



THE FOOTPRINT OF ENERGY: LAND USE OF U.S. ELECTRICITY PRODUCTION



STRATA

June 2017

Primary Investigator:

[REDACTED]

Student Research Associates:

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

Table of Contents

Coal.....	1
Energy Plant Land Use.....	2
Resource Production Land Use	2
Transmission/Transportation Land Use	3
Storage Land Use	3
Conclusion	4
Natural Gas	4
Energy Plant Land Use.....	5
Resource Production Land Use	5
Transmission/Transportation Land Use	6
Storage Land Use	6
Conclusion	7
Nuclear	7
Energy Plant Land Use.....	7
Resource Production Land Use	8
Transmission/Transportation Land Use	9
Storage Land Use	9
Conclusion	11
Hydro.....	12
Energy Plant Land-Use	13
Resource Production Land Use	14
Transmission/Transportation Land Use	14
Storage Land Use	15
Conclusion	15
Wind	15
Energy Plant Land Use.....	16
Resource Production Land Use	16
Transmission/Transportation Land Use	17
Solid Waste Land Use.....	17
Conclusion	18
Solar	18
Energy Plant Land Use.....	18
Resource Production Land Use	19
Transmission/Transportation Land Use	20
Storage Land Use	20
Conclusion	21
Conclusion.....	21

Modern society requires a tremendous amount of electricity to function, and one of this generation's greatest challenges is generating and distributing energy efficiently. Electricity generation is energy intensive, and each source leaves its own environmental and ecological footprint. Although many studies have considered how electricity generation impacts other aspects of the environment, few have looked specifically at how much land different energy sources require.

This report considers the various direct and indirect land requirements for coal, natural gas, nuclear, hydro, wind, and solar electricity generation in the United States in 2015. For each source, it approximates the land used during resource production, by energy plants, for transport and transmission, and to store waste materials. Both one-time and continuous land-use requirements are considered. Land is measured in acres and the final assessment is given in acres per megawatt.

Specifically, this report finds that coal, natural gas, and nuclear power all feature the smallest physical footprint of about 12 acres per megawatt produced. Solar and wind are much more land intensive technologies using 43.5 and 70.6 acres per megawatt, respectively. Hydroelectricity generated by large dams has a significantly larger footprint than any other generation technology using 315.2 acres per megawatt.

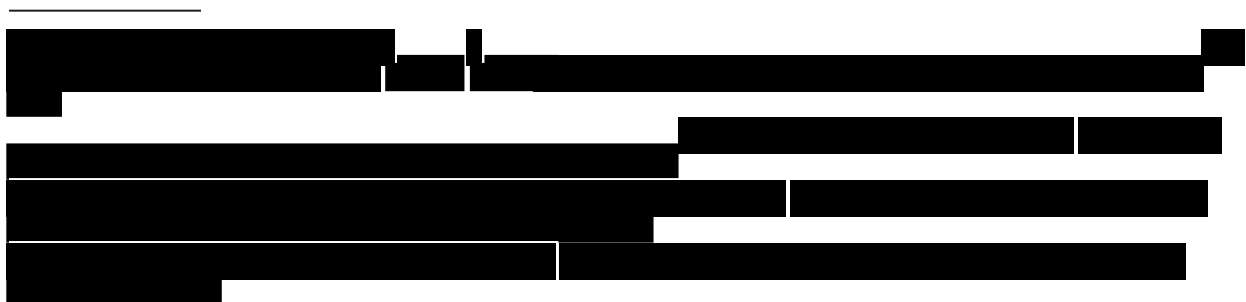
While this report does not attempt to comprehensively quantify land requirements across the entire production and distribution chain, it does cover major land components and offers a valuable starting point to further compare various energy sources and facilitates a deeper conversation surrounding the necessary trade-offs when crafting energy policy.

Chart 1: Land Use by Electricity Source in Acres/MW Produced

Electricity Source	Acres per Megawatt Produced
Coal	12.21
Natural Gas	12.41
Nuclear	12.71
Solar	43.50
Wind	70.64
Hydro	315.22

Coal

In 2015, the United States (US) was home to 427 coal-fired power stations that generated 1.4 trillion megawatt hours of electricity, accounting for 33 percent of the nation's total electricity production.¹² Coal produces electricity at a capacity factor of 54.7 percent.³ Capacity factor is the ratio of actual energy production to theoretical maximum output for a given power plant. This means that while U.S. coal-fired power stations had a total capacity of approximately 282,236 megawatts, they only actually produced 154,383 megawatts. Coal is currently the most widely used electricity source in the US, but that figure is declining with the growing natural gas industry.⁴ In addition, America's



coal plants are nearing retirement. Almost three quarters of coal plants in the US are 30 years old or older while a coal plant's average lifespan is only 40 years.⁵

Coal produces cheap, reliable electricity, but it comes with necessary environmental considerations. This report focuses specifically on the land requirements at various stages of coal electricity generation including resource production, energy plant size, transmission and transportation, and waste storage.

Energy Plant Land Use

The Natural Gas Supply Association (NGSA) divides coal plants into two categories. “Standard coal burning operations using advanced pollution control (APC) technology” are currently the most prevalent category, while “coal plant[s] using carbon capture & sequestration (CCS) technology” are much less common.⁶ The Center for Climate and Energy Solutions notes that eight CCS plants currently operate in the US, meaning the remaining 419 coal plants use APC technology.⁷ The NGSA estimates the acreage for APC plants is between 200 and 250 acres and CCS plants is about 400 acres.⁸ Assuming a high end estimate for APC plants, coal plants in the US required approximately 107,950 acres of land in 2015, or 0.699 acres per megawatt of electricity produced.

Resource Production Land Use

The vast majority of the US coal supply is mined domestically. Because imports account for less than two percent of the nation's coal consumption, this report only takes into account the land used to produce the nation's domestic coal supply.⁹

According to the United States Energy Information Administration (EIA), coal is typically mined by one of two methods. Surface mining is used to extract seams of coal that are up to 200 feet deep where “large machines remove the topsoil and layers of rock known as overburden to expose coal seams.” Fortunately, areas disturbed by surface mining can be recovered by filling them with topsoil and vegetation. Underground mining is used to access coal that can be up to 1,000 feet below ground.¹⁰ Underground mining improves access to more resources, however, it can lead to multiple problems including tunnel collapses, land subsidence, and environmental pollution.¹¹ Because surface mining is cheaper than underground mining, most coal mines in the US are surface mines.¹²

Renewable and Sustainable Energy Reviews found that surface mining in the US transforms an average of 0.000099 acres of land per megawatt hour (400 m² per gigawatt hour) of electricity and that underground mining transforms an average of 0.000049 acres per megawatt hour (200 m² per gigawatt hour).¹³ According to the EIA, surface mining accounted for 66.2 percent of coal production in 2015 and underground mining accounted for 33.8 percent.¹⁴

Because coal-fired power stations generated 1,352,398,000 megawatt hours of electricity in 2015, surface mines transformed approximately 88,513 acres of land and underground mines transformed approximately 22,581 acres of land for a total of 111,093 acres, or 0.720 acres per megawatt.

It should be noted, however, that coal resource production land use is likely higher than this report estimates. *Renewable and Sustainable Energy Reviews* assumed that coal had a capacity factor of 85 percent, but the EIA reported that in 2009, the year *Renewable and Sustainable Energy Reviews* published their report, the capacity factor for coal steam generators was about 65 percent and that in 2015, it was 54.6 percent.¹⁵¹⁶

Transmission/Transportation Land Use

Coal relies on trains, trucks, barges, and pipelines to be transported from mine to plant. In the US, trains are the most widely used means of transportation for coal. The EIA estimates that “Trains transport nearly 70% of coal deliveries in the United States for at least part of the way from mines to consumers.”¹⁷ Coal travels an average of 628 miles from the mine to the plant, and an average coal-fired power station requires 14,600 railroad cars a year to keep it supplied.¹⁸¹⁹ However, because rails serve for multi-use transportation purposes, the land used specifically to transport coal cannot reasonably be quantified. It is also impossible to determine whether rail is used because it is available, or to what degree the coal industry led to the expansion of the US rail system. While this report does not attempt to quantify rail use as a coal specific resource, it could be a relevant consideration in broader energy policy discussions and a possible source for future evaluation.

Transmitting electricity in the US requires an estimated 450,000 miles of high voltage transmission lines with safety buffer zones a minimum of 44 feet (13.5 meters) on each side, or approximately 4,800,000 acres of land.²⁰²¹ Because coal accounted for 33.17 percent of the nation’s electricity production in 2015, approximately 1,592,160 acres of land were required to transmit coal energy in 2015, or 10.31 acres per megawatt.

It should be noted, though, that this estimate does not account for the land requirements for local distribution lines and is likely lower than the actual number. Reliable data does not exist for the land around local distribution lines, and that land can many times be used for multiple purposes. For these reasons, this report does not account for distribution lines when quantifying land use for any electricity source.

Storage Land Use

Coal waste, or gob, is “the low-energy-value [discard] of the coal mining industry.”²² After gob is removed from the mine, it is typically dumped in massive piles that can increase at a rate of 500 tons per day.²³ Gob can retain up to 60

[Accessed 26 Jan. 2017].

[REDACTED]

percent of coal's energy potential, so some plants use it as either a primary or a secondary power source. However, much of it remains in piles that "look like hills or small mountains that are dark and barren."²⁴ Because most of these piles formed between 1900 and 1970, and coal waste is now disposed through impoundments and landfills, this report assumes that they do not contribute significantly to current land-use requirements.²⁵

Coal combustion waste (CCW) is what remains after coal has been burned. CCW is mostly composed of ash, and the majority of it is disposed of in landfills if it is solid or in surface impoundments if it is liquid.^{26,27} Some coal-fired power stations are allowed to dispose ash into local waterways, and approximately 20 percent of CCW "is injected into abandoned coal mines."^{28,29} Because waterways are not exclusively used to dispose of CCW, this report will not attempt to quantify their land-use requirements. The average CCW landfill requires about 120 acres of land, and the average CCW surface impoundment requires about 50 acres. Because there are about 310 active CCW landfills and 735 active CCW surface impoundments in the US, disposing of CCW requires approximately 73,950 acres of land, or 0.479 acres per megawatt.³⁰

Conclusion

Producing the US's supply of coal energy in 2015 required approximately 1,885,153 acres of land, or 12.211 acres per megawatt. The vast majority of that land was used to transmit electricity. The activities that led directly to energy production accounted for only 15.54 percent of coal's total land requirements.

In 2015, the United States consumed 376,826.5 megawatts of electricity (3.301 billion megawatt hours).³¹ Because coal energy accounted for 33.17 percent of the nation's electricity production, approximately 4,601,428 acres of land would have been required for coal energy to be the sole provider of electricity in the United States in 2015. This land mass is approximately the same size as the state of New Jersey.³²

Natural Gas

In 2015, natural gas plants in the US produced 1,333,482,000 megawatt hours of electricity,³³ accounting for 32.70 percent of the nation's total electricity production.³⁴ Natural gas is the second most widely used electricity source in the US and growing due to lower prices, improved technology, and aging coal plants.³⁵ When natural gas is used by



consumer appliances, only about 10 percent of its energy is lost, while burning gas at an energy plant and transmitting the electricity is much less efficient.³⁶

The EIA tracks data for four types of natural gas plants: natural gas fired combined cycle (FCC), natural gas fired combustion turbine (FCT), steam turbine (ST), and internal combustion engine (ICE). Each of these plant types produces electricity at a different capacity factor—FCC plants at 55.9 percent, FCT plants at 6.9 percent, ST plants at 11.5 percent, and ICE plants at 8.9 percent.³⁷ Based on their total in-service capacities at the end of September 2016, FCC plants accounted for 53.49 percent of natural gas's generating capacity, FCT plants for 27.88 percent, ST plants for 17.73 percent, and ICE plants for 0.85 percent.³⁸ Assuming these numbers are also representative of 2015, natural gas plants had an average capacity factor of 33.94 percent. In total, natural gas had a generating capacity of 448,529 megawatts and produced a total of 152,224 megawatts during 2015.

Energy Plant Land Use

The US was home to 1,740 natural gas power plants in 2015.³⁹ According to the Natural Gas Supply Association, the average natural gas plant requires between 20 and 40 acres of land.⁴⁰ Assuming a median of 30 acres as the average, natural gas plants in the US required approximately 52,200 acres of land in 2015, or 0.343 acres per megawatt produced.

Resource Production Land Use

The land natural gas uses for resource production is minimal. Excluding the land needed to mine fracking rig materials, the average initial disturbance of a single-well pad is 3.7 acres during production.⁴¹ However, the average multiple well-pad size is five acres as shown in a study of the Pinedale natural gas field in Wyoming.⁴² The EIA reported that most well pads are multi-well pads with four to six wells.⁴³ This study will use multi-well pads for calculating acreage. This report does not include access roads due to the large number of roads, and variations in land requirements. This study will assume land use based on multi use well-pads containing five drills using five acres each.

In the US, 27.31 trillion cubic feet of natural gas were consumed in 2015. 35 percent of that, or 9.67 trillion cubic feet, was used in electricity generation.⁴⁴ In 2015, the US imported 2.718 trillion cubic feet and exported 1.783 trillion cubic feet of natural gas, making imports about 12 percent of the total amount of natural gas used.⁴⁵ For the purpose of this paper, imports will not be calculated due to the large amount of natural gas that is produced domestically. In 2015, there were 555,364 producing gas wells in the US.⁴⁶ Assuming the average of five wells per five acres,



each gas well used around one acre. Multiplying the total well pad land use by the percentage of natural gas used for electricity generation equates to approximately 194,377.4 acres, or 1.28 acres per megawatts produced.

In order to extract natural gas from the earth, silica sand or “frac sand” is mixed with water and pumped into wells. Frac sand is used to break into the earth and keep it open, allowing the gas to reach the surface.⁴⁷ Silica sand needs to be mined, which increases the amount of land needed to extract natural gas. The majority of silica sand is produced domestically, therefore this study will use silica mines and processing stations in Wisconsin as a model to calculate land requirements per acre.⁴⁸ In Wisconsin, there were roughly 128 sand mines, processing stations, and rail loading stations in 2016.⁴⁹ To find the average size of a mine and associated facilities, this study used a report that averaged the mine acreage of over 100 operational mines and processing stations. The average silica mine and processing facility in Wisconsin covers 327.079 acres.⁵⁰ The estimate includes sand mines other than frac sand mines, but also includes the amount of land displaced by processing and transport stations. In Wisconsin, there are 78 frac sand mines.⁵¹ Multiplying 327.079 acres by the total number of frac mines produces a total of 25,512.162 acres used for frac mining in Wisconsin. Wisconsin alone was responsible for 44 percent of silica sand production used in the fracking industry in 2014.⁵² Assuming that Wisconsin’s average mine size is comparable to the national average, the land disturbed by frac sand mining and processing was 57,982.186 acres total, or 0.381 acres per megawatt produced.

Transmission/Transportation Land Use

Natural gas is transported by pipeline. In the US, 210 natural gas pipelines span 305,000 miles and service 48 states.⁵³ Most natural gas pipelines are underground or lack data on land use, therefore this report will not attempt to quantify land use requirements for pipelines. It should be noted that this report is a conservative estimate and land use for transportation is likely higher than these results. Further detailed work could be produced highlighting the land use requirements of US pipeline networks.

As noted in the previous section, transmitting electricity in the US requires an estimated 450,000 miles of high voltage transmission lines with safety buffer zones of 44 feet on each side, or approximately 4,800,000 acres of land.^{54,55} Because natural gas accounted for 33 percent of the nation’s total energy production, approximately 1,584,000 acres of land were required to transmit natural gas energy in 2015, or 10.406 acres per megawatt.⁵⁶

Storage Land Use

Natural gas emits gaseous waste, but it does not emit solid waste that requires specialized storage. Thus, we assume land requirements for storage to be minimal.



Conclusion

In 2015, the US consumed 376,826.5 megawatts of electricity (3.301 billion megawatt hours).⁵⁷ Natural gas in the US used roughly 12.41 acres per megawatt. The bulk of land use comes from transportation, but natural gas well pads used a considerable amount of land as well.

If the US were to use natural gas as its only power source, it would require 4,676,417 acres of land, which is the equivalent of 93.3 percent of the state of Massachusetts.⁵⁸

Nuclear

Nuclear energy is generated by nuclear fission reactions that release heat to boil water, spin steam turbines, and produce electricity. Besides the actual reactor, nuclear functions similar to coal and natural gas plants.⁵⁹ The US is home to 61 nuclear power stations with 99 reactors that generated 797,178,000 megawatt hours of electricity in 2015, accounting for 19.55 percent of the nation's total net electricity production.^{60,61}

Nuclear power stations produced at a capacity factor of 92.3 percent in 2015, which is significantly higher than all other power sources in the US.⁶² Nuclear energy is also more efficient in terms of BTUs per kilowatt hour than other steam-generated power sources like coal, petroleum, and natural gas.⁶³ However, storing nuclear waste is challenging because it can be highly radioactive for a prolonged period of time. Additionally, events like the Chernobyl and Fukushima disasters have magnified people's fears about the safety of nuclear energy, even though statistics indicate that it is one of the safer modes of electricity production.⁶⁴

Because nuclear power stations generated 797,178,000 megawatt hours of electricity in 2015 at a capacity factor of 92.3 percent, they produced 91,002 megawatts of electricity and had a collective capacity of approximately 98,594 megawatts. The land required to support this capacity comes mainly from energy plants, resource production, electricity transmission, and waste storage.

Energy Plant Land Use

Nuclear power stations do not require as much land per megawatt as other low-carbon methods of electricity production. The Arkansas Nuclear One Station requires only 1,100 acres (1.7 square miles) to produce 1,800 megawatts operating at a 90 percent capacity factor. A study by Entergy Arkansas estimates that for modern wind and solar plants operating at the same capacity, they would require 108,000 acres (169 square miles) and 13,320 acres (21 square miles) of land respectively to produce the same amount of power.⁶⁵



Other nuclear power stations in the US are similar. There are 61 nuclear power stations in the US, but four of them—the Salem and Hope Creek plants in New Jersey and the Nine Mile Point and James A. Fitzpatrick plants in New York—share sites.^{66,67,68} The 59 nuclear sites in the US require an average of 832 acres (1.3 square miles) for every 1,000 MW of installed capacity for a total of 82,030 acres, or 0.901 acres per megawatt.⁶⁹

Resource Production Land Use

The primary fuel used in nuclear reactors is an isotope of uranium called U-235. In 2015, owners and operators of nuclear power stations in the US purchased 56.6 million pounds of uranium, and only six percent of that was produced domestically. The other 94 percent was produced in Kazakhstan, Russia, Uzbekistan, Canada, Australia, Malawi, Namibia, Niger, and South Africa.⁷⁰ Mining uranium is land intensive, but the World Nuclear Association noted that:

Mining is generally considered a temporary land use, and upon completion the area with any waste rock, overburden, and covered tailings needs to be left fit for other uses, or its original use. In many parts of the world governments hold bonds to ensure proper rehabilitation in the event of corporate insolvency.⁷¹

In the United States, mine owners are required to pay upfront for any reclamation efforts needed over the entire life of mining operations.⁷² Still, current land-use requirements will be considered.

The Rössing Uranium Mine in Namibia is one of the world's largest uranium producers. In 2015, it produced 2.7 million pounds (1,245 tonnes) of uranium, representing 2.06 percent of the world's total uranium production of 133.4 million pounds (60,496 tonnes).^{73,74} Including the mining pit, waste rock dumps, storage facility, processing plant, roads, railways, and other infrastructures, the mine's activities used 6,286 acres (2,544 hectares) of land.⁷⁵ Assuming similar land-use requirements for other uranium mines, an estimated 305,444 acres of land were required to produce the world's uranium supply in 2015. Because the US purchased 42.44 percent of the world's supply, approximately 129,632 acres of land were required to produce the US's supply of uranium in 2015. The land used to produce America's uranium divided by total nuclear energy produces a land use estimate of 1.42 acres per megawatt.



Transmission/Transportation Land Use

As noted in previous sections, transmitting electricity in the US requires an estimated 450,000 miles of high voltage transmission lines with safety buffer zones of 44 feet on each side, or approximately 4,800,000 acres of land.⁷⁶⁷⁷ Because nuclear energy accounted for 19.55 percent of the nation's electricity production in 2015, approximately 938,388 acres of land were used to transmit nuclear energy in 2015, or 10.312 acres per megawatt.

Storage Land Use

Nuclear energy produces high and low-level radioactive wastes. According to the United States Nuclear Regulatory Commission (NRC), "High-level radioactive wastes are the highly radioactive materials produced as a byproduct of the reactions that occur inside nuclear reactors."⁷⁸ They can take hundreds of thousands of years to decay and become harmless to the public.⁷⁹ Other countries recycle high-level wastes, but nuclear reprocessing was prohibited in the US by Jimmy Carter in 1977.⁸⁰ Instead, nuclear operators must cool high-level wastes in storage pools for up to 10 years before they can be shipped to permanent storage sites in containers that reduce the heat and contain the radioactivity.⁸¹⁸² Although it is a complex process, thousands of shipments have been made over the past 40 years with no radiological releases or harm to either the environment or the public.⁸³

The two acceptable methods for storing high-level wastes on-site are spent fuel pools and dry cask storage. According to the NRC, "most spent nuclear fuel is safely stored in specially designed pools at individual reactor sites around the country."⁸⁴ Because of this, most of the land used for spent fuel pools is factored into energy plant land use. However, three nuclear plants listed on the NRC's Spent Fuel Pool Criticality Management database are in various stages of decommissioning and have not yet been factored in.⁸⁵ The Crystal River Nuclear Plant was one of five power plants at the Crystal River Generating Complex, and it occupies approximately 671 of the 4,700 acres the complex sits on.⁸⁶ The Kewaunee nuclear plant occupies 900 acres, and the San Onofre nuclear plant occupies 84 acres.⁸⁷⁸⁸ Collectively, they require an additional 1,655 acres of land, or 0.018 acres per megawatt, for spent fuel pools.

Dry casks are stored at independent spent fuel storage installations (ISFSIs) that are typically located at existing nuclear sites, although some are located on the sites of decommissioned nuclear plants or at independent locations.⁸⁹



ISFSIs are authorized by the NRC, and they must be licensed under a general license or a site-specific license to operate.⁹⁰ As of October 6, 2016, 62 ISFSIs operate under general licenses, 15 operate under site-specific licenses, and four operate under both.⁹¹ Of the 73 existing ISFSIs, 16 are not located on the sites of currently operating nuclear plants. Two of these, one at the Kewaunee nuclear plant and one at the San Onofre nuclear plant, have already been accounted for in the spent fuel pools section. Land requirements for the remaining 14 must be considered.

The Maine Yankee, Vermont Yankee, Yankee Rowe, Haddam Neck, Big Rock Point, and LaCrosse nuclear stations are each home to generally licensed ISFSIs and are each in various stages of decommissioning.⁹² Their ISFSIs require 11 acres, 125 acres, two acres, five acres, 107 acres, and 164 acres of land respectively.⁹³⁹⁴⁹⁵⁹⁶⁹⁷⁹⁸ The Fort Saint Vrain, Trojan, Humboldt Bay, and Rancho seco nuclear stations are each home to site-specifically licensed ISFSIs and are also each in various stages of decommissioning.⁹⁹ Their ISFSIs require four acres, 30 acres, six acres, and 11 acres of land respectively.¹⁰⁰¹⁰¹¹⁰²¹⁰³ The Department of Energy (DOE) operates two independent ISFSIs in Idaho, one of which stores the waste from the Three Mile Island Unit 2 reactor.¹⁰⁴ These two ISFSIs require two acres and eight acres of land.¹⁰⁵¹⁰⁶ General Electric and Private Fuel Storage operate two private ISFSIs in Illinois and Utah, and

storage.html [Accessed 30 Dec. 2016].

[REDACTED]

they require 892 acres and 820 acres of land respectively.¹⁰⁷¹⁰⁸¹⁰⁹ These 14 ISFSIs collectively require an additional 2,202 acres of land, or .024 acres per megawatt, to store high-level nuclear waste.

Low-level wastes are the lightly irradiated by-products of nuclear production such as gloves, lab supplies, and water purification filters, and they account for about 90 percent of the volume of all radioactive wastes.¹¹⁰ According to the Nuclear Energy Institute (NEI), “Low-level waste generally has levels of radioactivity that decay to background radioactivity levels in less than 500 years. About 95 percent decays to background levels within 100 years or less.”¹¹¹ Some low-level wastes will decay enough to be treated as regular trash, but others will accumulate until they can be shipped to low-level waste disposal sites.¹¹² In 2011, roughly 1.8 million cubic feet of low-level wastes were disposed of in the US.¹¹³

Low-level wastes are disposed of in one of four sites across the US. Energy Solutions operates two of these in Clive, Utah and Barnwell, South Carolina, and the other two are operated by US Ecology in Richland, Washington and by Waste Control Specialists near Andrews, Texas.¹¹⁴ The Clive facility occupies 640 acres, the Barnwell facility occupies 235 acres, the Richland facility occupies 100 acres, and the Andrews facility occupies 1,338 acres.¹¹⁵¹¹⁶¹¹⁷¹¹⁸ Collectively, they require 2,313 acres of land to store low-level wastes, or 0.025 acres per megawatt.

In total, storing nuclear waste in the US requires approximately 6,145 acres of land, or 0.0708 acres per megawatt.

Conclusion

In total, the United States supply of nuclear energy in 2015 required approximately 1,156,195 acres of land, or 12.71 acres per megawatt. The vast majority of that land was used to transmit electricity. Activities involved in actual production of nuclear energy, including mining and physical plant operations, accounted for only 18.84 percent of nuclear energy’s total land requirements.



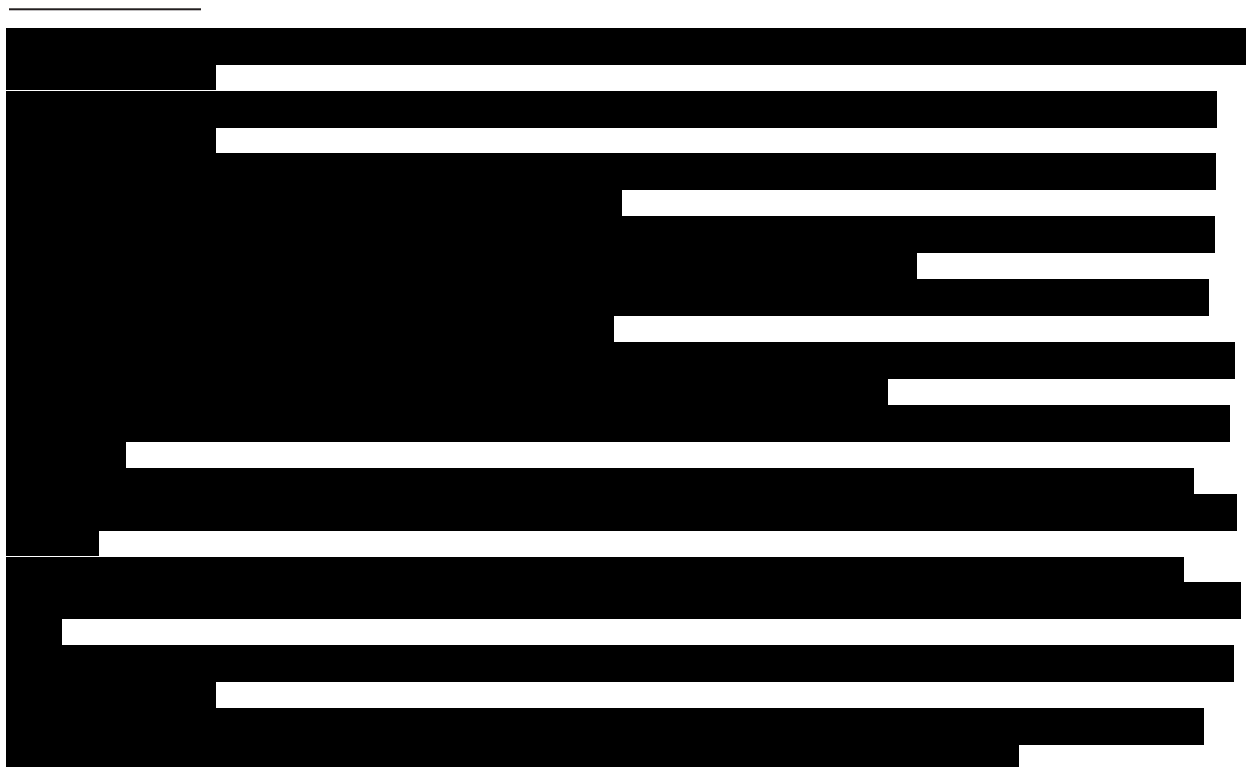
Because the US consumed 376,826.5 megawatts in 2015, approximately 4,789,465 acres of land would have been required for nuclear energy to be the sole provider of electricity in the US that year.¹¹⁹ This area of land is larger than Connecticut and Rhode Island combined.¹²⁰

Hydro

Hydro is the most widely used renewable energy source in the US. In 2015, conventional hydroelectric plants produced 249,080,000 megawatt hours of electricity, accounting for 6.11 percent of the nation's total electricity production. All other renewables accounted for only 7.24 percent combined.¹²¹ Hydroelectric plants produced at a capacity factor of 35.8 percent in 2015.¹²² They had a total generation and storage capacity of 101,000 megawatts and produced a total of 28,433.79 megawatts.¹²³¹²⁴

The first hydropower dam that allowed for long distance electrical transmitting was built in California in 1893.¹²⁵ The United States is home to more than 87,000 dams, but less than 2,200 of them “both generate electricity and serve non-generating needs like flood control, irrigation, recreation, navigation, and drinking water supply.”¹²⁶ Most large scale dams are already in operation as hydropower plants, which limits the potential growth of hydropower. However, in 2014, the DOE estimated that hydropower could produce an additional 12,000 megawatts of electricity from existing dams and 65,000 megawatts from new hydropower sites.¹²⁷

There are three different types of hydroelectric plants in the US. The most common type is an impoundment power plant where a dam slowly releases water into a turbine to create electricity. The second type is a diversion facility, sometimes called run-of-the-river, which “channels a portion of a river through a canal or penstock.” The third type is a pumped station, which is mostly used to store energy for other renewable energy sources.¹²⁸ Hydropower is the easiest type of energy source to use when electricity demand rises or falls in a short period of time because other sources require more start-up time and energy.¹²⁹ In addition to the different types of stations, most stations range in size from small to large. A small hydropower plant can produce at a capacity of less than 10 megawatts while



larger dams can produce up to 22,500 megawatts.¹³⁰¹³¹ Because diversion facilities and pumped stations are fairly infrequent, this section will focus mainly on impoundment power plants and large hydropower plants due to a lack of information on smaller sizes as well as the pumped stations. The rough estimate of acres per megawatts in each section is based on gathered data of 338 large hydropower plants, which are either run-of-the-river or conventional hydro plants.¹³²

Energy Plant Land-Use

The land used by hydropower dams differs vastly, but most are land intensive. Some dams are built in natural reservoir areas, while others are built in relatively flat areas, which causes large changes in the natural habitat. Constructing a new dam impacts the environment in many ways, however, most of the US dams have existed for years, meaning the impacts on the ecosystem have already been realized. As most of the large-scale dam sites in the US have been developed, few new hydropower construction sites are available. Instead, most of hydropower's future increases will come from efficiency improvements, which can increase a hydropower plant's energy production by 50 percent.¹³³

For example, one of the largest hydropower plants in the world is the Grand Coulee Dam in Washington.¹³⁴ The complex includes three power plants, one pumped power station, three switchyards, and two reservoirs.¹³⁵ Because the Grand Coulee Dam and hydropower plant are built almost entirely on top of a river, as most hydropower plants are, its land use comes mainly from the switchyards and reservoirs. Data could not be found for the dimensions of the switchyards, so this estimate takes into account the Grand Coulee Dam's reservoirs. Franklin D. Roosevelt Lake occupies 82,300 acres and Banks Lake occupies 26,888.3 acres for a total of 109,188.3 acres, or 23.8 acres per megawatt.¹³⁶¹³⁷¹³⁸

Based on data compiled for 338 hydropower plants in the US, the average size of a reservoir that runs a large hydropower plant producing 30 megawatts or more is 17,855.18 acres.¹³⁹ This number does not account for pumped storage plants or other plants for which information is unavailable. These 338 hydropower plants produced 25,405.36 megawatts in 2015 and occupied 6,035,043.27 acres of land.¹⁴⁰ Thus, the energy plant land use for large hydropower is 237.55 acres per megawatt.¹⁴¹



Resource Production Land Use

Although hydropower plants use no resources during the production of electricity, hydroelectric plants can be resource intensive in the construction process. Massive amounts of land are excavated during the process of dam construction, but fortunately, excavated dirt can be used elsewhere.¹⁴² Several different products are used to construct dams. However, this section will focus on the most prevalent materials: concrete and earthen material. The largest hydroelectric power plant in the US, the Grand Coulee Dam, took 11,975,521 cubic yards of concrete to build, or about 16,765,729.4 tons.¹⁴³¹⁴⁴ The concrete used in the Grand Coulee Dam is enough “to build a four lane highway stretching from Los Angeles to New York.”¹⁴⁵ Concrete production requires large amounts of land for the quarries and gravel pits that produce aggregate, which makes up about 60 percent of concrete, and most of the earthen dams use aggregate materials as well. Using the information from the 20 top producing aggregate quarries and pits, the average acres used to produce one ton of concrete is 0.0085, and the average acres used to produce one ton of earthen material is 0.0051.¹⁴⁶ The average number of acres needed to produce materials for one concrete dam is 8,033.97, and to produce the materials for one earthen type dam is 66,245.41 acres.¹⁴⁷ Adding the total materials required for the 338 large dams studied, and dividing that tonnage by the total megawatts produced, results in an estimate for concrete dams of 67.36 acres per megawatt of produced hydropower.¹⁴⁸

Transmission/Transportation Land Use

As noted in previous sections, transmitting electricity in the US requires an estimated 450,000 miles of high voltage transmission lines with safety buffer zones of 44 feet on each side, or approximately 4,800,000 acres of land.¹⁴⁹¹⁵⁰ Because hydro accounted for 6.11 percent of the nation’s total energy production, approximately 293,280 acres of land were required to transmit hydro energy in 2015, or 10.31 acres per megawatt.¹⁵¹

It should be noted, however, that this total does not include local distribution land use. Additionally, hydro power plants are usually in more rural locations and thus the total land use for transmission lines may be higher depending on the hydropower station. For example, the Snettisham hydro power plant in Alaska requires a 44 mile long transmission line to transport electricity to its consumers.¹⁵²



Storage Land Use

Hydroelectricity production does not generate any waste products that need to be stored as is common with other forms of electricity generation. Dams, however, produce waste after they are deconstructed. Several dams have been removed in the US, mostly due to faulty construction, and evidence has shown that the environment returns mostly to its natural state.¹⁵³ The concrete and steel used to build the dam does not decompose easily meaning dams have an expected lifespan of approximately 150 years before they need to be removed.¹⁵⁴ This may, however, cause problems in the near future as many dams in the US were built during the early 1900s.¹⁵⁵ At this time, however, hydropower has little to no storage land use and is not factored in this report.

Conclusion

The total estimated land used per megawatt of hydroelectricity produced is estimated at 315.22 acres per megawatt of electricity produced. According to the estimates in this report, in order for the US to be powered exclusively by hydropower, it would require 118,783,249 acres of land, or more than Utah, Idaho, and Maryland combined.¹⁵⁶¹⁵⁷ If hydroelectric produced at 100 percent capacity, and if both existing and potential hydropower sources were producing in the US, hydropower would generate 178,000 megawatts.¹⁵⁸ If the US produced 178,000 megawatts, hydropower alone would account for over 47 percent of all US electricity demand.

Wind

Wind energy is produced by offshore and onshore wind turbines. Although European nations have substantial offshore wind capacity, the US does not.¹⁵⁹ Consequently, this study focuses only on the land use requirements for onshore wind energy. Wind added 8,000 megawatts of capacity by September of 2016, making it the fastest growing renewable in the US.¹⁶⁰ By the end of 2015, the US had a total installed capacity of 75,714 megawatts, which produced 21,771.575 megawatts (190,719,000 megawatt hours).¹⁶¹¹⁶² However, despite being the fastest growing renewable energy, wind produces only 4.7 percent of total electricity demand.¹⁶³ Each wind turbine has an estimated lifes-



pan of up to 25 years, but some studies estimate that the actual lifespan of wind turbines is closer to 12-15 years.¹⁶⁴¹⁶⁵ Wind energy produces at an average of 32.2 percent capacity, making wind the least efficient energy source other than solar.¹⁶⁶ In addition, wind is intermittent and relies heavily on weather conditions to generate electricity.

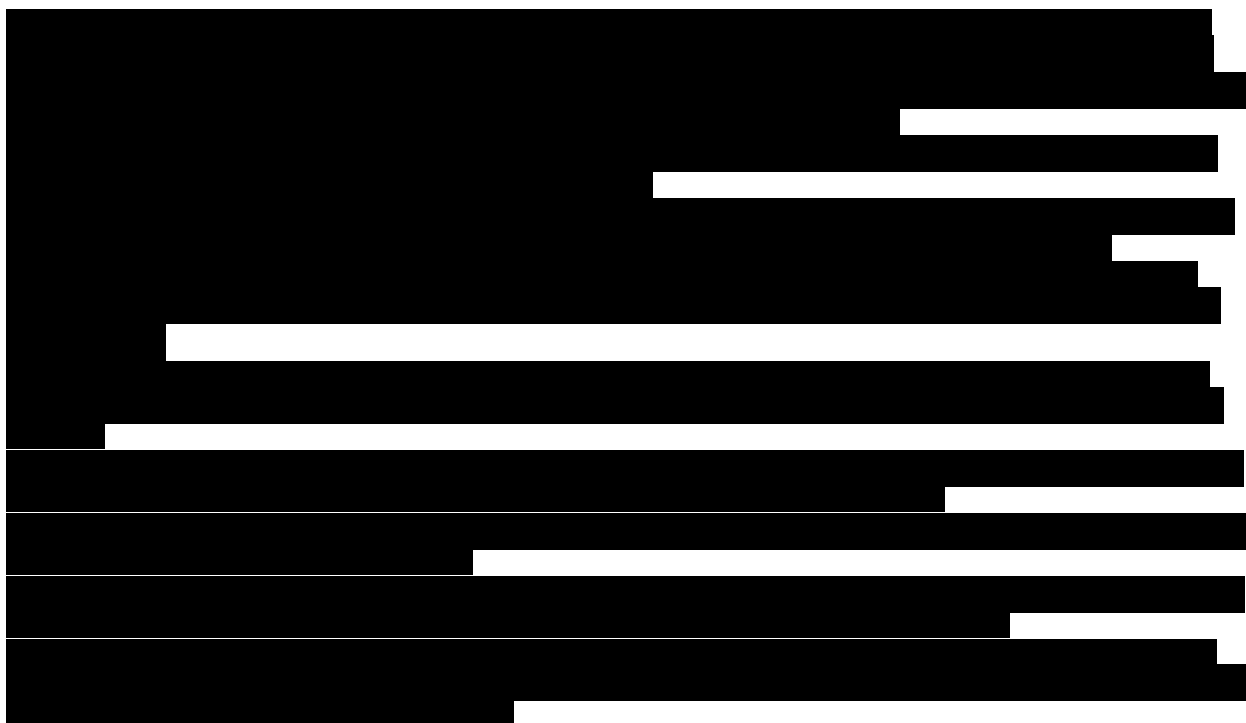
Energy Plant Land Use

Like all forms of energy production, wind turbines impact the environment through their use of land. The scope of this impact varies from site to site due to various site specific factors such as the topography of the area.¹⁶⁷ Wind farms have two separate forms of land impact: the total land area and the direct impact area. According to the National Renewable Energy Laboratory, large wind facilities use between 24.7 and 123.6 acres per megawatt of output capacity.¹⁶⁸ Most of the area is due to necessary spacing between turbines, which is typically five to 10 rotor diameter lengths.¹⁶⁹ According to Tom Gray of the American Wind Energy Association, the average total land use for wind is 60 acres per megawatt.¹⁷⁰ Such extensive land use requirements become staggering when considered on a national scale. For example, for a wind facility to match the output of a 1.3 square mile 1,000 megawatt nuclear plant, it would need an area of approximately 85,240 acres or 133 square miles.¹⁷¹ Although wind is land intensive in total land use requirements, the land in and around wind farms can be used for other purposes. Wind farms are commonly located on existing farms or ranches and allow most agricultural activities to continue unimpeded. However, construction and other buildings in and around wind turbines are restricted.¹⁷²

Within the total land use requirements are direct impact areas. Permanently disturbed land amounts to less than one acre and only 3.5 acres are temporarily disturbed by construction and other activities.¹⁷³ Wind turbines require vast tracts of land to operate, but the direct impact area is often comparable to other power sources. Despite smaller direct impact areas, this study will rely on the total land use requirements of 60 acres per megawatt due to the restrictions on development that the presence of wind turbines causes.

Resource Production Land Use

One of the severely understudied land use requirements for wind is the resource production process. Wind turbines are one of the largest consumers of neodymium magnets, which is a rare earth element.¹⁷⁴ According to a study by the Massachusetts Institute of Technology, the average wind turbine uses 377 pounds (171 kilograms) of neodymium



per megawatt of capacity.¹⁷⁵ China currently controls approximately 89 percent of the global rare earth production and the US consumes 13 percent of the global supply.¹⁷⁶ A recent study of China's rare earth mines found that for every ton of rare earth metals, 0.074 acres of vegetation and topsoil is destroyed, 2,000 tonnes of solid waste (tailings) is produced, and 1,000 tonnes of toxic wastewater is created.¹⁷⁷ This study does not include mine waste land use requirements, however storage of tailings and toxic waste do contribute the wind energy's land use footprint. Tailing ponds and toxins leaching into surrounding soil and agricultural land have proven problematic in and around China's major rare earth element mines.

A study by the United States Geological Survey found that China's five major rare earth mines were made up of 14.74 percent neodymium on average.¹⁷⁸ Consequently, for every ton of rare earth minerals produced, only 294.8 pounds are neodymium. According to the above estimates, to mine the neodymium necessary for one megawatt of wind capacity, 0.09 acres of land are directly harmed. Thus, the land use total for mining wind resources is 0.279 acres per megawatt of energy produced.

Neodymium processing is an energy intensive process that adds land use requirements to wind's total, however this report does not attempt to quantify every aspect of resource production and processing. Neodymium mining was considered due to the wind industry's heavy consumption of this resource, however there are multiple resources that are not being considered in each section of this report.

Transmission/Transportation Land Use

As noted in previous sections, transmitting electricity in the US requires an estimated 450,000 miles of high voltage transmission lines with safety buffer zones of 44 feet on each side, or approximately 4,800,000 acres of land.¹⁷⁹¹⁸⁰ Because wind accounted for 4.7 percent of the nation's total energy production, approximately 225,600 acres of land were required to transmit wind energy in 2015, or 10.362 acres per megawatt.¹⁸¹

Solid Waste Land Use

Most of a decommissioned windmill can be recycled and requires little storage land. Disposing the blades has proven to be the most serious issue. Both the blades and the plastics are completely landfilled, which will create increasing issues for wind's future land use requirements as wind grows and more turbines require decommissioning.¹⁸² According to the EPA, the average landfill requires 33 acres and can store 1.08 million tons (four million cubic yards) of

[REDACTED]

waste.¹⁸³ However, the current solid waste land use requirements for wind energy are minimal and thus not included in these estimates.

Conclusion

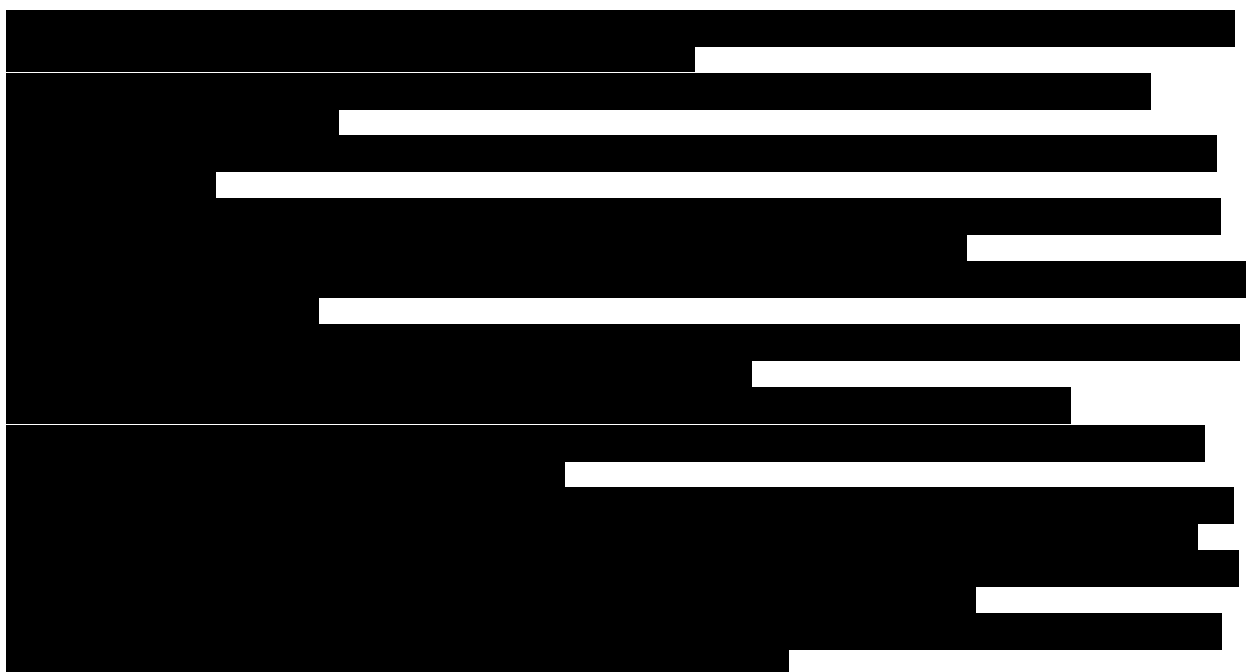
The total estimates for land use per megawatt of wind capacity is 70.641 acres per megawatt of electricity produced. In 2015, the total electricity consumption for the US was 376,826.5 megawatts (3.301 billion megawatt hours).¹⁸⁴ According to the estimates in this report, for the US to be powered exclusively by wind power it would require 26,619,401 acres of land, an area nearly equivalent to the state of Tennessee.¹⁸⁵

Solar

There are two types of solar power, photovoltaics and concentrated solar systems. Photovoltaics (PV) work by transforming pure sunlight into energy, similar to how plants perform photosynthesis.¹⁸⁶ Concentrated solar systems, or thermal systems, differ from photovoltaics by using mirrors or lenses to heat up water to drive turbines which generate electricity.¹⁸⁷ Today, solar produces roughly 0.65 percent of the nation's energy, or 24,893,000 megawatt hours (2,841.7 megawatts).¹⁸⁸¹⁸⁹ Solar power is the most inefficient of all renewable energy sources with an average capacity factor of 25.8 percent for PV solar and 22.1 percent for thermal (concentrated) solar.¹⁹⁰ Solar is also intermittent and depends on weather conditions, daylight, and seasons for production.

Energy Plant Land Use

One major drawback of solar energy is the large amount of land required to produce electricity. Solar power is unable to transform all the energy stored in sunshine into power. Consequently, utility scale solar requires an average of 8.1 acres per megawatt capacity of electricity generation and thermal solar plants require 10 acres per megawatt capacity.¹⁹¹ These estimates include land used for access roads and transmission lines. Unlike wind, this land is unusable for other purposes. An environmentally positive aspect of solar is small scale rooftop panels, which improve solar's land use footprint by utilizing otherwise dormant space on existing buildings. In 2015, "distributed solar," or small scale private generation, produced almost 36 percent of the total solar electricity output.¹⁹² With almost a third of all solar output requiring little to no land use, this renewable energy source can continue to grow with reduced impact on land. But, future growth of large scale utility plants remain land intensive. The majority of utility scale solar power is produced by PV panels rather than the thermal technology, therefore this paper will use the estimate of 8.1 acres per megawatt of solar capacity or 31.347 acres per megawatt of solar electricity produced.¹⁹³



Resource Production Land Use

Quartz Production

PV solar panels are manufactured from polysilicon, which is produced through several high temperature treatments of quartz. To produce one megawatt of PV solar, 13 tons of solar grade polysilicon is needed, which would require 18.21 tons of silicon metal due to the conversion rate of 0.714 from silicon metal to polysilicon.¹⁹⁴¹⁹⁵ To produce silicon metal, also known as metallurgical silicon, the conversion rate from raw quartz is 80-90 percent.¹⁹⁶ Thus, to produce the 13 tons of solar grade polysilicon needed for one megawatt of PV solar, roughly 20 tons of quartz is needed. The U.S. PV solar industry currently has 34,000 megawatts of installed solar capacity, which required roughly 600,000 tons of quartz to manufacture.¹⁹⁷¹⁹⁸ According to estimates from India, which is a major upcoming quartz exporter, the land necessary to produce one ton of raw quartz was 0.00717 acres, with the US PV solar industry affecting a total of 4,800 acres through quartz mining.¹⁹⁹ To produce one megawatt of PV solar, 0.143 acres are directly affected by quartz mining. Because quartz is such a common resource, there is not a substantial amount of tailings produced.

Solar Manufacturing

In addition to the resource production process, manufacturing solar panels is an energy intensive process, which increases energy demand and consequently, solar's land use. A one megawatt solar plant requires 3,240 solar panels, with the average solar panel at about 1.626 square meters.²⁰⁰²⁰¹ The total area of actual solar cells required to produce one megawatt is 5,268.24 square meters. PV solar is estimated to require 0.25 megawatt hours of energy to produce one square meter, which would require a total of 1,317 megawatt hours to produce the panels for one megawatt of solar.²⁰² America purchases the majority of its solar panels from China, which largely uses coal power in the production process. Assuming that the energy used to produce solar panels came from coal power, the land used for manufacturing one megawatt of solar is an additional 1.836 acres per megawatt.

These estimates do not consider additional factors that could increase solar's land use such as the actual land used for solar panel factories, land necessary to store waste from these facilities, and land used to produce additional chemicals and resources for production.



Transmission/Transportation Land Use

As noted in previous sections, transmitting electricity in the US requires an estimated 450,000 miles of high voltage transmission lines with safety buffer zones of 44 feet on each side, or approximately 4,800,000 acres of land.^{203,204} Because utility-scale solar energy accounted for 0.6 percent of the nation's electricity production in 2015, approximately 28,800 acres of land were used to transmit solar energy in 2015, or 10.135 acres per megawatt. It should be noted that this estimate does not include electricity produced from distributed rooftop solar because it does not require substantial land for transmission.

Storage Land Use

Solar panels produce little solid waste in comparison to other energy sources. The greatest solid waste comes from retiring solar panels, which must be disposed of as electronic waste to minimize environmental damage. Solar panels include rare earth minerals and chemicals that are toxic if not properly disposed, including lead, arsenic, telluride and different types of silicons and selenides.²⁰⁵ If solar panels are landfilled, these chemicals can leach into groundwater and if incinerated, they release harmful toxins into the atmosphere. Currently, there is no national regulation concerning solar panel disposal. Each state is responsible for regulating the disposal of spent panels. Despite some states regulating solar's disposal, many find their way to landfills. In 2015 alone, the US generated 60,000 tons of PV waste and is expected to generate 20 million tons in 2050.²⁰⁶ According to estimates by the International Renewable Agency, by the year 2050 the US is estimated to grow waste production between 7.5 and 10 million tons.²⁰⁷ Utility scale solar panels vary in weight, but using 2010 estimates from the Institute of Electrical and Electronic Engineers, the average weight of a panel was 40.8 pounds.²⁰⁸

Half of the world's panels are produced in China, which is problematic because there are fewer protections on waste disposal and regulations concerning environmental policies.²⁰⁹ In addition to producing the majority of solar panels, the US ships large quantities of its electronic waste (e-waste), including retired solar panels, to China and other foreign countries to be disposed of.²¹⁰ The EPA estimates that only 25 percent of electronic waste is recycled, which increases the likelihood that a vast majority of solar panels are being improperly disposed.²¹¹ Guiyu, China is known as one of the major e-waste dumping grounds for the world. Studies show that the 12,849.5 acre city is home to over 300 e-waste factories as well as 3,000 workshops and processes 20 million tons annually.²¹² According to the land



to ton ratio in Guiyu, each ton of e-waste requires 0.000642 acres of land to process. One megawatt of solar (3,240 panels at 40.8 pounds each) equals 66.096 tons of waste. The tonnage multiplied by land use returns a land use estimate for solid waste storage of 0.0424 acres per megawatt of solar.

These estimates do not include the solid waste that is created during the solar manufacturing process, which are substantial. For instance, California solar manufacturers produced 46.5 million tons of contaminated sludge and water from 2007 to 2011.²¹³ This paper, however, does not have adequate data to quantify the total manufacturing waste from the solar industry. This may be an area for further examination.

Conclusion

Solar power is a land intensive energy source. Although it carries many advantages in cutting emissions, all impacts must be considered when choosing whether or not to encourage one energy source over another. This report does not claim to quantify the comprehensive land use footprint of solar power, however it does attempt to quantify some of the more significant land aspects of solar. From the above estimates for each section, solar's overall land use estimate is 43.503 acres per megawatt produced.

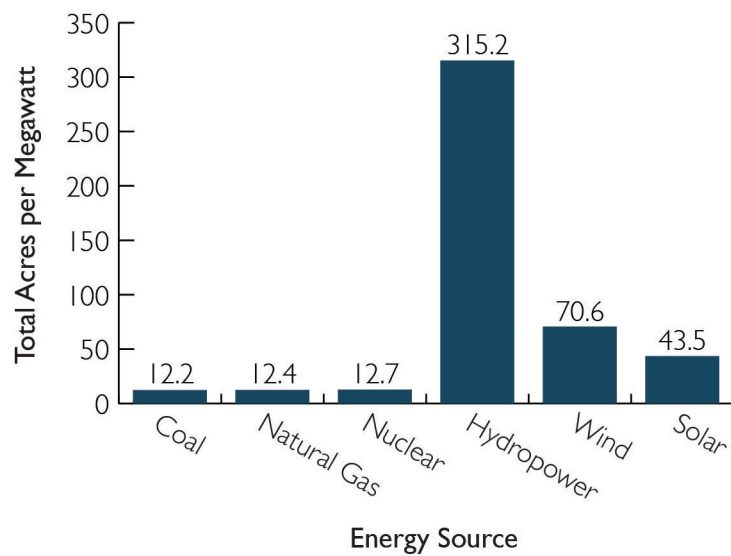
Currently, there is disagreement over the land requirements to power the US exclusively with solar power. The National Renewable Energy Laboratory released a 2008 report estimating that solar would require 13,601,207 acres (181 square meters per capita) to power the US.²¹⁴ Tom Tamarkin, President of USCL Corp, estimates that for solar to cover all of America's electricity needs it would require 7.2 million acres, which would cover all of Maryland and Delaware.²¹⁵

In 2015, the total electricity consumption for the US was 376,826.5 megawatts (3.301 billion megawatt hours).²¹⁶ This study estimates that for solar to exclusively power the US it would require 16,393,234 acres, an area larger than West Virginia and Rhode Island combined.²¹⁷

Conclusion

Electricity generation is energy intensive, and each source leaves its own environmental and ecological footprint. This report has considered the various direct and indirect land requirements for coal, natural gas, nuclear, hydro, wind, and solar electricity generation in the United States in 2015. The land used by each source was approximated to account for that expended during resource production, by energy plants, for transport and transmission, and to store waste materials. The final assessment can be seen below as the chart shows how many acres per megawatt each source of electricity uses.





Coal, natural gas, and nuclear power all feature the smallest, and nearly identical physical footprint, of about 12 acres per megawatt produced. Solar and wind are much more land intensive technologies using 43.5 and 70.6 acres per megawatt, respectively. Hydroelectricity generated by large dams has a significantly larger footprint than any other generation technology using 315.2 acres per megawatt.

By understanding the physical footprint impacted by electricity production, effective policy action can be taken that hopes to balance environmental impact, reliability, economy, and security. Realizing that these impacts go further than just the visible activities taking place onsite at generating power plants is essential for understanding the larger picture. If minimizing the overall land use in the electricity generation process is a priority, land efficient sources like coal, natural gas, and nuclear power should be considered while land intensive sources like hydro, wind, and solar power should be weighed against competing priorities.