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Converting Natural Resources into Electricity

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Paper No. 5—
Converting Natural Resources into Electricity

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Introduction

Carbon dioxide concentrations reached a record 400 parts per million in May 2013. This threshold represents a level “unsurpassed in at least 800,000 years.” According to measurements taken from arctic ice cores, atmospheric CO_2 had not reached this level during the entire course of human history (Samenow 2013).

The Fifth Assessment Report (AR5) by the United Nations Intergovernmental Panel on Climate Change (IPCC) concludes that “it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century” (IPCC 2011). While some may disagree about the cause of this CO_2 increase, there is general consensus that changes in global energy systems could mitigate the impacts (IPCC 2011). In 2011, the United Nations Intergovernmental Panel on Climate Change (IPCC) issued the *Special Report on Renewable Energy Sources and Climate Change Mitigation*, known as the SRREN (IPCC 2011). Authored by more than 120 experts from all over the world in IPCC Working Group III, the SRREN highlighted the opportunity to greatly reduce greenhouse gas emissions if countries around the world shifted their generation and consumption of energy from fossil-fuel sources to renewables. In fact, the SRREN noted that, with appropriate enabling public policies, renewable energy sources could contribute 80% of the world’s energy supply by mid-century (IPCC 2011).

There are multiple drivers for renewable energy, including energy security concerns associated with conventional fuel supplies and dependence on imported fuel sources, generation diversity and hedging against price volatility, environmental concerns, though the relative importance of these drivers differs significantly by sector.

For transportation greater use of RE in biofuels could lead to a reduced dependence of oil which may have important security and price hedging benefits – as price shocks and volatility are both thought to negatively impact GDP (Greene 2010, Rentschler 2013).

In the electric sector, oil based security is much less of a factor because very little oil is used to generate electricity. Increased RE deployment (solar in particular), is leading to a more distributed model for generation compared to the more the traditional centralized model. This dispersion of generation resources toward the end user, coupled with the diversity of RE technologies and resources across the United States, while posing some integration challenges, also has the opportunity to improve the grid infrastructure operational security well as the reliability and resilience of the system. Subsidies to aid deployment today, particularly where it is currently more expensive than conventional technologies, can also help limit the degree to which a narrower range of technologies – that might prove more expensive to consumers in the long run – get locked in (Weiss and Marin 2012). Related to this, RE in both the electric and transportation sectors may provide some degree of insurance to consumers against the impact of future but uncertain policies that put a price on carbon emissions (and in doing so effectively increase the cost of using fossil fuels).

Still, reaching 80% renewable energy would be an enormous increase over the current share of less that 15%. As Professor Ottmar Edenhofer, Co-Chair of Working Group III noted at the report launch, “The substantial increase of renewables is technically and politically very challenging.” [1] Renewable energy (RE) accounted for only 12.9% of the total 492 exajoules of global primary energy supply in 2008. In 2011, the United States has an installed renewable electricity capacity of more than 146 GW, which represented nearly 13% of the total installed capacity and more than 12% of total electricity generation (Gelman 2012).

Yet RE capacity has been growing quickly in the last decade. Globally, renewable electricity capacity almost doubled in the years 2000 to 2011 (Gelman 2012); renewable energy supplied an estimated of 19% of global energy consumption in 2011 (REN21 2013). In a recent study (NREL 2012), NREL assessed the extent to which renewable energy supply could meet the electricity demands of the continental United States and found that renewable electricity generation from technologies that are commercially available today, in combination with a more flexible electric system (including the greater use of gas turbines, storage, and demand side management), is more than adequate to supply 80% of total U.S. electricity generation in 2050 while meeting electricity demand on an hourly basis in every region of the country.

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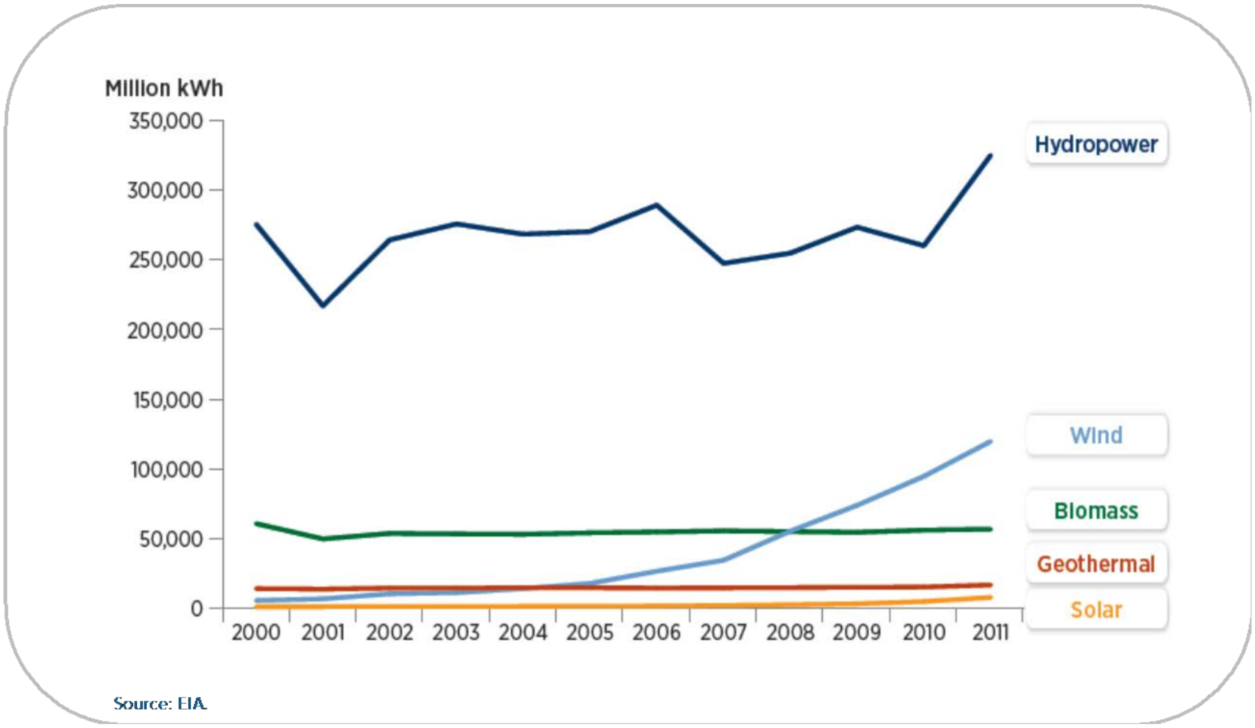
[1] Full quote: “With consistent climate and energy policy support, renewable energy sources can contribute substantially to human well-being by sustainably supplying energy and stabilizing the climate. However, the substantial increase of renewables is technically and politically very challenging. Developing countries have an important stake in this future – this is where most of the 1.4 billion people without access to electricity live yet also where some of the best conditions exist for renewable energy deployment.” See http://srren.ipcc-wg3.de/press/content/potential-of-renewable-energy-outlined-report-by-the-intergovernmental-panel-on-climate-change



Source: EIA

Figure 1. U.S. renewable generation by technology

According to data from the Energy Information Administration, U.S. generation from hydropower tends to be variable, while wind has experienced a dramatic increase since 2005.

In this paper and our companion presentation, we introduce six prominent renewable electricity sources: bioenergy, hydropower, wind energy, direct solar energy, geothermal, and ocean energy. We also describe some history of the resources and the technical potential for each, as well as land and water requirements for the different technologies.

1 Renewable Energy Overview

Renewable energy technologies tap resources that are driven by solar radiation, either directly (e.g., solar technologies) or indirectly (e.g., wind, hydro, waves, biomass), from gravity (e.g., tides due to the influence of the moon and to a less extent the sun) or from Earth’s interior heat (e.g., geothermal). These technologies offer a range of energy options that are low carbon and mitigate risks from fuel availability and price volatility over both short and long time horizons. Renewable generation technologies depend on resources which are continually replenished, resulting in low operational expenses relative to other technologies that depend on fossil or nuclear fuels. Consequently, for renewable generation technologies, the majority of the cost is capital cost, borne up-front, and these characteristics are reflected in the prevalence of purchase power agreement (PPA) contracts that guarantee payment for all fixed, or indexed price for all the variable output.

Large-scale, commercially-available technologies include the following:

- Bioenergy: a variety of feedstocks and plant specifications

- Hydropower: common applications include dams with reservoirs, run-of-river, or in-stream projects, and pumped storage
- Wind: a wide range of commercially-available wind turbines for both land-based and offshore operation
- Solar
    - Photovoltaics (PV): flat plate, concentrating (CPV) or high concentrating PV (HCPV), with a variety of cell types, inverters, system designs, and tracking choices (e.g. fixed, 1-axis, or 2-axis tracking).[2]
    - Concentrating Solar Power (CSP): solar thermal plants that focus direct sunlight to heat oil, molten salt or water that in turn is used to generate steam and drive a turbines. Technology approaches include: parabolic trough and linear Fresnel (1-axis) systems using synthetic oil or direct water/steam, power towers using molten salt or direct water/steam (2-axis), parabolic dish with Stirling engine, all with different component options, including storage in some cases.
- Geothermal: geothermal power (hydrothermal or enhanced geothermal system), geothermal co-production.

Ocean energy options are emerging though generally at an earlier stage; some are developmental and others are just entering the market.

The United States has abundant and diverse renewable resources. Geographic location, technical resource potential, and output characteristics are unique to each RE generation technology and vary significantly by region. This geographic diversity by resource type across the United States supports portfolio-driven energy solutions, which could support a more resilient and lower cost system.

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[2] 2-axis tracking is sufficient to follow the sun at any orientation from sunrise to sunset unless the "view" of the sun is blocked by an object or the panel is in a shadow.

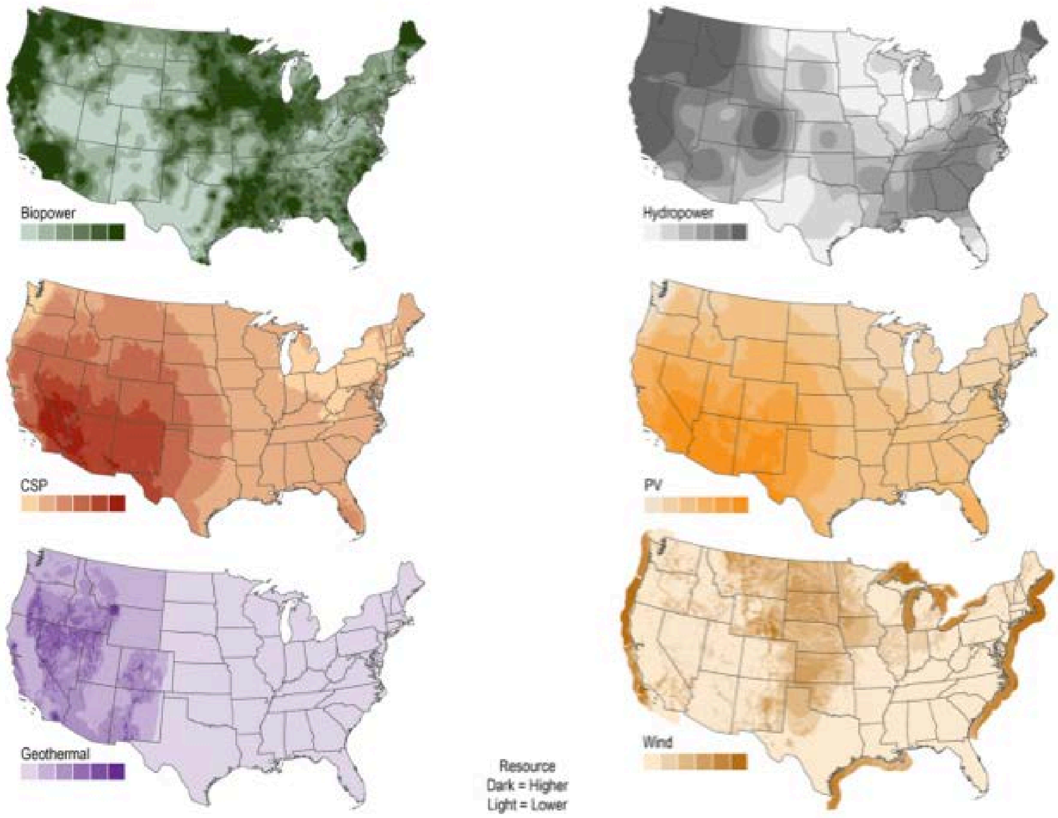

Figure 2. Technical potential of renewable energy technologies in the contiguous United States

Source: NREL 2012

Lopez et al. (2012) estimated the technical potential of renewable electricity generation technologies for the United States on a state-by-state basis. NREL's Renewable Electricity Futures Study (NREL 2012) made more granular technical potential estimates. Both reports provide technology-specific estimates of energy generation potential based on renewable resource availability and quality, technical system performance, topographic limitations, and environmental and land-use constraints. These estimates do not uniformly consider economic or market constraints, and they do not assess the likelihood that the technical potential will actually be reached. The reports can be considered to provide upper bound estimates of development potential. Nonetheless, as Table 1 demonstrates, there is significant potential for renewable energy technologies in the United States. The current capacity of U.S. electric system is slightly more than 1000 GW, less than1/10th of the technical potential of land-based wind and less than 1/100th of technical potential for PV.

Table 1. Total Estimated U.S. Technical Potential Generation and Capacity by Technology

Technology	Generation Potential (TWh)[a]	Capacity Potential (GW)[a]
Biopower[b]	500	62
Hydropower	300	60
Land-based wind power	32,700	11,000
Offshore wind power	17,000	4,200
Urban utility-scale PV	2,200	1,200
Rural utility-scale PV	280,600	153,000
Rooftop PV	800	664
Concentrating solar power	116,100	38,000
Enhanced geothermal systems	31,300	4,000
Hydrothermal power systems	300	38

[a] Non-excluded land was assumed to be available to support development of more than one technology.

[b] All biomass feedstock resources considered were assumed to be available for biopower use; competing uses, such as biofuels production, were not considered.

Geothermal, hydropower, and biopower technologies can provide baseload power, though hydropower faces resource constraints. Hydropower's average utilization, or capacity factor, in the United States over the 5-year period 2005–2009 was 39% (with annual variation from 36% and 42%). This year-round average is much lower than more conventional baseload technologies that are not resource constrained. Coal thermal and nuclear generation average capacity factors over the same period were 71% and 90% respectively (EIA 2011). Technologies that depend on variable and uncertain resources (e.g., wind and solar (without storage)) pose integration challenges in the operation of the grid, including the need for additional capacity and better forecasting, that play out in both institutional and jurisdictional arenas.

RE projects are financed through a range of financing mechanisms, depending on the technology type and project scale. Many RE technologies, such as solar and wind, have high upfront capital costs, variable output, and very low variable costs (as they have no fuel costs). Purchase power agreements (PPAs) that offer a fixed or index linked price lower risk to investors by providing a high degree of revenue certainty are an attractive and popular mechanism in the United States for RE deployment. This is particularly true for CSP, some proposed offshore wind projects, and other technologies that are significantly more expensive than conventional generation alternatives. NREL's System Advisor Model (SAM) is an online tool that provides performance predictions and cost of energy estimates for grid-connected power projects based on system design parameters specified by the user.[3] SAM includes financing options reflective of today's market, including residential and commercial PPAs, utility independent power producer (IPP), as well as some advanced utility IPP options.

Land use requirements for some renewable energy technologies span a wide range. There are often large differences between the areas directly impacted by a technology (i.e., disturbed land due to physical infrastructure development) and lands indirectly impacted. For example, Denholm et al. (2009) found that for existing and proposed modern large wind plants in the

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[3] Access SAM at http://sam.nrel.gov/.

United States, the ratio of direct impact to total impact area (i.e., land associated with the complete wind plant project) was on the order of 1:34 (in hectares/MW of capacity), with considerable variation.

More recently, Ong et al. (2013) assessed the land use requirements for utility-scale U.S. solar PV and CSP projects. They also found a wide range of total land-use requirements for solar power plants across the technologies and different regions. Generation-weighted averages for total area requirements range from about 3 acres/GWh/yr for CSP towers and CPV installations to 5.5 acres/GWh/yr for small 2-axis flat panel PV power plants. In many areas, co-location of agriculture or livestock production with wind and solar plants can significantly reduce the overall land footprint of renewables (Newmark et al. 2011).

Geothermal generation has low direct land use above ground, but the impact area can increase if the underground geothermal field is considered to manage risk of land subsidence (IPCC 2011). Run-of-river hydropower has low lifecycle land use, while the acreage of land use values for reservoir hydropower can differ greatly (IPCC 2011). It is expected that ocean energy systems would likely have direct and indirect impacts and access constraints similar to offshore wind plants (IPCC 2011).

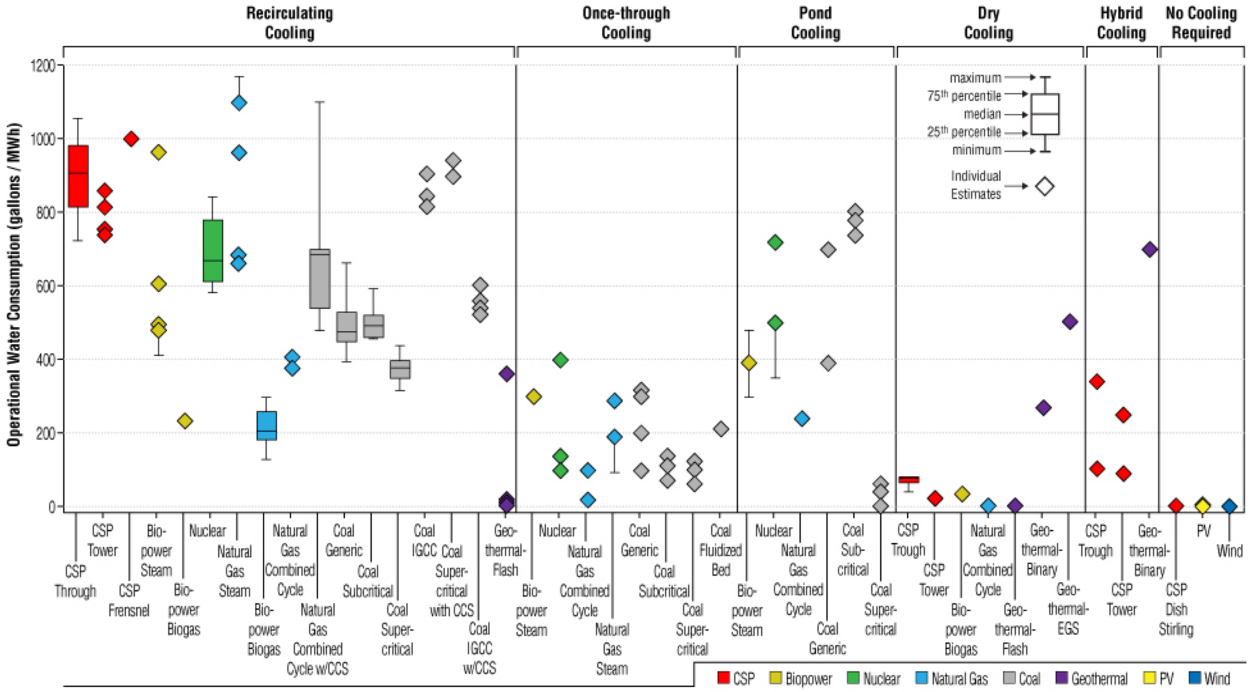

Figure 3. Operational water consumption factors for electricity generating technologies

Source: Macknick et al. 2012IGCC: Integrated gasification combined cycle.
CCS: carbon capture and sequestration; CSP: concentrating solar power.
Hydropower values are excluded due to the wide range of estimates.

Water use requirements provide another interesting lens through which to view power choices. Thermoelectric power production is the largest user of freshwater in the United States (Kenny et al. 2009). Depending on the selected sources of power generation and location, the power sector, particularly in areas with water constraints, could be vulnerable to changes in water resources that may result from climate change (e.g., DOE 2013). Many renewable energy technologies use less water through withdrawals or consumption than conventional generation technologies (Macknick et al. 2012).

Operational water withdrawal and consumption varies significantly across technologies, especially when coupled with the cooling technology (Figures 3 and 4). Technology choices can significantly affect both water withdrawals and consumption. For example, depending on the choice of cooling technology, CSP can be water intensive or use almost no water at all. In the latter case, “dry cooling” is achieved by using a fan, a process that takes energy and so will typically lead to a small reduction in net output and slightly greater electricity costs. Water is used in many phases of the geothermal life cycle, from the drilling and construction of wells through operations. As with CSP, the choice of cooling system can cause the largest variation in water use during aboveground operations (Harto et al. 2013). Enhanced geothermal systems (EGS) may require substantial water for operations; alternative water sources for geothermal systems can provide flexibility (this is especially important as many geothermal resources are located in areas of water stress). Recent studies highlight the value of making strategic investments in energy and cooling technologies to support a low-carbon, “water-smart” electricity system (Rogers et al. 2013).

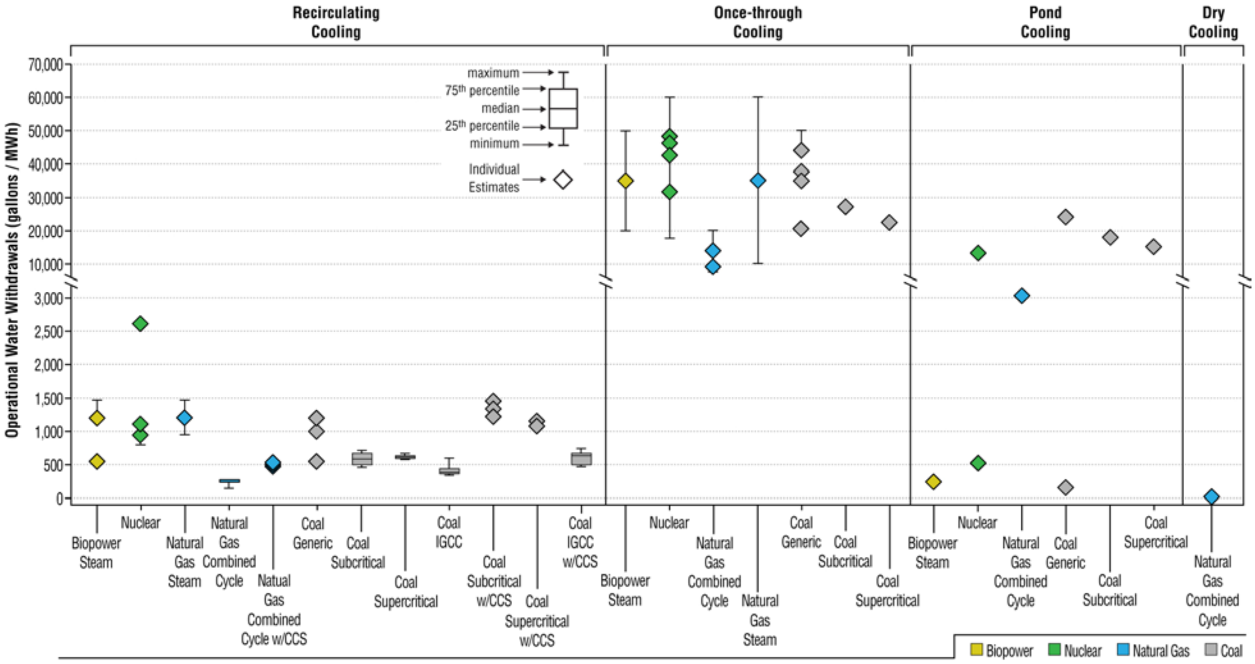

Figure 4. Operational water withdrawals for fuel-based electricity generating technologies

Source: Macknick et al. 2012
IGCC: integrated gasification combined cycle; CCS: carbon capture and storage.

1.1 Bioenergy

Bioenergy utilizes biomass to generate electricity, heat, or fuels. Bioenergy technologies range from quite mature (e.g., for heating or cooking) to those under development, such as those that support the production of cellulosic ethanol. A variety of feedstocks can be used in bioenergy projects, including agricultural, livestock, and forest residues; energy crops (such as switchgrass or corn for ethanol); and municipal solid waste (IPCC 2011).

At 10.2% of primary energy globally, biomass represented the largest source of renewable energy in 2008. However, approximately 60% of the biomass share is attributable to the traditional burning of wood, dung, and other waste products for heat and cooking. The second largest contribution of bioenergy is biofuels used in the transportation sector. The amount of bioenergy used for generating electricity worldwide—the focus of this special institute—is relatively small at 1.4% (Gelman 2012).

When biopower is used for electricity generation, it generally involves biomass co-firing or direct combustion. As noted above, because it is dispatchable, biopower is one of the renewable sources that can offer constant or controllable electricity output in contrast with others that are more dependent on weather. While biomass projects traditionally depended on local or regional fuel supply, international trade in solid biomass (e.g., pellets) and liquid biofuels is increasing (IPCC 2011).

The Public Utilities Regulatory Policies Act of 1978 (PURPA) drove significant growth of the U.S. biopower industry by guaranteeing that regulated utilities would purchase electricity at a price equal to the utilities' avoided cost of electricity from small generators (less than 80 MW capacity). Avoided costs decreased with the deregulation of the electric industry in the early 1990s and the increase in natural gas supply and decrease in fuel costs, and the decrease made biopower projects less attractive (NREL 2012).

Solid biomass annual power generation of 400 TWh accounts for 82% of the total estimated annual U.S. bioenergy generation technical potential. Of that, crop residues are the largest contributor. Gaseous biomass has an estimated annual technical potential of 88 TWh, of which landfills are the largest contributor (Lopez et al. 2012).

1.2 Hydropower

Water mills drove much of the early industrial revolution in the 18th century, so it is not surprising that water was also one of the first sources of power for creating electricity. Michigan's Grand Rapids Electric Light and Power Company generated electricity by a dynamo belted to a water turbine in 1880, and the first hydroelectric power plant began operation on the Fox River in Appleton, Wisconsin, in 1882.[4]

Hydro provided 40% of U.S. electrical generation capacity in 1940, but because hydro generation capacity has remained fairly flat while electricity demand has grown, hydro now provides only about 7% of total U.S. generation capacity (Gelman 2012) with significant seasonal variation.

Hydropower harnesses the energy of water moving from higher to lower elevations, primarily by converting the potential energy of water to generate electricity. Like wind power, hydroelectric generation is an indirect manifestation of solar radiation, depending as it does on the hydrologic

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[4] DOE provides more on the history of hydropower at http://www1.eere.energy.gov/windandhydro/hydro_history.html.

cycle. Through different scale projects (from large dams with reservoirs to run-of-river or in-stream projects), hydropower can be used to meet centralized urban needs as well as decentralized rural needs (IPCC 2011). The National Hydropower Association recently set a goal of doubling the nation's 96,000 MW of hydroelectric capacity,[5] and Congress passed the Hydropower Regulatory Efficiency Act of 2013 that could help meet this goal.

Traditional hydropower systems with reservoirs can be used to provide baseload electricity and to help balance electricity systems with large amounts variable RE generation. However, hydropower operations face significant resource constraints because they rely on the hydrological cycle, and the seasonal streamflow variations of the cycle may be affected by climate change (DOE 2013). Hydropower reservoir operations often provide multiple services in addition to energy supply, including flood and drought control, drinking and irrigation water supply, environmental controls, and navigation (IPCC 2011).

Pumped-storage hydroelectricity (PSH) utilizes low cost, off-peak power to pump water from a lower level reservoir to a higher elevation storage site. During periods of high demand or to balance other needs, the potential energy of stored water is allowed to flow downward through turbines at the lower elevation to produce electricity. Pumped storage devices can be quite large, which can also make them useful to provide backup capacity and energy for long periods (e.g. Raccoon Mountain, part of TVA's system can provide more than 1,500 MW of power for over 20 hours).[6] As the most common form of energy storage, PSH can provide valuable grid flexibility. PSH operations often need to balance power generation needs along with environmental requirements regarding flow and fisheries protection.

According to Hall et al. (2006), the Northwest and Alaska have a combined technical potential for hydropower estimated at 69 TWh annually, which accounts for roughly 27% of the entire estimated U.S. annual technical potential for hydropower (259 TWh).

1.3 Wind Energy

Wind power energy has been harnessed for hundreds to thousands of years to power transportation such as sailing ships, grind grain, and pump water. In the 20th century, its utility expanded to producing electricity. Wind arises indirectly from energy from the sun, the result of pressure differences in the air arising from differential heating on the Earth's surface on a variety of geospatial and temporal scales. Wind energy technologies harness some of the kinetic energy of moving air. There is a theoretical maximum kinetic energy of wind that can be extracted by a wind turbine, though in practice actually efficiency is considerably lower. Land-based wind energy technologies are already being manufactured and deployed on a large scale. Offshore wind technologies are relatively new and currently more expensive; these technologies have potential for continued technical advancement in both performance and cost reduction. The United States has yet to deploy an offshore wind farm, but some projects are currently under development. There has been significant offshore wind development in Europe. In both land-based and offshore projects, there is a trend toward larger and higher wind turbines that enable higher energy capture and electricity production (see e.g., Wiser and Bolinger 2013). This

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[5] Learn more about National Hydropower Association goals at http://www.hydro.org/hydrofacts/two-pages4.pdf.

[6] Learn more about TVA's Raccoon Mountain pumped storage plant at http://www.tva.gov/sites/raccoonmt.htm.

improves the economic value proposition of wind power in part due to higher wind speeds at higher elevations.

Wind electricity is both variable and, to some degree, unpredictable, which poses some challenge to integration into existing grid systems. However, successful integration of wind energy at significant levels has been demonstrated in many regions (see e.g., IPCC 2011, Cochran et al. 2012).

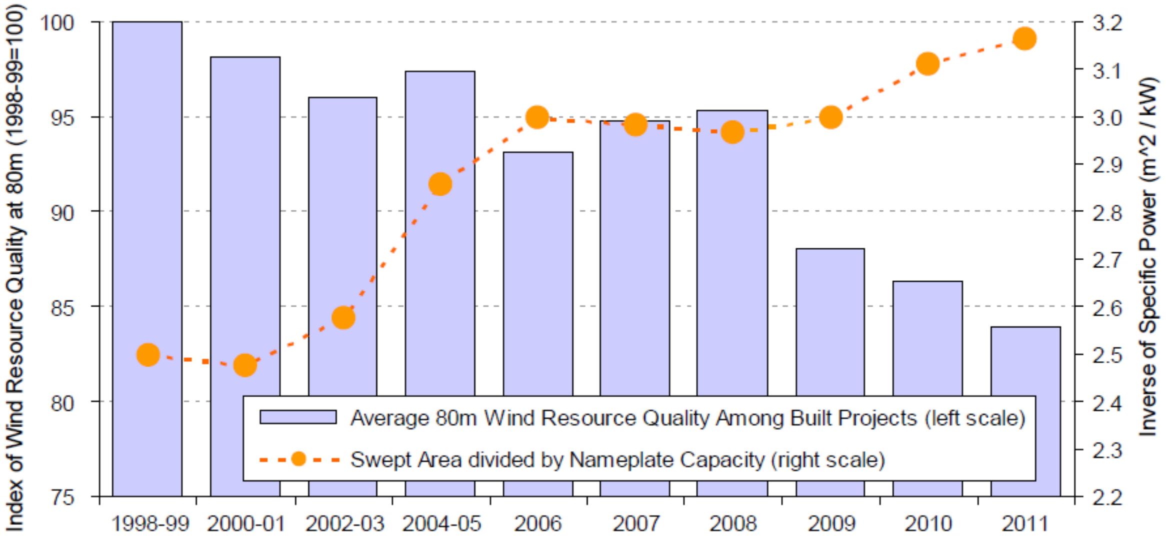

Figure 5. With larger wind turbines, lower quality wind resources can become more economic due to the greater energy capture of the larger machines

Source: Wiser and Bolinger 2013

Technical potential for U.S. land-based wind power is largest in the western and central Great Plains and lowest in the southeast. Texas has the highest estimated annual potential (5,552 TWh), which accounts for roughly 17% of the entire estimated U.S. annual technical potential for land-based wind. Technical potential for offshore wind power is present in significant quantities in all offshore regions of the United States. Hawaii has the highest estimated annual potential (2,837 TWh), which accounts for roughly 17% of the entire estimated U.S. annual technical potential for offshore wind (Lopez et al. 2012).

Table 2. Technical Potential for U.S. Wind

Wind Power Technology	Total estimated annual U.S. technical potential (TWh)
Land Based	32,784
Offshore	16,975

Source: Lopez et al. 2012

In the United States, installed wind electricity capacity increased more than 18 fold between 2000 and 2011 (Gelman 2012). Motivated by the expected expiration of federal tax incentives at the end of 2012 and improvements in the cost and performance of wind power technology, annual wind power capacity additions in the United States achieved record levels in 2012 (13.1 GW of new capacity added and $25 Billion invested). Wind power represented the largest source of U.S. electric-generating capacity additions in 2012 (Wiser and Bolinger 2013).

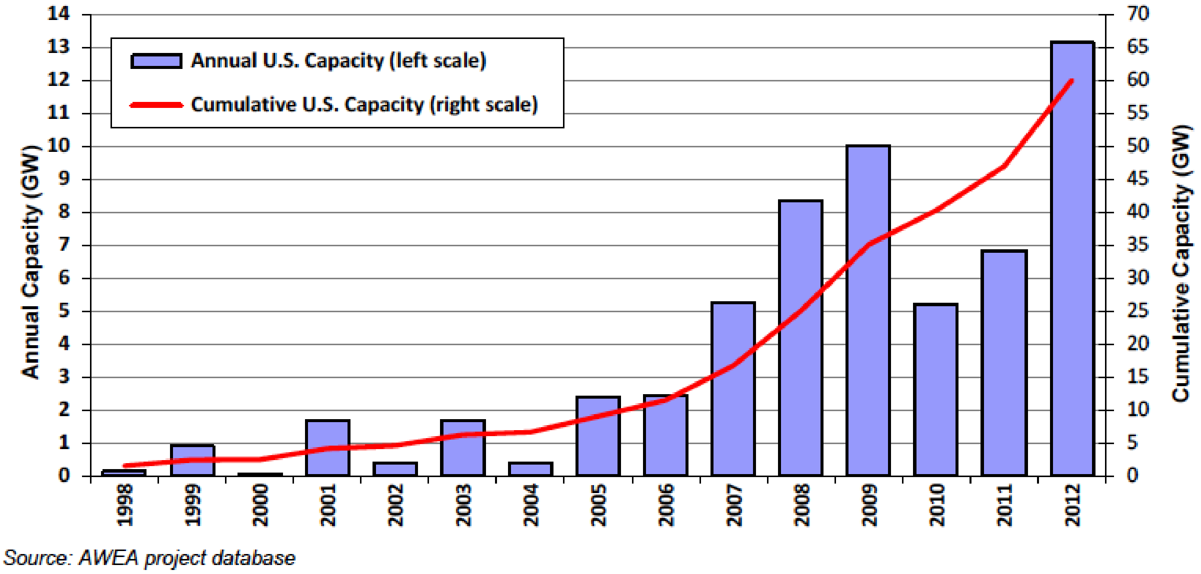

Figure 6. Annual and cumulative growth in U.S. wind power capacity

Source: Wiser and Bolinger 2013

1.4 Solar Energy

Theoretically solar power goes back further than any other energy source as humans almost instinctually oriented their dwellings to take advantage of the sun's warmth and light. However, direct conversion of the solar radiation to electricity is one of the newest forms of electric generation and dates to Bell Laboratories' invention of the "power photocell" in 1954. Initially, solar cells were generally only affordable for space program applications. Not until the late 1980s did solar cells begin to become more affordable for a broader range of applications. Even in the early 1980s, laws related to solar power were mostly drafted with solar thermal heating systems in mind.

Photovoltaics (PV) produce electricity directly from solar radiation. Solar PV technologies produce electricity when bound electrons in a semi-conductor, such as silicon are "excited" by photons from one state (in the valence band) to a higher state (in the conduction band); this allows the electrons and the "holes" they leave behind to act as charge carriers for an electric current. The difference between the valence band and the conduction band is known as the band gap. The power output of a solar cell (P = IV) reflects the number of electrons that "jump" per second (the current, I) and the energy these electrons are able retain (voltage, V) to do useful work, which is related to but lower than the band gap (which for silicon is 1.1eV).[7] The use of silicon in PV is an example of a single junction cell because it has only one band gap. Multi-junction cells (which are often used in concentrated PV) can increase efficiency substantially, though are more costly. A multi-junction cell uses two or more PV cells with different band gaps that are placed on top of one another. The top layer is made of a PV cell that has the higher band

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[7] The silicon is doped to form a p-n junction. This creates an electric field within the part of the device so that the electrons reaching the conduction band are driven around the electric circuit rather than simply falling back to the valence band without doing useful work.

gap, the next cell the next highest band gap and so on. Higher energy photons passing through the first layer causes some of the electrons to jump. The remaining lower energy light passes through to the second layers with the lower band gap and the process is repeated.

In contrast, concentrating solar (thermal) power (CSP), another direct solar energy technology, concentrates direct light, typically with mirrors, to heat a working fluid that in turn is used to drive a more conventional steam turbine connected to an electrical power generator. The working fluid in a CSP system might be oil, molten salts, or water, depending on the technology. CSP can be used in place of conventional sources such as burning pulverized coal or nuclear fission.

Solar technologies range from R&D stage (e.g., fuels produced from sunlight) to mature (e.g., solar heating and wafer-based silicon PV). Many of the technologies are modular in nature and can be used in systems scaled to different needs.

Solar energy is variable and, to some degree, unpredictable since it can be affected by cloud cover and rain. However, solar energy's temporal profile in some circumstances correlates relatively well with peak energy demands. In addition, the insolation varies significantly across the United States. For this reason, plans for CSP are typically suggested in the Southwest which has very high relative insolation, and PV use is much more widespread. Thermal energy storage offers an option to improve output control for some technologies such as CSP and direct solar heating (IPCC 2011), in principle allowing CSP to eliminate much of the daily weather-induced variability and provide stable, dispatchable power for long periods. Active research is focused on improving sunlight-to-electricity conversion efficiencies, including the use of multi-junction cells, and lowering manufacturing costs, including advances in crystalline silicon (the dominant current PV technology), thin-film technologies, and concentrating PV systems (CPV).

The United States has abundant solar resources; the technical potential will depend on the way that resource would likely be tapped. Table 3 shows the total estimated annual U.S. technical potential from Lopez et al. (2012). Some of the nuances are revealed in the different state-wide statistics as described by Lopez et al. (2012): Texas and California have the highest estimated technical potential for utility-scale, urban PV, a result of a combination of good solar resource and large population. The highest potential is for utility-scale, rural PV, due to the relatively high power density, absence of minimum resource threshold, and the availability of large land areas for development. Texas accounts for roughly 14% (38,993 TWh) of the U.S. total. The largest technical potential for rooftop PV typically is associated with large populations, where building rooftops, parking garages, and commercial structures are available. California has the highest U.S. rooftop PV technical potential of 106 TWh due to its high population and relatively good solar resource. U.S. technical potential for CSP exists predominately in the Southwest. Texas has the highest estimated CSP technical potential (22,786 TWh), which accounts for roughly 20% of the U.S. total.

Table 3. Technical Potential for U.S. Solar

Solar Power Technology	Total estimated annual U.S. technical potential (TWh)
Utility-scale PV (urban)	2,232
Utility-scale PV (rural)	280,613
Rooftop PV	818
Concentrating Solar Power (CSP)	116,146

Source: Lopez et al. 2012

Overall, solar electricity generation has grown by a factor of more than 9 between 2000 and 2011, although it still represents a small part (0.2%) of overall U.S. electricity generation (Gelman 2012). Solar installations have risen as system costs have decreased (see Figure 7). The deployment of grid-connected solar photovoltaic (PV) systems has increased, and installed prices continued to decline in 2012 (Barbose et al. 2013). A number of CSP plants came online in 2011, including 11.7 MW in the United States (Gelman 2012).

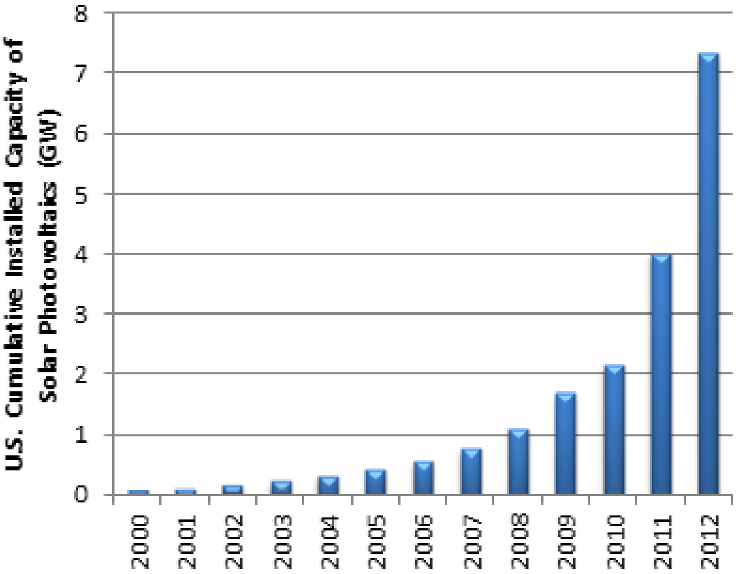

Figure 7. U.S. solar photovoltaic capacity increased dramatically in 2011–2012

Source: Gelman (2012); SEIA (2013)

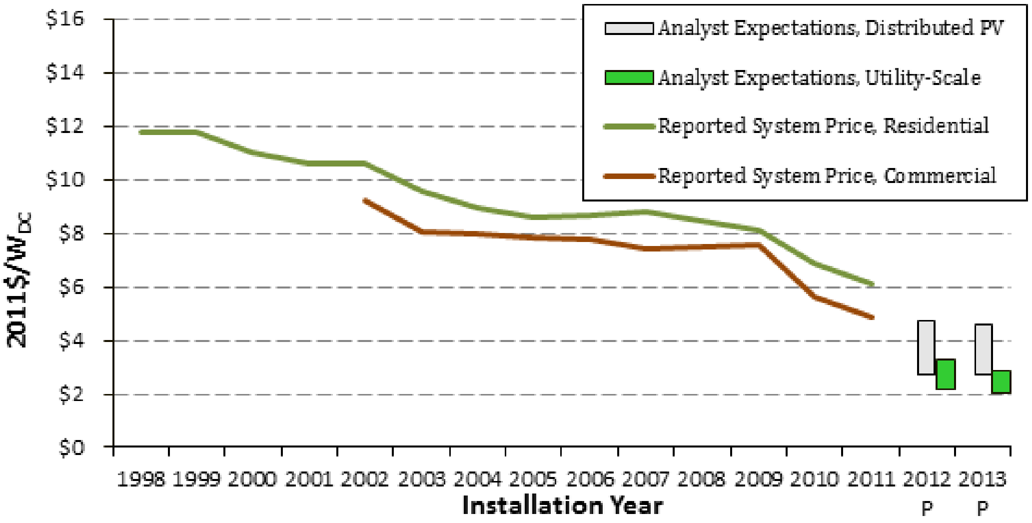

Figure 8. U.S. residential and commercial PV pricing fell 24% and 36% respectively, 2009–11

Source: Feldman et al. 2012

The land and water requirements for solar energy technologies vary substantially. Due to water supply limitations and the need for cooling, a number of large-scale solar systems now in planning and development phases will be dry cooled and will rely on molten salt or other materials for heat transfer. These steps substantially reduce water demands. However, dry or hybrid cooling systems cost more and lower plant thermal efficiency, in part because they require additional energy to operate. A recent study examined the efficiency and impact of dry and hybrid cooling systems on a nominal parabolic trough CSP plant under different geographic/climatic conditions. Switching from wet to dry cooling increases levelized cost of electricity (LCOE) 3–8% in most locations in the southwestern United States and 2.5% at cooler, higher altitude areas. The switch also reduced water consumption by 90% (Turchi et al. 2010). Overall, dry cooled systems should be less vulnerable to the drier conditions projected to occur with climate change.

1.5 Geothermal

Geothermal power taps the heat of the earth for a number of direct uses, including district heating. In addition, the natural differential between the heat of the earth and surrounding air creates the opportunity for employing “geothermal” or ground-source heat pumps for heating or cooling applications. In the context of generating electricity, however, geothermal technologies generally work by extracting heat from geothermal reservoirs using wells or other means. Wells often conduct the heat to the surface in the form of hot water under pressure. The water can then be “flashed” into steam to drive a turbine and generate electricity. The “flashing” process, where some of the water turns to a gas, is due to a pressure drop. Some geothermal plants increase both power output and efficiency by using a multi-stage flashing process (across decreasing pressure drops) to increase the amount of water that is turned to steam (and minimize the amount of cooler (but still quite hot) unused water that is returned to ground. In some cases, the fluid from the well is already in the form of dry superheated steam. This is the case at Geysers hydrothermal field in northern California, a complex of more than 20 geothermal power plants that range from 12 to 119 MW, draw steam from more than 350 wells. The largest hydrothermal field in the world, the Geysers has 1517 MW of active installed capacity with an average production factor of 63% (955 MW). In the late 1980s, the Geysers hydrothermal field had a generating capacity of approximately 2,100 MW of electricity from 26 individual power plants. Production peaked in 1988 and has since declined because of a loss in pressure. However, a 1997 project to inject wastewater into the heat zones has resulted in recovery of some generating output (Duffield and Sass 2003). At the other the end of the spectrum lower temperature water from wells can still sometimes be used to generate electricity via a heat exchanger to evaporate organic liquids under pressure that have lower boiling points than water, and where the vapor is then used drive a turbine. This two-phase, binary system technology is often referred to as an Organic Rankine Cycle because the organic liquid is in a closed system that operates in a similar manner to the close water/steam (Rankine) cycle used in some conventional generation technologies, such as coal thermal plants and pressurized water nuclear reactors.

When used to generate electricity, geothermal power plants generally provide constant output, or baseload generation (IPCC 2011). Table 4 shows some geothermal electric resources.

Table 4. Ranges of Geothermal Electric Resources

	Distinguishing Features	Development
Enhanced Geothermal Systems (EGS)	These areas are often shallower and adjacent to producing natural hydrothermal areas but have been considered uneconomic because of low permeability.	Traditionally, only hydrothermal systems with sufficiently high temperatures and permeable, water-saturated rock have been commercially developed for generating electricity. Research is underway to enhance uneconomic areas adjacent to natural hydrothermal areas by stimulating permeability through hydraulic fracturing, directional drilling to intersect favorably oriented fractures, and injecting groundwater or wastewater to replenish fluids and to reverse pressure declines.
Hydrothermal Electricity Systems	Hot and sufficiently porous and permeable to be saturated with fluids that mobilize the heat to generate electricity.	Approximately twenty geothermal fields in the United States generate electricity. The three subcategories of hydrothermal electricity systems vary based on what turns the turbines: • Steam (vapor dominated systems) • Liquid hot water • Secondary fluid (using moderate-temperature water in a binary process.
Steam or Vapor-dominated	When a potent heat source intersects with a restricted source of water, the pore spaces of rocks in a high-temperature hydrothermal system are saturated with steam, rather than by liquid water, and only steam is produced through the wells and directly routed into turbine generators.	Vapor-dominated systems are the most desirable for electric power production because they do not require the separation of steam from water, so the energy they contain is relatively simple and efficient to harness. Vapor-dominated systems are rare compared with valuable, but less-simple-to-develop, hot-water systems. The world's largest developed vapor-dominated system is at The Geysers in northern California.
Hot Water (212–700°F)	These systems are in porous and permeable rock naturally saturated with enough water to drive electric turbines. The water partly "flashes" into steam when it rises up production wells.	The hotter the hydrothermal fluids, the more capable they are of producing steam and generating electricity. To extract the most energy from the fluid, it sometimes can be "flashed" two or three times to drive additional turbine generators. Examples of hot-water systems are Coso and Imperial Valley in southern California.
Binary Systems (Below 212°F)	Moderate-temperature hydrothermal systems are incapable of producing steam at sufficient pressure to directly drive a turbine generator. They are, however, hot enough to produce a high-pressure vapor by transferring heat to a secondary working fluid.	A binary cycle generates power by transferring the heat from the geothermal fluid to another fluid whose boiling temperature is lower than that of water (for example, isobutene). Binary systems producing electricity include California plants at Mammoth Lakes and in the Imperial Valley. By taking advantage of the more widespread distribution of moderate-temperature geothermal water, binary systems may contribute significantly to the overall generation of electricity from geothermal sources.

Source: K.K. DuVivier, *The Renewable Energy Reader,* Figure 6.3, pp. 225-26 (Carolina Academic Press 2011).

As Table 4 indicates, some hydrothermal reservoirs are sufficiently hot and permeable and contain sufficient water to produce geothermal electricity. Conventional thermal applications of geothermal energy and hydrothermal power plants are considered mature technologies. Lopez et al. (2012) estimated 71 TWh of electric power generation from identified hydrothermal sites spread among 13 states. An additional 237 TWh of undiscovered hydrothermal resources are estimated to exist among these same states.

Other reservoirs that are sufficiently hot but lack porosity or natural water can be improved with hydraulic stimulation called enhanced geothermal systems (EGS). EGS projects are undergoing research and development in the demonstration and pilot phase. The vast majority of the geothermal potential for EGS (31,344 TWh) within the contiguous United States is located in the westernmost portion of the country. The Rocky Mountain region and the Great Basin contain the most favorable resource for EGS (17,414 TWh). However, even the central and eastern portions of the country show potential for 13,930 TWh of EGS. In addition, new binary technologies allow for low temperature electricity production, such as from hot brines produced in oil fields.

1.6 Ocean Energy

A range of potential technologies can tap the energy of seawater to provide electricity, thermal energy, or potable water from seawater.[8] These technologies include:

- **Tidal technologies**: Barrages for tidal range, submarine turbines for tidal and ocean currents.
- **Wave technologies:** Devices or prototypes being designed to potentially capture the kinetic and potential energy of waves include: surface or underwater "heaving" devices, including tethered floating buoys; oscillating wave columns (OWC) (typically, but not always on coastline) that drive air in both directions through a bi-directional turbine; pitching devices; and overtopping devices, that collect the water of incident waves to drive lower-level turbines.
- **Ocean Thermal Energy Conversion (OTEC)**: OTEC refers to the concept of using engines to take advantage of temperature differences between the "warm" surface waters and the colder deeper water to generate power that. The efficiency of OTEC devices is low because the temperature difference is quite small. Surface temperature is typically only 20°–25° C warmer than water at 1000m, leading to a theoretical maximum efficiency 6%–7% or less. The waste heat can be used to produce drinking water.

EPRI recently conducted an assessment of the U.S. wave energy resource (EPRI 2011).

Table 5. Estimated Total and Recoverable Wave Energy Resources the U.S. Continental Shelf (TWh/yr)

	Total Wave Energy Resources	**Recoverable Wave Energy Resources**
West coast	590	250
East coast	240	160
Gulf of Mexico	80	60
Alaska	1,570	620
Hawaii	130	80
Puerto Rico	30	20
TOTAL	**2,460**	**1,170**

Source: EPRI 2011

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[8] The energy in the ocean associated with temperature gradients and all non-tidal waves originates from the sun, though in the case of waves the effect is indirect; the direct source of energy in waves is the wind. Tides –which are also waves– result from the combined effects of gravity between the Earth and the moon and (to a lesser extent) the sun, and the rotation of Earth.

Ocean technologies, with the exception of tidal barrages, are at the demonstration and pilot project phases and many require additional R&D. Some of the technologies have variable energy output profiles with differing levels of predictability (e.g., wave, tidal range, and current), while others may be capable of near-constant or even controllable operation (e.g., ocean thermal and salinity gradient) (IPCC 2011).

2 Supportive Policies

In a recent assessment, UNEP (2012) found that "increasing renewable energy as a part of the total primary energy supply provides multiple benefits." With respect to energy development in North America, clusters of policies that were found to affect RE adoption include:

1. Policies providing financial support, including production tax credits, feed-in tariffs and renewable portfolio standards as well as support for R&D
2. Incentives or policies to encourage behavioral change, including designating transmission cost recovery and allocation, managing the grid through independent system operators, developing smart grids, and phasing out coal plants
3. Decreasing institutional barriers, including consolidating siting authorities and conducting integrated resource planning (UNEP 2012).

Despite the differences in global markets, resources, and power systems, some common policy practices have emerged in countries that are successfully managing high levels of variable renewable energy on the grid. Cochran et al. (2012) describes these five areas:

- Leading public engagement, particularly for new transmission
- Coordinating and integrating planning
- Developing rules for market evolution that enable system flexibility
- Expanding access to diverse resources and geographic footprint of operations
- Improving system operations.

3 Conclusion

The above descriptions show that the United States possesses sufficient renewable resources to more than meet its electricity generation needs. But as one of the authors of the SRREN noted: "It is not the availability of the resource, but the public policies that will either expand or constrain renewable energy development over the coming decades."[9]

These policies are beyond the scope of this paper, but will be addressed in other sessions of the Rocky Mountain Mineral Law Foundation special institute.

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[9] Ramon Pichs, Co-Chair of the Working Group III http://srren.ipcc-wg3.de/press/content/potential-of-renewable-energy-outlined-report-by-the-intergovernmental-panel-on-climate-change (quote continued "Developing countries have an important stake in this future – this is where most of the 1.4 billion people without access to electricity live yet also where some of the best conditions exist for renewable energy deployment.")

Additional Resources

U.S. Department of Energy Websites

The U.S. Department of Energy supports research and development in renewable energy technologies, including the following:

- Bioenergy—http://www1.eere.energy.gov/bioenergy/
- Hydropower—http://www1.eere.energy.gov/water/
- Wind—http://www1.eere.energy.gov/wind/
- Solar—http://www1.eere.energy.gov/solar/sunshot/
- Geothermal—https://www1.eere.energy.gov/geothermal/index.html
- Marine and hydrokinetic—http://www1.eere.energy.gov/water/.

NREL Models and Tools

NREL provides models and tools to assess, analyze, or optimize renewable energy technologies and performance, energy systems, and economics and finance.

- **System Advisor Model (SAM)** (https://sam.nrel.gov)—Make performance predictions and cost of energy estimates for grid-connected power projects based on system design parameters that you specify.
- **Cost of Renewable Energy Spreadsheet Tool (CREST)** (https://financere.nrel.gov/finance/content/crest-cost-energy-models)—Assess solar, wind, or geothermal projects, design cost-based incentives, and evaluate the impact of tax incentives or other support structures with this cash flow model.
- **Job and Economic Development Impact (JEDI) Model** (http://www.nrel.gov/analysis/jedi/)**—**Use these spreadsheet-based tools to analyze the economic impacts of constructing and operating power generation and biofuel plants at the local and state level.
- **BioPower Atlas and BioFuels Atlas** (http://maps.nrel.gov/bioenergyatlas)—Compare biomass feedstocks and biofuels by location using this interactive map. It also displays bioenergy (biopower and biofuels) and conventional power plants and refineries and alternative fuel stations.
- **Biomass Scenario Model** (https://bsm.nrel.gov/)—Determine which supply chain changes would have the greatest potential to accelerate the deployment of biofuels.
- **Wind Prospector** (http://maps.nrel.gov/windprospector)—Map and measure wind energy.
- **PV Watts** (http://gisatnrel.nrel.gov/PVWatts_Viewer/index.html)—Calculate electrical energy produced by a grid-connected photovoltaic (PV) system for U.S. locations.
- **Solar Prospector** (http://maps.nrel.gov/prospector)—Use geospatial data to map solar resources and site utility-scale solar plants.
- **Geothermal Prospector – Beta** (http://maps.nrel.gov/gt_prospector)—Find sites for developing large-scale geothermal plants.
- **MHK Atlas** (http://maps.nrel.gov/mhk_atlas)—Explore marine and hydrokinetic energy resources.

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