]. The efficiencies with silicon-based solar cells have been reached around 15–17% for polycrystalline silicon and 16–18% for monocrystalline silicon [48].

In recent years, organic materials have been emerged as new materials for making solar cells. The use of organic materials for solar photovoltaic cells has some benefits such as lower production cost and environmental friendliness. On the other hand, the efficiencies obtained from organic solar cells tend to be lower than the efficiencies of traditional silicon-based solar cells. The efficiencies of organic-based solar cells fall between 7–10% [49, 50]. Furthermore, organic-based solar cells have the tendency to be degraded after being exposed under outdoor environment [50]. Various techniques have been implemented to manufacture higher-efficiency and better-weather-resistance organic solar cells.

### *3.6. Wind energy*

Wind energy in the U.S. has been developed to be a major renewable energy resource. Due to the atmospheric pressure difference, air flows are generated that rotate wind blades. Kinetic energy of the wind blades is converted into electrical energy by wind turbines. Wind energy can be divided into two categories: onshore wind energy and offshore wind energy (see Fig. 6).

Urban wind energy has been emerged as an alternate method of capturing wind energy in dense urban areas by using micro turbines [51, 52, 53]. Urban wind energy has the potential to be integrated with building rooftops and surrounding areas in urban areas. Furthermore, buildings with wind energy conversion in the initial design process are important additions to the expansion of urban wind energy development. A potential issue with applying urban wind energy in dense urban areas is the difficulty to characterize wind energy potential due to high influence of atmospheric flow [54]. Characteristics of wind on top and around buildings can be highly turbulence due to obstacles and distribution of buildings [18].

Table 2: Categorizing renewable energy technologies [55, 56, 57, 58].

| Renewable Energy Source | Energy Type | Dispatchability | Current Max Capacity |
|---|---|---|---|
| Hydropower | Gravitational Potential | Dispatchable | 6,809 MW |
| Micro-hydro | Gravitational Potential | Dispatchable | 100 kW |
| Run-of-river Hydro | Kinetic | Non-dispatchable | 50 MW |
| Pumped Hydro | Gravitational Potential | Dispatchable | 300 MW |
| Geothermal Power Plant | Heat | Dispatchable | 1,517 MW |
| Biofuel Power Generation | Chemical Potential | Dispatchable | 130 MW |
| Tidal Energy | Kinetic | Non-dispatchable | N/A |
| Wave Energy | Kinetic | Non-dispatchable | N/A |
| Current Energy | Kinetic | Non-dispatchable | N/A |
| Temperature Gradient | Heat | Dispatchable | N/A |
| Salinity Gradient | Osmotic | Dispatchable | N/A |
| Solar PV | Light | Non-dispatchable | 579 MW |
| Solar Thermal | Heat | Non-dispatchable | 377 MW |
| Onshore Wind | Kinetic | Non-dispatchable | 1,548 MW |
| Offshore Wind | Kinetic | Non-dispatchable | N/A |

## 4. Transforming the existing energy systems with renewable energy

### *4.1. Dispatchability*

Dispatchable generation is a type of electricity generation that can be dispatched based on the electricity demand. Dispatchable renewable energy resources can be very flexible in term of load matching and peak matching within a short notice [59]. Additionally, dispatchable generation can be useful to cover intermittent renewable energy sources when the demand is high.

When comparing different dispatchable generation technologies, the dispatch time reveals how fast the electricity generation can be ramped up or shut down. Fast dispatch times can happen in the matter of seconds. For example, hydroelectric facilities are capable of ramping up to the maximum generation within a few seconds [60]. Furthermore, medium dispatch time power plants can often take minutes to reach full plant capacity. Examples of medium time dispatchable power plants are geothermal steam power plants. The last type of dispatchable generation is slow dispatch time power plants, which require hours for full potential. Biofuel-driven power generation is a typical example of slow dispatch time power plants [60]. As a result, slow dispatchable generation can be inflexible to meet the electrical demand in random, unpredictable events.

Non-dispatchable generation is the opposite of dispatchable generation. Non-dispatchable generation refers to renewable energy technologies that electricity generation cannot be dispatched at the moment of notice. Non-dispatchable generation is rather intermittent due to the dependence of non-dispatchable renewable technologies on out-of-control external conditions [61].

Wind energy, solar energy, wave energy, tidal energy, and current energy are some examples of highly intermittent renewable energy sources [62]. Wind energy is highly non-dispatchable since electrical output from wind turbines depends on external conditions such as wind speed and atmospheric conditions. Similarly, solar energy relies on hours of the day, geographical location, and weather conditions. As a result, solar energy can be an important renewable energy resource for some regions while it is practically not applicable in other regions. Besides the two main non-dispatchable resources solar and wind energy, some emerging ocean energy technologies such as wave energy, tidal energy, and current energy are also intermittent. Their power generation highly depends on the conditions of waves, tides, and ocean current, respectively.

### *4.2. Geographic limitations*

Geographic location plays an important role in determining the availability of renewable energy technologies. Some renewable energy resources are considered to be abundant in some areas while other renewable energy resources are very limited in other areas. For example, hydro energy is a significant part of renewable energy production in areas with nearby rivers (Columbia River, Colorado River, Sacramento River, Missouri River, Tennessee River, Mississippi River, Ohio River, etc.) while hydro power plants do not exist in areas with no rivers nearby (see Fig. 7). Similar geographic limitations can be applied for other renewable energy resources such as wind energy, solar energy, ocean energy, geothermal energy, and bio energy. Various studies have been done to determine the availability of renewable energy across the U.S. [57, 63, 64, 65].

The solar maps have shown that the solar energy potential in the U.S. heavily concentrates in the Southwest region [63]. The solar energy potential in the Northeast region is significantly less than that of the Southwest region. As seen in Fig. 8 and Fig. 9, once the geographic location spreads out to the Northeast direction, the solar energy potential gradually decreases.

Wind energy potential does not only vary across different geographic regions, but it also depends on the height of wind turbines from the ground. Figure 10 shows onshore and offshore wind potential at 80 m in the U.S. The Midwest region has large onshore wind resource due to high wind speeds, whereas the West, the East, and the Southeast regions have considerably slower wind speeds. Additionally, offshore wind energy resources are heavily located in the West Coast, the East Coast, the Great Lakes, and parts of the Mexico Gulf.

Geographic limitations are also applied to geothermal resource in the U.S. As seen in Fig. 11, geothermal energy resource mostly lies in the West region, whereas the resource in the East region is very limited. Geothermal power plants are exclusively located in the western part of the country.

Ocean energy resources have tremendous potential to be harvested in the U.S. due to the location of the country with oceans on its borders. Wave energy resource has been estimated to be 2640 TWh/year. Alaska and the West Coast lead as the most populated wave energy resources, 1570 TWh/year and 590 TWh/year, respectively. Other areas such as the East

Figure 7: Hydropower plants map in the U.S. [57].

Coast and the Gulf of Mexico have considerably lower wave energy resources, 240 TWh/year and 80 TWh/year, respectively [66].

Furthermore, Alaska, Maine, and Washington are the three states in the U.S. that have the largest tidal energy resources [67]. Number of locations with high kinetic power density have reported in these states. Other states such as Oregon, California, New Hampshire, Massachusetts, and New York also have considerable tidal energy resource [67].

Together with wave energy and tidal energy, PRO is also an emerging renewable energy technology and its potential is geographically dependent. Locations in the U.S. with rivers and oceans nearby are considered to be potential locations for future osmotic power plants. In particular, the river delta areas are more likely to be suitable for osmotic energy. The Great Salt Lake in Utah is an exception due to the high salinity content of the lake. The power generation potential from the Great Salt Lake has been estimated to be 400 MW [9].

As presented above, geographic limitations of renewable energy resources are present in the U.S. The energy production potential from renewable energy resources varies from state to state. Furthermore, the energy consumption also varies from state to state. Figure 12 illustrates the total energy consumption in all U.S. States in 2014. The shares of renewable energy in the primary energy consumption are also displayed. Texas, California, Louisiana, Florida, and Illinois were the top five states with highest energy consumption. Texas and California were also among the top states with highest renewable energy production in the country. Other states, such as Washington and Oregon, had lower annual energy consumption. However, the annual renewable energy consumption was nearly 50% of the total energy consumption. This was due to the hydro energy resources in the two states. Net interstate flow of electricity or net electricity imports (from Canada and Mexico) can occur to meet

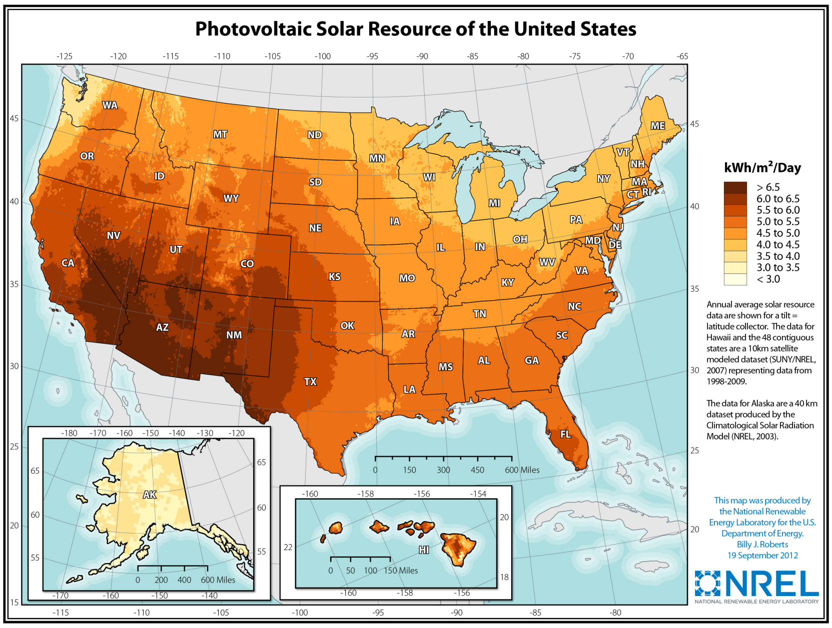


Figure 8: Photovoltaic solar resources in the U.S. [63].

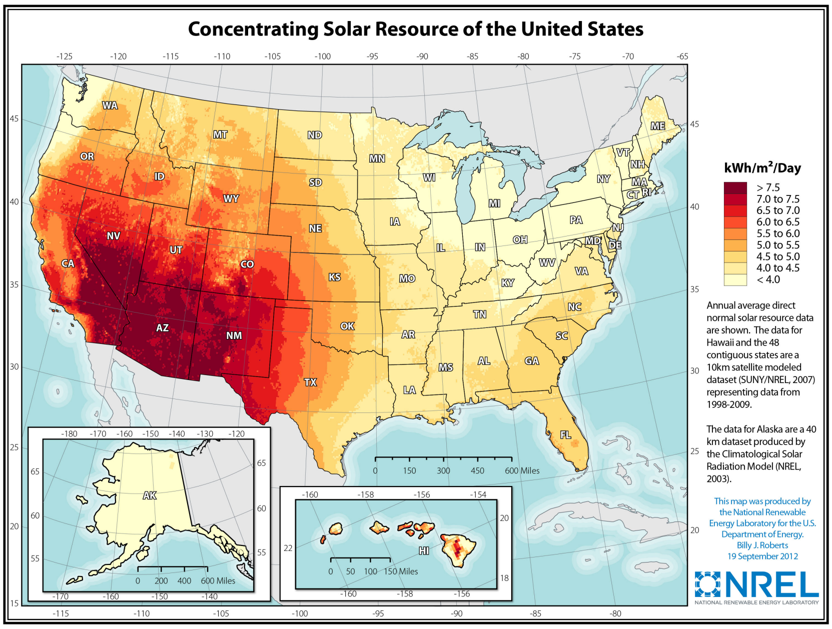
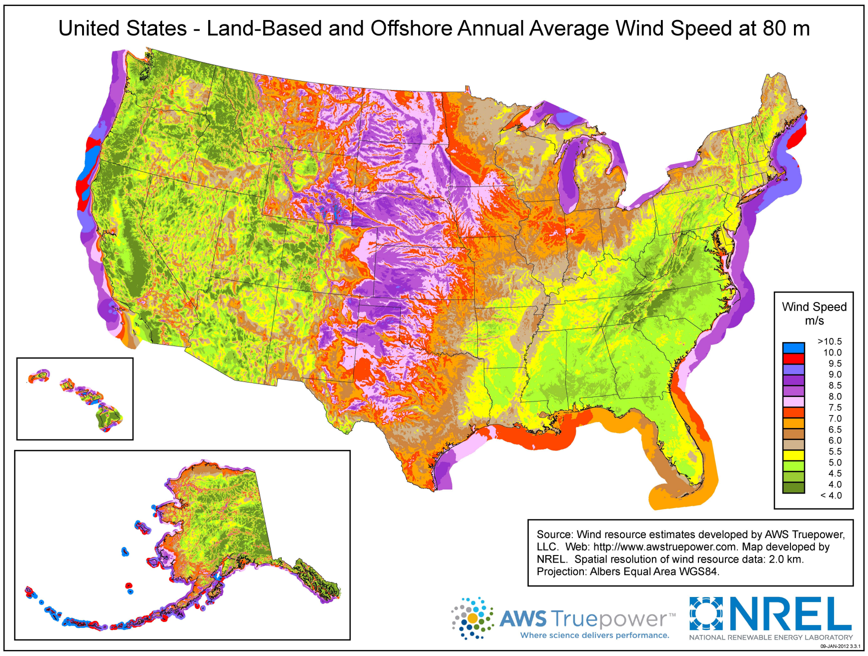
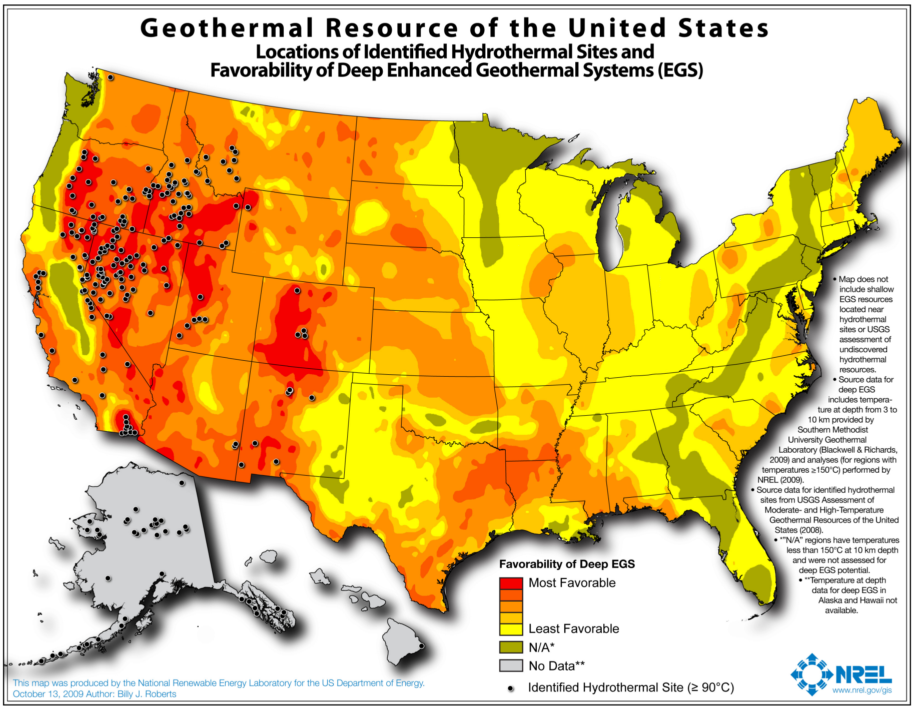


Figure 9: Concentrating solar resources in the U.S. [63].



Source: Wind resource estimates developed by AWS Truepower, LLC. Web: http://www.awstruepower.com. Map developed by NREL. Spatial resolution of wind resource data: 2.0 km. Projection: Albers Equal Area WGS84.

Figure 10: Onshore & offshore wind energy resources at 80 m in the U.S. [64].



- Map does not include shallow EGS resources located near hydrothermal sites or USGS assessment of undiscovered hydrothermal resources.
- Source data for deep EGS includes temperature at depth from 3 to 10 km provided by Southern Methodist University Geothermal Laboratory (Blackwell & Richards, 2009) and analyses (for regions with temperatures ≥150°C) performed by NREL (2009).
- Source data for identified hydrothermal sites from USGS Assessment of Moderate- and High-Temperature Geothermal Resources of the United States (2008).
- *"N/A" regions have temperatures less than 150°C at 10 km depth and were not assessed for deep EGS potential.
- **Temperature at depth data for deep EGS in Alaska and Hawaii not available.

This map was produced by the National Renewable Energy Laboratory for the US Department of Energy. October 13, 2009 Author: Billy J. Roberts

Figure 11: Geothermal energy resources in the U.S. [65].

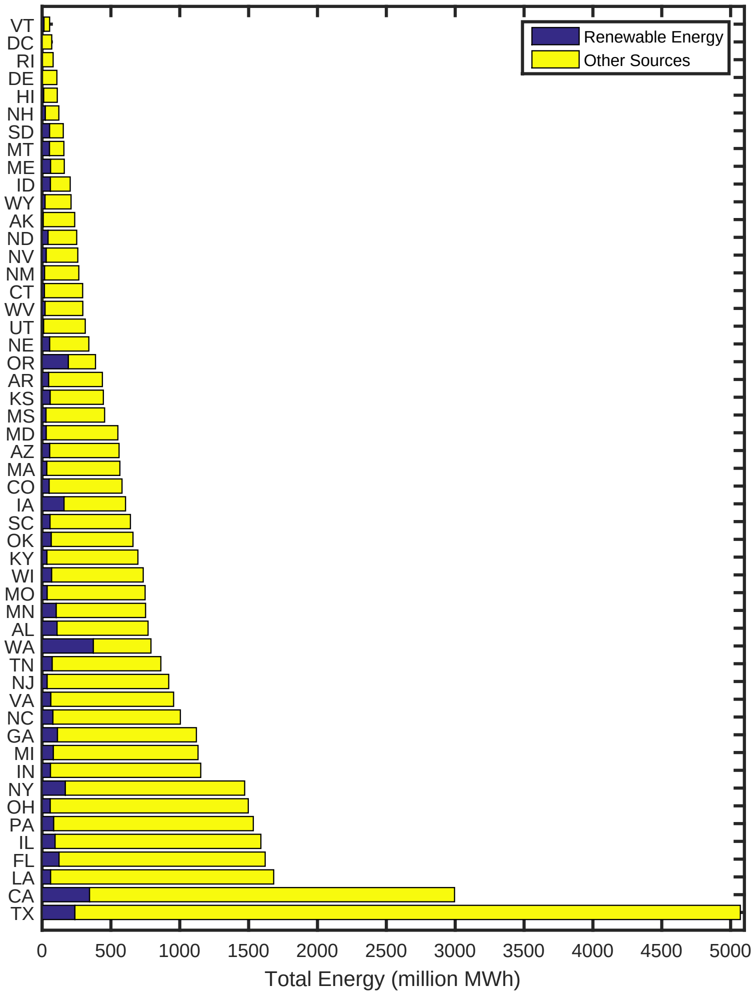


Figure 12: State energy consumption in 2014 [68].

the demand. Understanding the renewable energy potential and energy consumption can help system owners and operators ensure the reliability of their systems.

### *4.3. Variability of renewable energy resources*

The integration of renewable generation sources into the existing power system is complicated because of the variability of renewable energy. Solar and wind energy, in particular, are inherently variable on small time scales due to atmospheric conditions. Clouds can reduce solar power generation and light or no winds can reduce wind power generation [69]. Hydropower, the largest source of renewable energy in the U.S., is affected on much longer time scales, but can be severely reduced or even stopped by drought conditions [69].

Variability creates uncertainty around the availability of a generation resource, presenting major challenges for the dispatchability. Generation that is highly variable presents concerns for the management of the electrical grid [70, 71, 72], which prioritizes safety, reliability, and affordable pricing of electricity.

The research and regulatory communities do not have a standard or consistent way to describe and quantify the variability of renewable power generation. Because electricity markets operate on a variety of time scales, from day-ahead to minute-to-minute, the information needed around variability will be different according to the concerns of the regulators and grid operators. Stoutenburg et al. [72], looking at wind power generation on the California grid, calculate both variability and uncertainty, with variability quantified as an hour-to-hour change in power generation, and uncertainty quantified as an hour-ahead error in forecasting. Stein et al. [70], created a variability index for solar PV generation that quantifies the irradiation, or incoming solar radiation per unit area, when compared with a clear sky, meaning that irradiation would be constant.

In order to coordinate energy resources, numerous modeling techniques exist for the grid and for the renewable resources; however, the specific modeling method will "profoundly impact" how renewable energy is treated within the generation mix [72]. The constraints related to grid management will determine how the grid evolves and system integration proceeds [71].

### *4.4. Renewable energy scalability*

The performance of renewable energy systems is highly influenced by the size of the power plant. Although similar prime mover technologies can be used for power plants with different capacities, overall plant efficiencies, capital costs and operating costs are not necessarily the same. The efficiencies of large-scale setups can be vastly different from the efficiencies of small-scale setups. Emerging renewable energy technologies are often developed at small scales or laboratory scales before being adopted into the market. As a result, the practical efficiencies at larger scales can dramatically be changed. The scalability of the renewable energy technology can determine the feasibility of the technology at large-scale setups. Technologies which are difficult to scale up are not likely to be feasible for larger, more profitable power stations.

As shown in Table 2, hydropower is the most scalable renewable technology in use, with installations of tens of GW possible, due to its prevalence and long history in the U.S. Geothermal power plants are also highly scalable, with installations of over 1 GW possible, depending on the quality of the geothermal resource present at the site. Biofuel power generation is also highly scalable; any combustion technology that is suitable for the particular fuel may be used: engines and turbines may generate power in the tens or even hundreds of MW [73]. Solar PV and solar thermal power generation are also currently installed at utility-scale, with installations into the hundreds of MW up to 1.6 GW. Wind generation at wind farms currently reaches 1.5 MW at the largest U.S. facility in Kern County, California [74].

The size of renewable power generation facilities will also vary according to expected energy performance and projected costs. Uncertainty in the amount of electricity that can be generated or the economic return that can be realized tends to discourage investment, or to keep the size of the facility smaller to resemble pilot projects. These uncertainties in energy production and economics are greater for renewable and emerging technologies than they are for well-established and widely used utility-scale technologies, due to rapidly changing costs for renewable power generation, the inherent uncertainty in the availability intermittent resources, or the lack of established similar installations against which expected performance can be benchmarked. For example, pressure retarded osmosis, described in Section 3.3, has been recognized for its significant energy recovery potential since it was proposed by Sidney Loeb in the 1970s [75, 76, 77]. However, despite much recent research advancing understanding of the technology itself and its potential applications [15, 78, 79, 80, 81, 82, 83], only one full-scale demonstration has been proposed, and it was abandoned by the company sponsoring it in favor of pursuing more established technologies.

### *4.5. Distributed generation vs. centralized generation*

Large, utility-scale generation of electricity is also known as centralized generation. Locations of centralized generation facilities are often far away from the end-users (see Fig. 13). As a result, networks of high-voltage transmissions lines are built to deliver electricity from centralized generation facilities to consumers [84]. Within renewable energy resources, centralized generation often come in forms of hydroelectric dams, geothermal power plants, wind farms and solar farms. These type of technology can generate electricity in large-scale. In the U.S., centralized generation is coordinated by regional system operators, which means that end-users can consume electricity that may be produced by a different company in another city or state [85]. The main benefit of centralized generation is the ability to utilize large-scale facilities to generate electricity for large regions. Centralized generation, however, has some drawbacks such as losses in transmission lines, large land usage (facilities and transmission lines), large capital cost, technical complexity, and local environmental impacts (waste use and discharge) [85].

In some cases, power generation in large scales cannot be feasible due to the limitation of renewable energy technologies and the availability of resources. Distributed generation is an alternate option to generate on-site electricity or aggregate from various supplies to meet the energy demand [86]. As opposed to centralized generation, distributed generation in renewable energy technologies utilizes small-scale renewable energy systems that are close to the end-users (see Fig. 13). Within distributed generation, the size of renewable energy systems can be varied, depending on the application. In the residential sector, the most popular form of distributed generation in renewable energy is solar PV panels. In some areas, small wind turbines can also be another option for distributed generation systems. The options for distributed generation in the commercial and industrial sectors can range from solar PV, wind, hydropower, and biomass [87]. These systems are typically smaller than centralized generation systems while being big enough to generate electricity for small commercial and industrial regions. The main advantages of distributed generation are the ability to deliver clean, reliable power and to reduce losses in transmission and distribution [87]. However, distributed generation can be less efficient than centralized generation due to the effect of scaling.

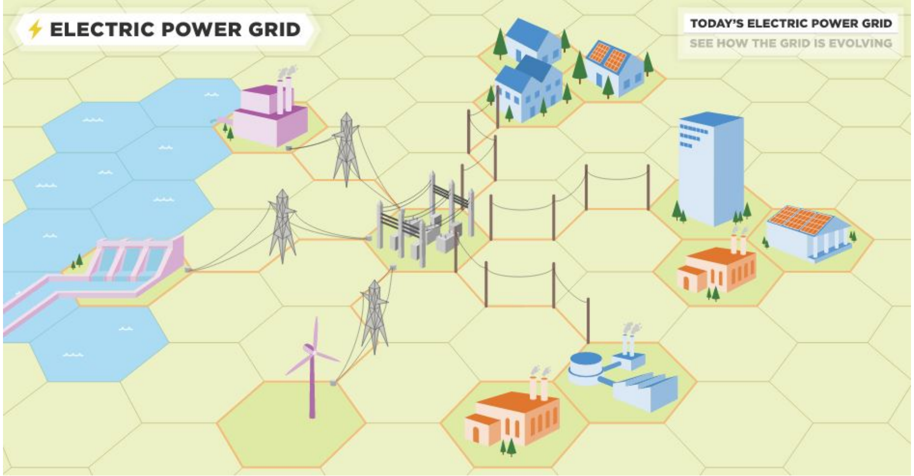


Figure 13: Distributed generation vs. centralized generation [88].

### *4.6. Power plant size*

Renewable energy power plants vary in nameplate capacity, which mostly depend on available resources, advancement of technology, and capital investment. Table 2 shows the typical capacity for different types of renewable energy as of 2016. Power plants with developed renewable energy technology such as hydropower tend to have larger capacity. In the U.S., the current largest hydropower plant is the Grand Coulee Dam on the Columbia River in Washington [89]. The nameplate capacity of this hydropower plant is 6809 MW and the hydropower generation is 21 million MWh per year.

Solar power plants in the U.S. have grown significantly in the last few decades. As mentioned earlier, there are two main types of solar power plants: solar PV power plants and solar thermal power plants. Compared to hydropower plants, solar PV power plants have much smaller nameplate capacities. The largest solar PV power plant in the U.S. is the the Solar Star Projects, which combines two solar farms in Kern and Los Angeles Counties in California. The combined nameplate capacity of these two co-located solar farms is 579 MW [90]. There are two solar PV power plants that tie for the second largest installed solar PV power plants in the U.S., the Topaz solar farm in San Louis Obispo County, California and the Desert Sunlight solar farm in Riverside County, California. Both solar PV farms have the installed capacity at 550 MW [91, 92]. Concentrated solar thermal power plants are also a important sector in solar energy in the U.S. The largest concentrated solar thermal power plant, which is the Ivanpah Solar Electric Generating System in the California Mojave Desert, has the capacity of 377 MW [93]. In general, solar thermal power plants have smaller nameplate capacities than solar PV power plants.

Wind farms have become an important part of renewable energy generation. Electricity generation from wind energy in 2016 was 167 million MWh, in which 12 states produced about 80% of the total wind generation. Texas is the leading state in wind power generation with nearly 36 million MWh. Iowa and California are trailing as second and third state with largest wind power generation [94]. The current largest onshore wind farm is the Alta Wind

Energy Center in Kern County, California. This wind farm has the name capacity of 1548 MW, which is considerably larger than capacity of the largest solar farm [95]. There are other onshore wind farms with nameplate capacities over 500 MW such as the Shepherds Flat Wind Farm (845 MW in Oregon), the Roscoe Wind Farm (781.5 MW in Texas), and the Horse Hollow Wind Energy Center (735.5 MW in Texas). As opposed to the rapid development of onshore wind farms, offshore wind farms in the U.S. are still in the early stage of development. According to the U.S. Department of Energy, offshore wind resources in the U.S. are considered to be abundant, uniform, and more consistent than onshore wind resources [96]. There are no current offshore wind farms operating in the U.S., but wind power projects are being developed and deployed offshore along U.S. coastal cities.

The U.S. is the world's largest geothermal power producer [97]. The net electricity generation from geothermal was 16,767 million MWh in 2016 [97]. The combined capacity of all facilities around the country was around 3.5 GW [98]. The largest geothermal power plant in the U.S. is the Geysers, which is located north of San Francisco in the Mayacamas Mountains [99]. The nameplate capacity of the Geysers is rated at 1517 MW, which is enough to power 725,000 homes [99]. Even though geothermal is one of the main renewable energy sources in the U.S., the rate of growth of geothermal is slower than wind energy or solar energy [100]. Geothermal power plants mostly reside in Western states, where geothermal resources are available. California in the leading state for installing geothermal power plants. The current geothermal capacity in California is around 2565 MW [100]. On the other hand, geothermal power plants are almost non-existing in the Eastern states due to limited resources.

Biomass power plants in the U.S. are capable of producing 1382 million MWh of primary energy in 2016 [8]. The current largest biomass power plant is the New Hope Power Co., which is located in South Bay, Florida [101]. This facility has the capacity of 128.9 MW and uses bagasse and wood as its feedstock. The second largest biomass power plant in the U.S. is the Somerset Power Plant (116.9 MW) in Skowhegan, Massachusetts. Unlike the New Hope Power Co., the Somerset Power Plant utilizes mill residue as its feedstock [102]. On the other hand, most U.S. biomass power plants have the capacity less than 100 MW [58].

### *4.7. Capacity factor*

Capacity factor in renewable energy technology is an important measurement, which is defined as the ratio of the actual output to the maximum potential output. The actual output is measured over the same period as the potential output, which is calculated from the nameplate capacity of a given facility. The capacity factor of power generation facilities is often less than 100% due to several factors. Renewable energy resources are not available all the time to be used for power generation. Most renewable energy technologies are subjects to high variability and intermittency. For instance, wind does not blow or the wind speed is too low to generate electricity from wind turbines. Similarly, solar farms are not capable of producing electricity when the sky is too cloudy or the Sun does not shine at night. Hydropower is also highly influenced from the availability of the amount of water in rivers. Power generation from hydropower plants can be interrupted in events of low or high water levels. Market demand is another factor that affects the capacity factor of renewable energy facilities. Off-peak or low energy demand can curtail the operation of power plants. Moreover, if the price of electricity is too low, the operation of renewable power plants can be reduced to save operating cost. Furthermore, rotating maintenance of power generation units in the facility can happen regularly, which means that part of the facility is shut down for scheduled service. Under those circumstances, the nameplate capacity of renewable power generation facilities are never met, which results in low capacity factors.

The U.S. Energy Information Administration (EIA) publishes data which measures monthly capacity factors of different technologies, and the following results and Fig. 14 outline important findings [103]. Among different renewable energy technologies, geothermal power plants have the highest capacity factor. EIA data shows that the capacity factor of geothermal power plants in the U.S. in 2016 was between 68.9% and 80.7%, with most of the months the capacity factor was greater than 70%. Geothermal energy is generally less variable than other type of renewable energy technologies. Geothermal energy is dependent on geographic locations, but the resource is constantly available where geothermal energy exists. Consequently, geothermal power plants are able to operate with less interruptions and achieve higher capacity factor. Biomass power plants also have high capacity factor. Biomass power plants with landfill gas and municipal solid waste as stockfeed had capacity factors between 63.5% and 76.3% in 2016. Similarly, other biomass-powered electricity generations were observed to have capacity factors from 36.4% to 54.9% in 2016. Biomass power generation tends to have high capacity factor is the result of high availability of input resources. Hydropower plants are often operating at one third of their nameplate capacities. Their capacity factors in 2016 were ranging from 28.4% to 45.2%. The water level is the main factor that influences the capacity factor of hydropower plants. Renewable energy technologies with high non-dispatchability often have lower capacity factors. Wind farms operated between 24.5%–40.4% of the nameplate capacity. Similarly, solar PV and concentrating solar thermal power plants had capacity factors range of 15.5%–35.0% and 6.8%–36.9%, respectively.

### *4.8. Energy storage*

The implementation of energy storage in renewable energy systems is necessary due to the intermittent nature of some renewable energy technologies such as wind energy and solar energy [104, 105, 106, 107]. Wind power production only occurs when the wind blows at proper speeds, which make wind energy fairly variable. Similarly, solar power production is very intermittent since the Sun only shines for certain hours during the day at any given location. As a result, power generation from highly variable renewable energy technologies can be challenging. The question of under production or over production from renewable energy remains a primary concern. Energy storage is a logical choice to store the unused energy from the production of renewable energy, especially for renewable energy with high variability. With the aid of energy storage, variable renewable energy technologies will have greater penetration into existing electrical grid systems.

There are some notable benefits for the electrical grid such as load leveling, firm capacity, operating reserves, load following, transmission & distribution (T&D) replacement and

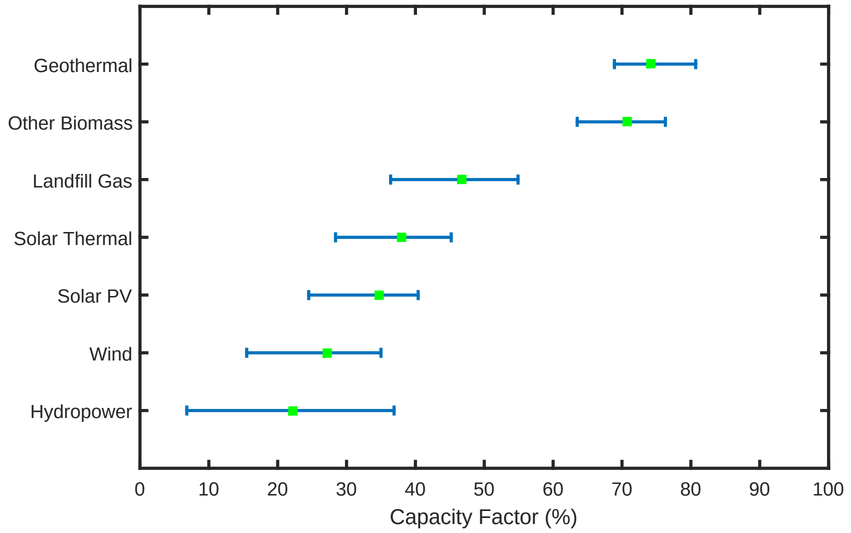


Figure 14: Capacity factor of different power generation technologies in 2016 [103].

deferral, black-start, and end-use applications [108]. Energy storage can be used to supply the unused energy that has been stored to match the electrical load. The unused energy can economically be stored at low costs when the electrical demand is off-peak, and is sold at higher prices when electrical demand is peak. Additionally, energy storage tends to have faster response time than any other dispatchable generation method. As a result, energy storage can be used to fulfill the electrical demand in irregular events such as system failures. Furthermore, energy storage can be used to bring the system back online after blackouts [109].

There are three common categories of energy storage: power quality, bridging power, and energy management [108]. Power quality can be used to stabilize transient and regulate frequency. As a result, the discharge time must be short, typically ranging from seconds to minutes. The second category of energy storage is used for bridging power, which has longer discharge time (minutes to about an hour). The last type of energy storage is for energy management. Some applications for this category are load leveling, firm capacity, and T&D deferral. The discharge time for this category often takes hours. Depending on the type of applications, energy storage technologies are available in multiple forms. Some of the most popular energy storage technologies are flywheels, capacitors, superconducting magnetic energy storage, high-energy batteries, pumped hydro storage, compressed air energy storage, and thermal energy storage [109]. A technical report from the National Renewable Energy Laboratory (NREL) on the role of energy storage with renewable electricity generation details different energy storage technologies for various applications [108]. As seen in Fig. 15 some energy storage technologies are exclusive for certain applications while other technologies can be used for different applications. The discharge time is the main parameter that differentiate the use of energy storage technologies.

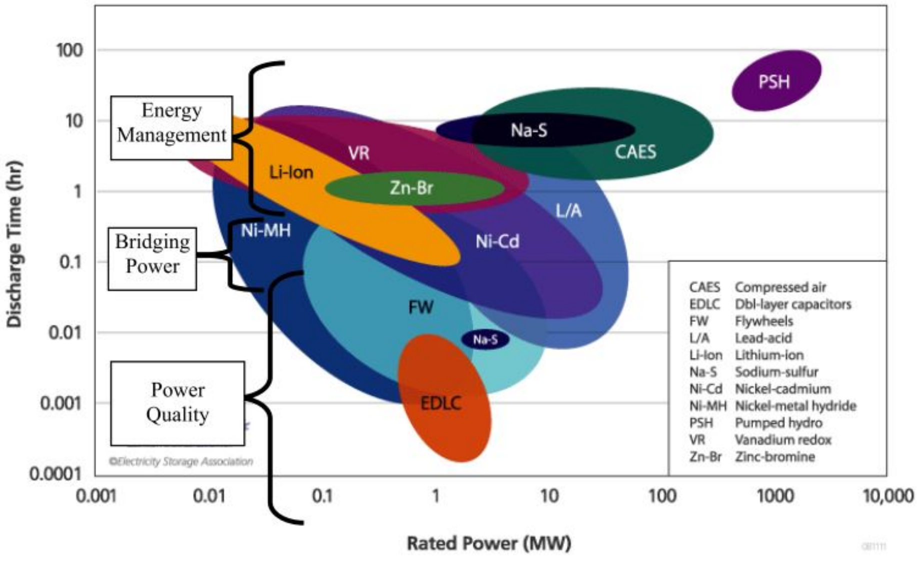


Figure 15: Energy storage applications and technologies [108].

## 5. Systems view applied to economic analysis of renewable energy systems

### *5.1. System cost*

Two of the most important aspects determining the commercial feasibility of renewable energy technologies are technical performance and economic viability. The technical performance of a certain renewable energy technology is determined by the availability of resources and the efficiency of converting raw inputs into useful forms of energy. The economic viability of the technology is the most critical for investors, and therefore strongly affects whether the technology can be successfully implemented or not. The economic aspect measures various costs that are required to build and operate the facility. Furthermore, the price of electricity can be calculated to compare the competitiveness with other technologies.

#### *5.1.1. Capital costs*

Capital costs of renewable energy systems are often measured in $/kW. Capital costs are heavily dependent on the type of technology, project system size, and project geographic location. Proven renewable energy technologies such as geothermal energy, biomass, solar energy, and wind energy are more widely commercially available, which helps to reduce installed costs and uncertainty in the installed costs. On the other hand, ocean energy (including wave energy, tidal energy, and osmotic energy) is largely in the early developmental stages, which make the installed costs highly uncertain. Furthermore, the project's system size is important factor. Comparing different system sizes of the same base technology, installing larger systems can often reduce the initial capital cost in term of $/kW. Similarly, the project's geographic location has a significant influence on the capital cost of the project. Geographic limitations on resources, local policies, government incentives, and price of electricity can potentially impact the capital costs of renewable energy systems that are going to be installed at a given location [110].

Table 3: Costs of generating electricity expected lifetime from renewable energy systems [110, 111, 112].

| Renewable Energy System | Capacity | Capital Cost ($/kW) | Fixed O&M ($/kW-yr) | Lifetime (Years) |
|---|---|---|---|---|
| Biomass Combined Cycle | 20 MW | $8,180 | $356.07 | 25-30 |
| Geothermal | 50 MW | $6,243 | $132.00 | 35-40 |
| Hydroelectric | 500 MW | $2,936 | $14.13 | 50-100 |
| Pumped Storage | 250 MW | $5,288 | $18.00 | 50-100 |
| Solar PV | <10 kW | $3,897 ± $889 | $21.00 ± $20 | 30-40 |
| Solar PV | 10-100 kW | $3,463 ± $974 | $19.00 ± $18 | 30-40 |
| Solar PV | 100-1,000 kW | $2,493 ± $774 | $19.00 ± $15 | 30-40 |
| Solar PV | 1-10 MW | $2,025 ± $694 | $16.00 ± $9 | 30-40 |
| Solar PV with Tracking | 150 MW | $3,873 | $24.69 | 30-40 |
| Solar Thermal | 100 MW | $5,067 | $67.26 | 25-35 |
| Wind | <10 kW | $7,645 ± $2,431 | $40.00 ± $34 | 15-20 |
| Wind | 10-100 kW | $6,118 ± $2,201 | $35.00 ± $12 | 15-20 |
| Wind | 100-1,000 kW | $3,751 ± $1,376 | $31.00 ± $10 | 15-20 |
| Wind | 1-10 MW | $2,346 ± $770 | $33.00 ± $16 | 15-20 |
| Onshore Wind | 100 MW | $2,213 | $39.55 | 15-20 |
| Offshore Wind | 400 MW | $6,230 | $74.00 | 15-20 |

#### *5.1.2. Operating costs*

Operating and maintenance (O&M) costs can be broken down to fixed O&M cost and variable O&M cost. Fixed O&M costs are associated with expenses that do not change significantly during power generation [110]. Some examples are fixed O&M costs are staffing fees, routine equipment maintenance, and administrative expenses. Fixed O&M costs are often measured in $/kW-yr. On the contrary, variable O&M costs fluctuate considerably during power generation. The variable O&M cost is predominantly dependent on the cost of raw material supplies. Most of the raw materials used in renewable energy systems are essentially “free” since they are renewable natural sources such as wind and solar energy. The only exception in renewable energy system that has variable O&M is biomass power generation, in which the raw materials supplies are valued differently throughout the year. The variable O&M cost of biomass power is about $17.49/kWh [110].

### *5.2. Expected lifetime*

The expected lifetime of renewable energy systems is heavily dependent upon the type of renewable energy technology. Since renewable energy systems are relatively new, the information about the actual lifetime of renewable energy systems are very limited. Alternatively, the information about the expected lifetime of renewable energy systems are estimations and predictions from experts in the field. Table 3 shows the estimated lifetime of different renewable energy technologies. The approximated lifetime can be used to estimate the total cost of the system, which is useful for calculating the levelized cost of electricity.

### *5.3. Scaling effects*

Scaling effects on renewable energy systems occur on systems with different nameplate capacities, which is common in renewable energy systems due to available resources and capital investment. As a result of the variety in capacities, the capital and O&M costs are the two most impacted parameters. As seen in Table 3, the capital and O&M costs tend to vary when the nameplate capacity of a renewable energy system changes. In general, O&M costs are mostly dependent on the type of technology and project system size. Technologies which are more exploratory or less widely implemented may also require maintenance or replacement more frequently than expected, resulting in increased labor costs. Various types of technology have particular system components that require being maintained and operated differently. Moreover, the project size can also influence the operating cost of a given renewable energy system. Bigger facilities will need to spend more money on O&M costs, even though the larger power generation capacity can offset this increasing in expenses, resulting in lower costs per unit of energy delivered. On the other hand, increasing the nameplate capacity of the same technology type tends to reduce the capital cost. Scaling effects studies can be used to predict the capital cost and O&M cost for new renewable energy projects.

### *5.4. Levelized cost of electricity*

The levelized cost of electricity (LCOE) of different renewable energy technologies indicates the cost of each unit of electricity energy produced, considering all costs and incentives. The LCOE, often calculated in \$/kWh or \$/MWh, is a useful measurement to indicate how feasible a renewable technology is for implementation and its competitiveness with other technologies. The LCOEs of established renewable energy technologies are more certain and lower than the LCOEs of emerging renewable energy technologies. Furthermore, renewable energy technologies may receive government incentives, which ultimately reduces the cost of generating electricity. Table 4 details the LCOEs of renewable energy technologies, as taken as average total system LCOE values for plants entering service in 2022 [113]. Information about the LCOEs of emerging renewable energy technologies are limited due to the lack of commercial implementation. As a result, the LCOEs of emerging renewable energy technologies are often estimated based on case studies.

Table 4: LCOE of different renewable energy technologies [113].

| Plant Type | Total System LCOE (\$/MWh) | | |
|---|---|---|---|
| | Minimum | Average | Maximum |
| Geothermal | 41.1 | 45.0 | 51.8 |
| Onshore Wind | 43.0 | 64.5 | 78.5 |
| Hydroelectric | 59.6 | 67.8 | 78.1 |
| Solar PV | 65.6 | 84.7 | 126.2 |
| Biomass | 81.5 | 96.1 | 115.6 |
| Offshore Wind | 137.1 | 158.1 | 213.9 |
| Solar Thermal | 172.3 | 235.9 | 363.4 |

The LCOEs of different renewable energy technologies are presented in Fig. 16. Among all renewable energy technologies, geothermal has the smallest variation in LCOE. In contrast, solar thermal has the largest range of LCOE. The wider range of LCOEs of renewable

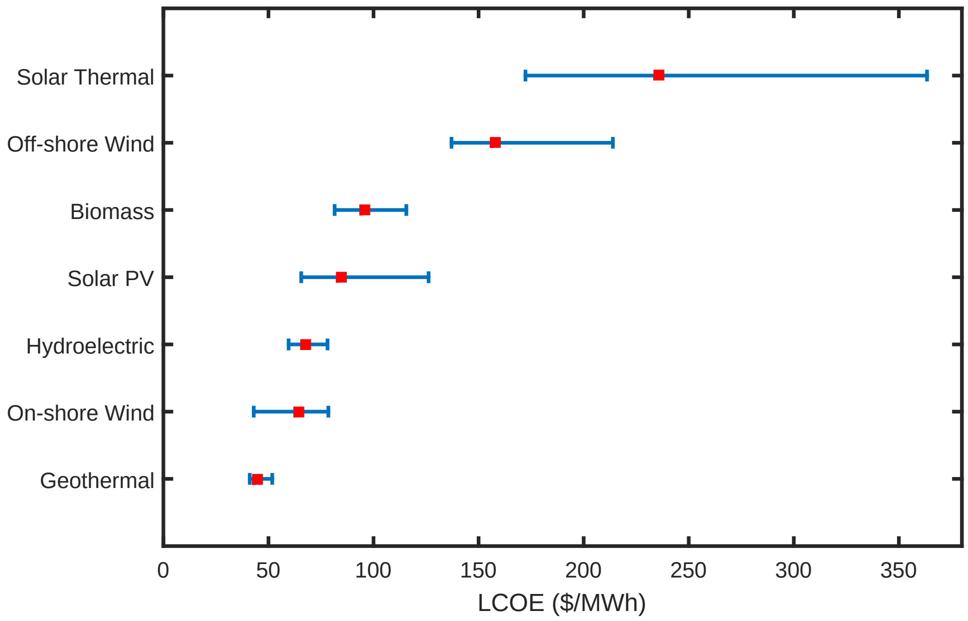


Figure 16: LCOEs of different renewable energy technologies [113].

energy technologies are due to the combination of several factors. Within a certain renewable energy technology, there are many different methods of power generation, which creates variations in terms of capital investment and system efficiencies. Moreover, the development of newer renewable energy technologies can bring major changes and significant improvements, which drives the LCOEs down. Furthermore, geographic locations of installed renewable energy systems can also affect the LCOEs. The local price of electricity and availability of government incentives for renewable energy vary widely across the country, which shapes the differences between LCOEs in different regions and ultimately impacts the average LCOEs of renewable energy technologies.

### *5.5. Sensitivity analysis*

The sensitivity analysis in this section focuses on renewable energy technologies that have high variation in the LCOE such as solar and wind energy. As mentioned above, the LCOE is often seen as the measurement for the feasibility and economic competitiveness of a renewable energy technology. As a result, changes in the LCOE are most sensitive toward the development and implementation of the technology. In this section, the capital cost, O&M cost, lifetime are varied based on their uncertainties and the LCOEs are observed accordingly. The discount rate is kept at 3% as recommended by the DOE for energy analysis [114].

Figures 17, 18, 19, and 20 illustrate the changes in LCOE with respect to the capital cost, the fixed O&M cost, and the operating lifetime. A few general conclusions can be drawn from these graphs. The impact of the fixed O&M cost on the LCOEs are considerably less than those of the capital cost and the project lifetime. Additionally, the LCOEs are linearly dependent on the capital cost and the O&M cost while the relationship between the LCOEs and the lifetime are exponential. Nonetheless, lowering the capital cost and the fixed O&M cost while extending the project lifetime can eventually bring the LCOEs down.

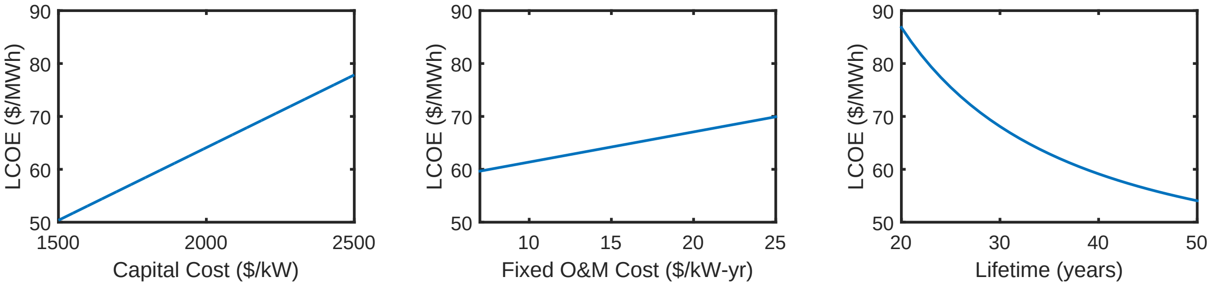


Figure 17: Sensitivity analysis on PV energy systems with capacity from 1 to 10 MW.

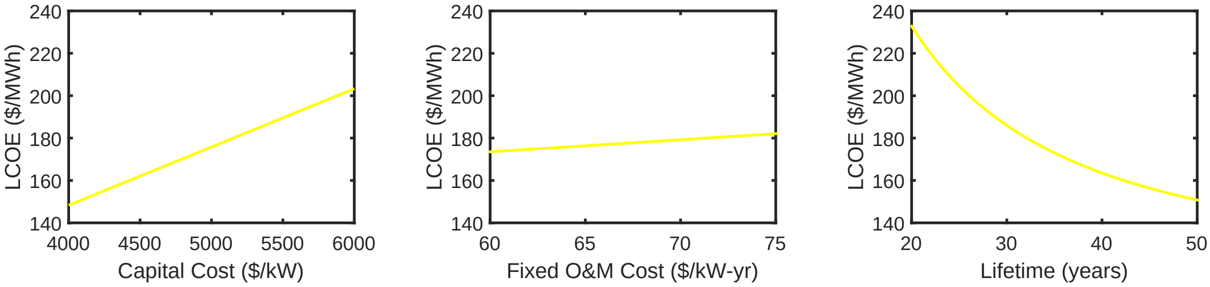


Figure 18: Sensitivity analysis on solar thermal energy systems with capacity of 100 MW.

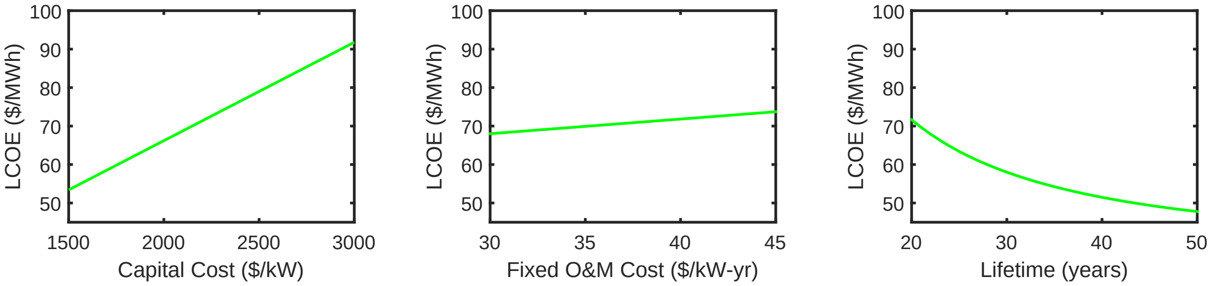


Figure 19: Sensitivity analysis on onshore wind energy systems with capacity of 100 MW.

## 6. Conclusions

Developed and emerging renewable energy technologies in the U.S have been reviewed in this paper. Power generation in the U.S. is currently dominated by non-renewable energy resources, mainly from fossil fuels. The introduction of renewable energy systems into the electrical grid system has increased the presence of electricity generation from renewable

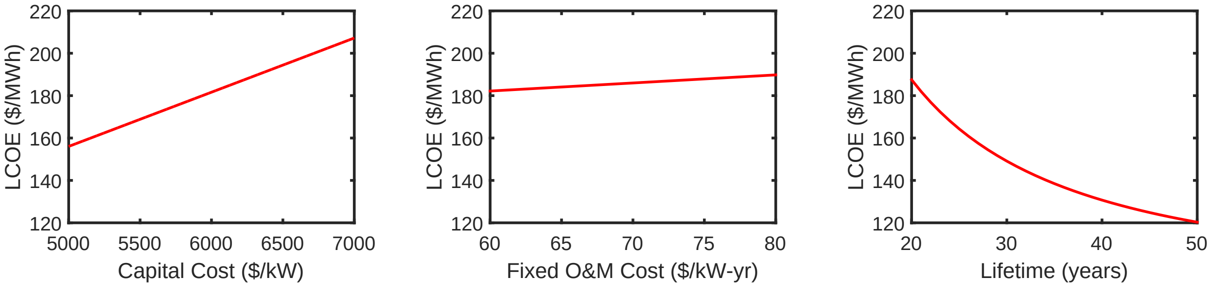


Figure 20: Sensitivity analysis on offshore wind energy systems with capacity of 400 MW.

energy in the U.S. More importantly, renewable energy resources in the U.S. have the potential to be replace traditional power generation methods in the country. Renewable energy technologies with long history of development such as hydropower, biomass and geothermal have been contributing a large portion of electricity generation toward the national energy consumption. Furthermore, fast-growing technologies, such as solar and wind energy, have been significantly advanced in the last few decades. Commercialized wind and solar farms have been installed around the country and evolved to be important parts of renewable energy electricity generation. Emerging renewable energy technologies, especially ocean energy, have generated research interests within the research community. The potential from ocean energy (wave energy, tidal energy, current energy, and salinity gradient energy) are considerably significant as seen above. The development of these technologies need to be advanced in order to reduce the LCOE and increase their competitiveness against other renewable energy technologies in the renewable energy industry.

Nonetheless, renewable energy resources are certainly the future of power generation. The development of renewable energy technologies can be mostly viewed as individual developments of various technologies. However, it is often seen in practice that combined renewable energy systems are not uncommon. One renewable energy source can be more advantageous than others in terms of LCOE, available resources, efficiencies or government incentives. In contrast, developing renewable energy as combined systems has its own advantages. Renewable energy resources can be existed in different forms at a given location. An integrated renewable energy system can capture different forms of renewable energy resources, which ultimately generate more electricity than stand-lone renewable energy systems. As a result, integration of different renewable energy technologies can maximize the power generation from nearby renewable energy resources. This approach certainly increases the effectiveness of utilizing multiple renewable energy technologies, as opposed to focusing on a single technology. Future development of renewable energy systems that can incorporate different technologies at a given location is recommended for maximizing the amount of energy delivered from renewable resources.

## Abbreviations

| | |
|---|---|
| EIA | Energy Information Administration |
| LCOE | Levelized cost of electricity |
| NERC | North American Electric Reliability Corporation |
| NREL | National Renewable Energy Laboratory |
| O&M | Operations and maintenance |
| PV | Photovoltaics |
| PRO | Pressure retarded osmosis |
| RED | Reverse electrodialysis |
| RPS | Renewable portfolio standard |
| T&D | Transmission & Distribution |

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