5-2021

A Comparison of the Environmental Effects of Renewable and Non-Renewable Energies

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By

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Honors Thesis

Submitted to the Bumpers Honors College in partial fulfillment of the Bumpers Honors Program

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University of Arkansas

April 2021

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Abstract

This study presents current energy data from the United States and data from literature reviews to create life cycle assessments (LCA) for comparing the environmental impacts of wind and coal-fired energy generation and use. The environmental impacts were evaluated using emissions data, principally carbon dioxide emissions and carbon dioxide equivalents from methane. Other environmental impacts such as avian mortality and land use were compared as well. The LCA includes four phases: raw materials, transportation, use/retail, and waste. Overall, wind energy has a smaller environmental impact than coal-fired energy for the raw materials, transportation, use/retail, and waste phases. Wind energy resulted in significantly fewer avian deaths than coal-fired energy per GWh; however, wind energy requires a far greater amount of land than coal-fired energy. Using the data gathered, this study also discusses the timeline for transitioning from non-renewable energy to renewable energy sources. Non-renewable energy sources are finite. The United States relies heavily upon coal energy, and the transition to renewable energies will be lengthy. All energy sources create negative environmental impacts and associated costs that must be assessed when planning for the future of sustainable energy. An immediate transition to renewable energy is idealistic, whereas the country should strive to find a suitable balance between non-renewable and renewable energies. Researching the environmental impacts of each phase of energy systems in a LCA can pinpoint where emissions and environmental concerns arise. This process aids in future efforts to decrease emissions and environmental costs for both wind and coal-fired energy. Wind energy ultimately has less of an overall environmental impact and is a sustainable alternative to coal-fired energy as detailed in the LCA.

Introduction

Background and Need

The environmental effects of various energy processes are crucial to understand in order to progress society. Approximately 60.3% of the energy in the U.S. is generated from fossil fuels (Energy Information Administration, 2020e). Natural gas, coal, petroleum, and other gases constitute 38.4%, 23.4%, 0.4%, and 0.3%, respectively (Energy Information Administration, 2020e). There is a worldwide push for a transition to renewable energy as greenhouse gas levels in the atmosphere rise. Currently, renewable energy in total contributes 17.6% of the United State's energy generation (Energy Information Administration, 2020e). Wind energy is the most widely used renewable energy in the United States with 7.1% of total generation, and solar energy falls behind with 1.7% (Energy Information Administration, 2020e).

Greenhouse gases are causing global issues of increased temperatures and weather anomalies (Environmental Protection Agency, 2020a). Since the industrial revolution, the amount of greenhouse gases introduced to the atmosphere from anthropogenic sources has significantly increased (National Aeronautics and Space Administration, 2021). Climate change has become a largely political issue, and this presents an obstacle to widespread adoption of renewable energy construction. The challenge today is to find a balance between using the "dirty" energy that has been the backbone of the country and implementing renewable energy to sustain energy production and the environment for the long term. Burning fossil fuels creates many concerns about public health and environmental health. Every day, about 12.6 million Americans are exposed to harmful toxins emitted from the extraction of fossil fuels (National Resources Defense Council, 2018). According to the EPA, burning oil, natural gas, and coal is responsible for emitting the most greenhouse gases globally (Environmental Protection Agency, 2020a). The emissions of carbon dioxide from burning fossil fuels from 1900 to 2010 follows an exponential curve (Environmental Protection Agency, 2020a). These greenhouse gas emissions are accelerating global warming (National Aeronautics and Space Administration, 2021). One way to slow down global warming is to implement more renewable energy systems that emit fewer greenhouse gases. Several forms of renewable energy exist today: solar energy, wind energy, geothermal energy, hydropower, and renewable natural gas. Although the potential of renewable energy is promising, each sector has its own challenges. The concept of immediately converting to renewable energies is idealistic rather than realistic.

Life Cycle Assessments (LCA) for coal (non-renewable) and wind (renewable) energy generation were compared. Life Cycle Assessments track the environmental impacts of a material or process throughout the raw material extraction, transportation, use and retail, and waste (Ecochain, 2019). For the purposes of this study the LCA was conducted from "cradle-to grave". Cradle-to-grave follows the process from extraction through the final waste materials (Ecochain, 2019).

Problem Statement

Energy generation of any kind results in environmental consequences. Understanding how renewable energies reduce environmental consequences from energy generated by fossil fuels is essential to accepting the need to shift to more sustainable technologies. Land degradation is a major environmental issue that should be evaluated in the LCA of energy generation. Mining the coal results in severe damage to the soil and nearby waterways, destroys wildlife, and disturbs the entire ecosystem. The raw materials used for both coal generation and wind generation involve mining but of different materials. Land use for energy is also a consideration because land allotted for energy generation is land that is not being used for agriculture or urban expansion. The fossil fuel industry will decline in the future simply due to the finite resources. Investing in renewable energies, then, prepares the country for the loss of an energy source in addition to reducing greenhouse gas emissions and reducing global climate change. This study was conducted to provide evidence through LCAs that the use of fossil fuels is more detrimental to the environment than if the U.S. were to transition to renewable energies.

Purpose Statement

The purpose of this study was to analyze the extraction, transportation, processing, delivery, and use of fossil fuel (coal) as an energy source and renewable energy (wind) to identify and compare the environmental impacts. LCA methodology was used to aggregate data from multiple sources to better evaluate the environmental impacts. Exploring environmental and economic impacts of different energy systems underscores how energy generation affects the environment and whether a rapid or gradual transition to renewable energy is necessary.

Objectives

The following objectives guided this study:

1. Construct a LCA for coal and another for wind energy.
2. Compare the results of the LCA.
3. Use the data gathered to construct a conceptual plan to transition the country from fossil fuels to renewable energies.

Literature Review

LCAs explore the environmental impacts of a product or process throughout its lifetime (Pandey et al., 2017). The LCA methodology compares the environmental impacts of generating energy from coal from raw materials extracted from the land, to transporting those raw materials, processing the materials, producing the power, delivering the power, use of the power, and waste at the end of the life cycle. The LCA examines inputs and outputs in each stage and compares these data to overall environmental impacts (Bhandari et al., 2019). The following Literature Review explores the components of the LCAs for the energies of interest.

Coal Energy

The formation of coal requires millions of years. Coal is a finite resource because the current rate of consumption surpasses the limited geologic reserves of coal. Coal is classified into four categories: Anthracite, Bituminous, Sub-Bituminous, Lignite (Energy Information Administration, 2020c). High carbon content is important because it results in a higher heating value which allows for more efficient use of the carbon (Energy Information Administration, 2020c). Anthracite has the highest percentages of carbon at 86-97% (Energy Information Administration, 2020c). Although anthracite has the highest heating values of the four categories of coal, it only accounts for a small percentage of coal mined in the United States because it is not as abundant in the United States (Energy Information Administration, 2020c). Bituminous coal contains 45-86% carbon and is the most common coal mined for electricity generation (Energy Information Administration, 2020c).

Raw Materials

Coal mining decreased in the United States from 2009 to 2019 (Energy Information Administration, 2020b). In 2019, the United States mined 706.3 million short tons (2000 pounds) of coal (Energy Information Administration, 2020b). Legislation was enacted throughout the years resulting in a reduction of coal mining and energy generation using coal (Betz et al., 2014). The 1990 amendments to the Clean Air Act were designed to combat acid rain, air pollution and emissions, and ozone depletion (Environmental Protection Agency, 2005). In effect, these amendments called for more coal produced in the west rather than Appalachia because the western coal is low-sulfur and produces fewer emissions (Betz et al., 2014). Additionally, climate change reform in the United States resulted in an increase in renewables and natural gas because coal produces so much carbon dioxide. Carbon dioxide is the main greenhouse gas that is depleting the ozone.

Still, the United States relies on coal. Accurately quantifying the amount of coal left to mine in the United States is important to assess how long the country can operate on coal-generated electricity. The Energy Information Administration quantifies their coal estimations by calculating the amount of coal in three categories: recoverable reserves at producing mines, estimated recoverable reserves, and demonstrated reserve base (Energy Information Administration, 2020d). The recoverable reserves at producing mines is essentially a calculation of the coal that can be mined today (Energy Information Administration, 2020d). The estimated recoverable reserves number includes the amount of coal that can be mined with current technologies (called the demonstrative reserve base), but it excludes coal that is considered unavailable due to restrictions on land use (Energy Information Administration, 2020d). Therefore, the demonstrated reserve base would have the highest amount of coal, followed by the estimated recoverable reserves, and the recoverable reserves at producing mines would have the least quantity of coal. According to the U.S. Energy Information Administration (2020d), at the present rate of coal mining, the recoverable reserves will last 357 years while the recoverable reserves from producing mines will last for 20 years.

The greatest greenhouse gas emissions in coal mining are due to the release of methane at coal mines and carbon disturbances in the Earth as a result of extraction (Whitaker et al., 2012). Underground coal mining typically emits more methane than surface level mining (Whitaker et al., 2012). Therefore, Whitaker et al.'s (2012) study suggests that if the country were to shift to more surface mining, there would be fewer harmful emissions attributed to coal-fired electricity generation (Whitaker et. al, 2012). However, mountaintop removal of coal contributes a significant amount of carbon dioxide emissions (Whitaker et al., 2012).

Methane is also a greenhouse gas released by coal mining, and in 2018 mining accounted for 11% of the methane emissions in the United States (Energy Information Administration, 2020g). Before mining is initiated, the coalbed methane is vented out of the mine for safe working conditions, releasing the methane into the atmosphere (Pandey et al., 2017). Carbon dioxide and nitrous oxide generation are also associated with coal extraction. In 2019, carbon dioxide, nitrous oxide, and methane emissions from coal mining were 0.1, under 0.05, and 34.1 million metric tons of carbon dioxide equivalent (CO_2e) for underground mines, respectively (Environmental Protection Agency, 2020d). The emissions of carbon dioxide, methane, and nitrous oxide are all greenhouse gases released from coal mining (Pandey et al., 2017).

Coal mining results in several negative environmental consequences. Mining destroys vegetation, harms soil properties, contaminates the soil, disrupts hydrologic processes, and disturbs wildlife (Feng et al., 2019). The degree of disturbance to the land dictates the degree to which the land can be reclaimed (Feng et al., 2019). Reclamation can be difficult to achieve because environmental effects can be extensive, especially in the case of mountaintop removal methods.

Transportation

The transportation of coal from mines to the power plant adds to the price of coal when it is delivered (Energy Information Administration, 2020c). Coal is transported by train, barge, or truck (Energy Information Administration, 2020c). Transportation costs can become more expensive than the coal itself when coal must be transported long distances; coal mined in

Wyoming and transported to eastern states is more expensive due to transportation costs (Energy Information Administration, 2020c). Oil and diesel fuel prices influence the cost of transportation (Energy Information Administration, 2020c). The reliance of transportation on oil and diesel adds to the emissions factor (Energy Information Administration, 2020c). In 2019, the average price of a short ton of coal for bituminous, sub-bituminous, and lignite coal was 30.93$ (Energy Information Administration, 2020c). The price of the coal (bituminous, sub-bituminous, and lignite), including delivery costs, in 2019 was 38.53$ (Energy Information Administration, 2020c). Therefore, the additional price due to deliver was 7.60$ which is about 20% of the original price of coal (Energy Information Administration, 2020c).

Both commodity costs and transportation costs decreased from 2010 to 2019 (Energy Information Administration 2020a). Data from 2010 to 2019 indicated coal transported by rail was more costly than by barge or truck (Energy Information Administration, 2020a). In 2019, rail transported coal was about 18 dollars per ton whereas truck and barge transported coal were around 5 dollars per ton (Energy Information Administration, 2020a).

Transportation emissions may be overlooked when evaluating emissions from energy generation even though transportation emissions constitute a large portion of coal’s carbon footprint (Sherwood et al., 2020). Coal is dominantly transported by rail (Sherwood et al., 2020). The five major coal producing states in decreasing order are Wyoming, West Virginia, Pennsylvania, Illinois, and Kentucky (Energy Information Administration, 2020c). After the coal is mined, the coal has to be transported to any state that generates electricity by coal combustion. Sherwood et al. (2020) used geospatial technology to follow coal transportation routes, power plant coal purchasing data, and greenhouse gas emissions directly and indirectly from transportation to evaluate the total emissions caused by coal transportation by rail. According to

Sherwood et al. (2020), 70% coal by mass is transported by rail. Transportation route distances varied from 0 kilometers to 3500 kilometers (Sherwood et al., 2020). The median distance traveled was reportedly 700-1000 kilometers (Sherwood et al., 2020). The transportation emissions for reaching most of the power plants studied were less than 5% of the operational emissions (emissions from the plant); however, there were some outliers that had greater percentages of operational emissions when compared to operational emissions (Sherwood et al., 2020).

Sherwood et al. (2020) emphasized a concern with “clean coal” (Sherwood et al., 2020). “Clean coal” is coal with low sulfur content, and it exists in high quantities in the Western coal basin (Sherwood et al., 2020). The Clean Air Act amendment in 1990 set sulfur dioxide emission limits, and companies were incentivized to produce less power, using low-sulfur coal, or to implement pollution control systems (Sherwood et al., 2020). Therefore, due to economic incentive and the sulfur dioxide threshold, companies purchase low-sulfur coal (Sherwood et al., 2020). For some companies, this increases the distance the coal has to travel to the power plant because low-sulfur coal is only available in specific areas of the country (Sherwood et al., 2020). Sherwood articulated that if power plants shift to purchasing more clean coal, the emissions would correspondingly shift from operations to transportation (Sherwood et al., 2020). If companies purchase “cleaner coal” from mines that are farther away from the coal usually purchased, this will result in an increase of emissions in the transportation sector.

Use and Retail

The greatest source of emissions from coal generated electricity comes from the combustion of coal (Energy Information Administration, 2020c). About 99% of greenhouse gas emissions from coal-fired electricity generation are related to the coal fuel cycle (Whitaker et al., 2012). Therefore, the factors that affect the amount of coal burned have the most influence on the life cycle greenhouse gas emissions (Whitaker et al., 2012). Coal combustion produces sulfur dioxide, nitrogen oxides, carbon dioxide, heavy metals and mercury, fly and bottom ash, and particulates (Energy Information Administration 2020c). In 2019, the United States electric power sector emitted 1,618 million metric tons of carbon dioxide (Energy Information Administration, 2020h). This value accounts for 31% of all United States energy related emissions of carbon dioxide in 2019 (Energy Information Administration, 2020h). Of the 1,618 million metric tons of carbon dioxide emitted, 973 million metric tons was attributed to the combustion of coal (Energy Information Administration, 2020h). When coal is burned, a greater amount of carbon dioxide is released into the atmosphere than when burning other fossil fuels per unit of heat energy (Energy Information Administration, 1994).

Coal combustion releases carbon dioxide and nitrous oxide (Green America, 2020). The combustion of one short ton (2000 pounds) results in 5,720 pounds of carbon dioxide released (Energy Information Administration, 1994). Coal accounts for 60% of the energy sector's carbon dioxide emissions, and in 2019, 539 million short tons of coal were consumed in the United States for electricity generation (Energy Information Administration, 2020c). The coal power plants produce more greenhouse gases per unit energy than other electricity sources (Green America, 2020).

For the raw materials, transportation, and use/retail phases of coal-powered electricity generation, the environmental impacts are extensive. Mining contributes to land degradation, ecosystem disturbance, soil acidity, water pollutants, and habitat destruction. In addition to these environmental concerns, mining also releases large amounts of carbon dioxide and methane in the atmosphere which advance global warming. Transporting coal by barge, truck, or rail also contributes to the rise in greenhouse gases because transportation relies heavily on oil and gas fossil fuels. Lastly, the majority of environmental concerns for emissions comes from the burning of coal.

Waste

Fly ash, a powdery silica material, is a major waste product of burning coal. Fly ash pollutes surrounding waters and can enter ground water and drinking water (Environmental Protection Agency, 2021). If fly ash is in drinking water, the water becomes unfit for drinking purposes (Environmental Protection Agency, 2021). Fly ash is also a concern for air pollution (Environmental Protection Agency, 2021). Sludge ponds are created to dispose of fly ash and prevent it from entering the atmosphere (Environmental Protection Agency, 2021). Potential environmental impacts from sludge ponds include toxins leaching into the soil and groundwater, reductions in vegetation due to chemicals from the fly ash, and accumulation of toxins in wildlife around the sludge pond (Carlson & Adriano, 1993). The chemical composition of the water is affected after fly ash is added (Carlson & Adriano, 1993). The toxins that can be present in fly ash are arsenic, lead, mercury, cadmium, chromium, selenium, and barium (Carlson & Adriano, 1993). Although fly ash can become an environmental issue when disposed in sludge, some fly ash is used as an amendment for agricultural soils (Carlson & Adriano, 1993). This can result in higher soil fertility, but there are some risks of excessive concentration of soluble salts, potential toxic trace elements, and high pH (Carlson & Adriano, 1993).

Coal combustion also results in a large amount of air emissions: sulfur dioxide, nitrogen oxides, carbon dioxide, and particulates (Energy Information Administration, 2020g). Presence of these emissions can cause health and environmental concerns. Sulfur dioxide, nitrous oxides, and particulates contribute to respiratory illnesses (Energy Information Administration, 2020g).

Sulfur dioxide can cause acid rain, and mercury and heavy metals cause neurological problems in humans and wildlife (Energy Information Administration, 2020fg). Scrubbers in coal plants are used to reduce the amount of sulfur dioxide emissions, and coal plants also use equipment to reduce nitrous oxide, particulates, and mercury (Energy Information Administration, 2020g).

Wind Energy

Wind power is a form of renewable energy. Environmental concerns over non-renewable energies have increased demand for sustainable energy generation. Wind power has grown globally from 1990 (International Energy Agency, 2021).

Raw Materials

The five main raw materials used to create wind turbines are steel, cast iron, fiberglass (with related composite materials), copper, and aluminum (Cotrell et al, 2014). These materials constitute 98% of the turbine weight (Cotrell et al, 2014). Steel provides for 70% of the turbine weight, and consequently, the price of turbines tends to reflect price changes in steel (Cotrell et al, 2014).

A study conducted by David Wilburn (2011) on the wind turbine industry analyzed the amounts of raw materials needed for turbine construction. Wilburn's study (2011) reported that "6.8 million metric tons of concrete, 1.5 million metric tons of steel, 310,000 metric tons of cast iron, 40,000 metric tons of copper, and 380 metric tons of neodymium" (Wilburn, 2011, p.1) will be needed to meet the demand for wind energy construction if the United States is to achieve 20% wind-energy generation by 2030. The study incorporated data from the USGS in order to analyze the potential supply of raw materials for future wind turbine construction. According to Wilburn (2011), the material requirements of wind turbines by weight equal 89.1% steel, 5.8% fiberglass, 1.6% copper, 1.3% concrete, 1.1% adhesives, 0.8% aluminum, 0.4% core materials made from foam, plastic, and wood. The nacelle consists of the generating components of the turbine and is responsible for energy conversion (Wilburn, 2011). The materials used for the nacelle are aluminum, cast iron, copper, plastic, stainless steel, and steel alloys which make up the two main components of the nacelle: drivetrain and auxiliary equipment (Wilburn, 2011).

Greenhouse gas emissions are mainly emitted from the manufacture and installation stages of wind turbines (Haapala et al., 2014). Facility construction and transportation of the turbines account for 24% of wind energy's lifecycle emissions (Ordway & Kille, 2015). Manufacturing steel emits a large amount of carbon dioxide because of the chemical reduction process involved (Luvside, 2020). Carbon gases are used as the reducing agent to convert iron ore to steel (Luvside, 2020). Because steel is a prominent raw material for wind turbines, the construction of turbines relies on the use of fossil fuels such as coal or natural gas to convert the iron ore into steel (Johns, 2015). Therefore, the emissions produced from either coal or natural gas must be accounted for in the emissions for raw materials. The iron and steel industry globally accounts for 5% of carbon dioxide emissions (Bellona Europa, 2019). An average value of 1.9 tons of carbon dioxide is generated per ton of steel (Bellona Europa, 2019).

Offshore windfarms have greater emissions than onshore windfarms (Weisser, 2007). This is because offshore windfarms require more steel than onshore farms (Weisser, 2007). The foundation and development of offshore windfarms also cause higher emissions (Weisser, 2007). In general, larger wind turbines have fewer emissions over their lifetime (Weisser, 2007).

Transportation

The transportation of wind turbines from production to their destination also contributes to emissions. The transportation section of the LCA has fewer emissions than turbine construction but more than the combustion phase (Tremeac & Meunier, 2009). Tremeac and

Meunier (2009) explored the impacts of transporting wind turbines. Wind turbines can be transported by rail, truck, or boat (Tremeac & Meunier, 2009). Haapala et al. (2014) showed that transporting wind turbines significantly increases emissions when the materials must be transported over long distances.

The environmental impacts of the transportation phase for wind turbines are determined by the energy used to transport the main parts of the turbine (Chipindula et al., 2018). Typically, the distance the turbine travels is multiplied by the weight of the turbine (Chipindula, et al., 2018). This number represents the amount of energy it took to transport the main parts of the wind turbine, and the unit for this number is kilogram kilometers (Chipindula, et al., 2018).

Wind turbine size increased in the United States from 2000 to 2014 (Cotrell et al., 2014). The increase in wind turbine size extends the longevity of the wind turbines lifespan and increases energy production (Weisser, 2007). Installing bigger wind turbines increases the production potential of the turbine (Weisser, 2007). The turbine can produce more power because the blades cover a greater area (Weisser, 2007). However, bigger wind turbines create logistic difficulties for transporting the turbines to the place they will be constructed (Cotrell et al., 2014). In their study of two 2 MW wind turbines, Guezuraga et al. (2012) revealed that transportation accounts for 7% of the environmental impact overall. In this study the turbines were transported by truck (Guerzuraga et al., 2012).

Use and Retail

Wind energy in the United States has grown about 23% annually since 2000 (Wilburn, 2011). Wilburn (2011) reported that wind energy, although it can supply a significant amount of MWh, is limited due to the availability and variability of wind. Additionally, production capacity is different for each state. A fundamental understanding of wind patterns is necessary to evaluate the potential success of a wind farm (Wilburn, 2011). Because of the specific wind requirements needed for sufficient energy generation, it can be difficult to find land where the turbines could be used as an alternative to fossil fuel energy sources (Wilburn, 2011). Wilburn (2011) reported that lands with annual wind speeds of at least 23.4 km/hr at the height of a general rotor (80m above the ground) are required for wind farm development. Although allocating land for wind turbine development can be an obstacle, wind energy produces hardly any emissions during the use and retail phase of its life cycle.

Wind turbines do not produce any carbon dioxide or other harmful pollutants when in use (Global Wind Energy Council, n.d.) Two aspects of the use and retail phase for wind energy that produces some emissions are the on-site construction of wind turbines and maintenance over time (Ordway & Kille, 2015). The operations on wind turbines are responsible for 19.4% of total life cycle emissions (Ordway & Kille, 2015). Overall, wind turbines can offset all emissions caused by the turbine's construction in three to six months while the total average lifespan of wind turbines is 20 years (Global Wind Energy Council, n.d.).

One issue is that wind farms have to have enough wind to be productive. Wind is highly variable, and this is an obstacle for wind generated electricity becoming competitive with coal-fired electricity. Another obstacle for wind renewable energy is the availability of land. Between agriculture, forestry, and urbanization, there is not much land left to use for the development of renewable energies (Pimentel et al., 1994). Additionally, the large size of the windmills limits how many windmills can fit on a plot of land (Pimentel et al., 1994). Although land use poses a problem, windfarms can have multipurpose use. Windfarms can incorporate agriculture or grazing for the majority of the land while the turbines generate energy on a small fraction of the land. The common environmental issues with wind energy include turbine interference with bird migration patterns and noise pollution (Pimentel et al., 1994). Noise from wind turbines can be heard from 1 km away, and it is suggested that wind farms be placed at least 300 meters away from nature reserves to decrease the chances of bird deaths (Pimentel et al., 1994). Implementing windfarms may also be difficult because local populations may deem them aesthetically unpleasing (Pimentel et al., 1994).

Waste

Several parts of a wind turbine can be recycled (Anderson et al., 2014). Specifically, steel can be recycled and used for further production of wind turbines (Anderson et al., 2014). This aids in decreasing greenhouse gases produced by the raw materials section in the LCA because the majority of emissions come from the production of steel (Haapala et al., 2014). However, there are some environmental concerns with disposing of wind turbine waste. Recycling blades is a concern because the blades contain fiberglass (Anderson et al., 2014). When the blades are cut, dust is produced which creates a safety hazard (Anderson et al., 2014). Not all blades are recycled because of this, and instead, may be thrown into a landfill (Anderson et al., 2014). The nacelle can be a waste concern because they contain many components such as composites and PVC foam (Anderson et al., 2014). Extending turbines lifespan would decrease emissions for waste because this would then result in fewer wind turbines needing to be disposed.

Methods

Energy generation and use has a major impact on the environment for both renewable and nonrenewable energies. Wind power is more environmentally friendly and shifting to more wind power and less coal power can help alleviate environmental consequences associated with energy generation. This section will describe the method by which the LCAs were constructed as well as how the information was analyzed to evaluate the environmental impacts of each.

Research Design

Life cycle assessment (LCA) was used in this study for comparison of the environmental impacts of coal and wind energy generation based on current published sources. LCAs use data from different phases of the life cycle to evaluate the overall environmental effects caused by the production of products or services (Ecochain, 2019). For coal and wind energy, the environmental impacts of raw material extraction, transportation, use/retail and waste were evaluated.

Resources Used

The resources used for this LCA study consisted of readily available literature including previous LCAs for coal and wind energy, published data on emissions and other environmental impacts, as well as data regarding the economics of energy generation. Additionally, sources were found to estimate the degree of land degradation associated with coal power and wind power.

Data Mining/Extraction

Data were aggregated from multiple sources to quantify greenhouse gas and other chemical emissions as well as additional environmental impacts. Additionally, current energy emissions data were obtained from the Energy Information Administration. Data on environmental impacts of both coal and wind power were also extracted from the Environmental Protection Agency. The Web of Science database provided several sources on emissions from coal and wind energy. Keywords searched in the database include “coal life cycle emissions”, “turbine avian death data”, “coal energy versus wind energy”, and “United States energy data”. Compendex is another database that was used to collect data. Data on carbon emissions, land degradation and use, and ecosystem disturbance were aggregated from 22 literature sources to provide a comprehensive review of the environmental consequences of each source of energy.

Data Synthesis

The data synthesis for this study consisted of taking the data for the environmental impacts of coal and wind power energies for each life cycle phase (raw materials, transportation, use/retail, and waste) and comparing and contrasting between coal and wind energy. This comparison allowed for a discussion about where, in each energy's life cycle, the most emissions are occurring.

The LCA was divided up by coal and wind energy. Under each energy source were raw materials, transportation, use/retail, and waste phases. The raw materials section includes information about what raw materials are involved with coal and wind power and how they are procured. Additionally, the raw materials section includes information about the environmental effects of the materials extraction. The transportation section for coal and wind power outlines the rail method of transportation of the raw materials. Coal and wind use a combination of barge, truck, and rail for transport. This study focuses on the emissions from rail transportation because rail is the main transportation method used for coal and wind raw materials. Then, this section discusses the environmental impact that the transportation contributes to the LCA. The use/retail phase of the LCA for both coal and wind power details how electricity is generated from each energy source and provides accounts of environmental impacts for this stage. Lastly, both coal and wind have a waste section that describes how the product waste is disposed.

Results and Discussion

Raw Materials

The environmental concerns for raw materials extraction for coal power is the mining of coal. Methane emissions are the main concern when mining for coal. Underground mines contribute the majority of emissions; therefore, this study focused on emissions data from underground mines only. In 2019, the methane carbon dioxide equivalent (CO_2e) emissions were 34.1 million metric tons whereas the carbon dioxide and nitrous oxide emissions were 0.1 and under 0.05 million metric tons, respectively (Environmental Protection Agency, 2020d). Figure 1 displays the methane CO_2e values from underground mining in 2019 and the CO_2e value associated with steel produced and used for wind turbine construction to compare emissions from the raw materials phase.

Wind energy requires steel as the primary raw material. Greenhouse gases emitted from the production of steel influence the total amount of greenhouse gases for wind turbines in the raw materials phase. Specifically, the concern is the amount of carbon dioxide released. For the United States in 2019, emissions from iron and steel production accounted for 72.2 million metric tons of CO_2e. (Environmental Protection Agency, 2020e). Due to limited data on emissions from steel production specifically used for wind turbines, the number in Figure 1 was calculated using a variety of sources. Each wind turbine requires 200-230 tons of steel (World Steel Association, n.d.). The 230 tons value was used in the calculation to account for the greatest amount of steel that could be used for a single wind turbine. This number was then converted to metric tons which resulted in 208.7 metric tons of steel per each wind turbine. Nearly two metric tons of CO_2 are estimated to be emitted for each one metric ton of steel produced; therefore 396.55 metric tons of carbon dioxide are emitted for one wind turbine (World Steel Association, n.d.). There are approximately 67,000 wind turbines currently in the United States (United States Geological

Survey, 2021). Therefore, the CO_2 emissions from steel specifically used for all wind turbines in the United States was calculated as 26.6 million metric tons (Figure 1). The emissions from steel production for wind turbines built in 2019 was also calculated by multiplying the number of wind turbines added in 2019 (2,166 units) by 396.55 metric tons of carbon dioxide (Energy Efficiency & Renewable Energy, n.d.).

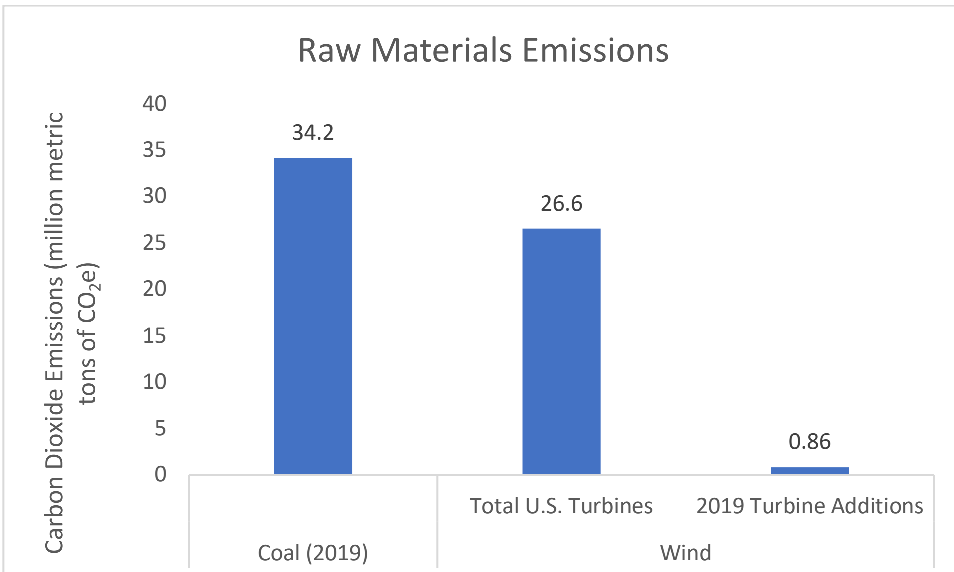

Figure 1: Carbon dioxide equivalent data for the raw materials phase of coal and wind energy (Energy Information Administration, 2020f).

Transportation

Transportation of coal and wind turbine materials adds economic and environmental costs to the LCAs. Coal and wind turbines are primarily transported by boat, truck, or rail. Transportation is an environmental concern for both coal and wind power because the products are mined and obtained in one location, but they need to be transported to the power plant/where they need to be constructed. Additionally, for both wind and coal power, the emissions become greater as the distance traveled is farther away from the mining source/production area. Seventy percent of coal is transported by rail, and rail has the least emissions out of barge, truck, and rail transportation (Sherwood, 2020). One problem posed to the coal industry is the drive for "cleaner coal" (coal with lower sulfur content) because this will increase transportation costs and emissions (Sherwood, 2020). The "cleaner coal" is only located in a few select areas of the country, and therefore if companies move towards purchasing "cleaner coal", transportation emissions can increase. These sustainability efforts can be counterproductive as the emissions saved with "cleaner coal" from the use phase would be transferred to the transportation phase of the coal lifecycle.

Figure 2 shows the emissions from transportation from onshore and offshore wind turbines in 2018. Limited data is available for the direct CO_2 emissions for rail transport of coal; therefore, the transportation emissions value is calculated from a percent of the operational emissions in 2019. Coal transportation in the United States accounts for approximately 1.5% of its operational emissions based on previous life cycle assessments (Sherwood, 2020). Using this percent and the operational emissions from coal in 2019, the estimated transportation emissions from coal are 14.6 million metric tons of CO_2e (Sherwood, 2020).

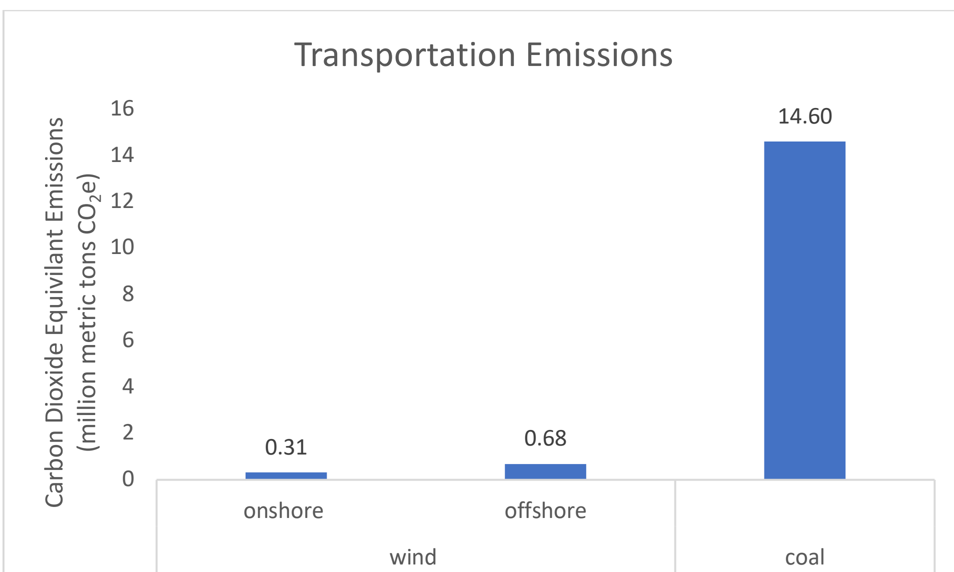

Figure 2: Carbon dioxide emissions from the transportation phase for coal and wind energy (Sherwood, 2020) (Wang et al., 2018).

The transportation data for wind turbines separates onshore and offshore emissions. Offshore wind turbines have greater transportation emissions because of the extended distances the materials have to travel by barge, truck, and/or rail (Wang et al., 2018). Emissions from transportation are hard to quantify and are often overlooked in LCAs; however, transportation data is crucial to understand the comprehensive environmental effects of a system.

Use/Retail

Coal combustion from all power plants in the United States accounted for 973 million metric tons of carbon dioxide emissions in 2019 (Energy Information Administration, 2020h). For the use/retail phase of the LCA for wind, the carbon dioxide emissions are zero (Global Wind Energy Council, n.d.). Wind turbines do not produce any emissions while generating energy (Global Wind Energy Council, n.d.).

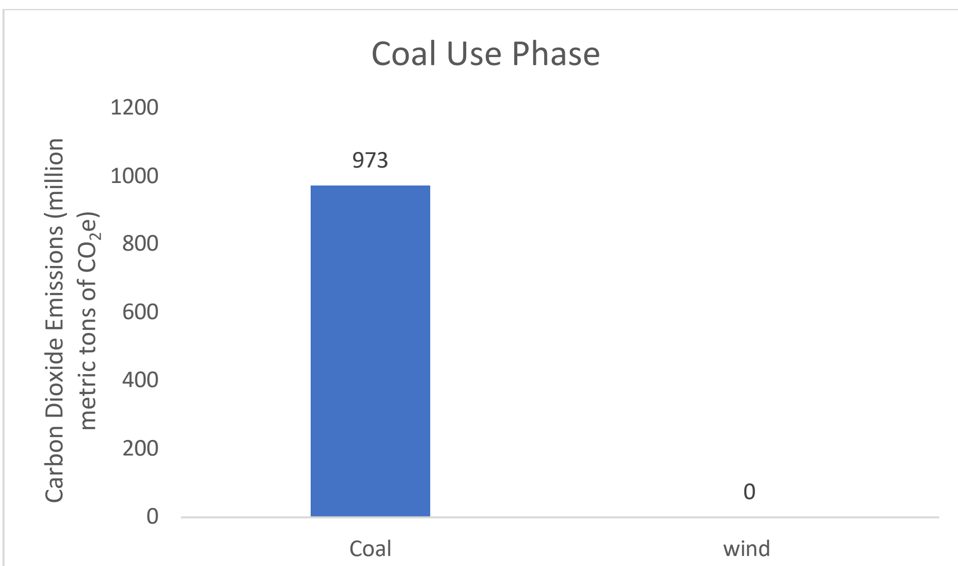

Figure 3: Carbon Dioxide equivalent data from the use/retail phase of coal and wind energy

Figure 3 depicts the amount of carbon dioxide equivalent emissions released for coal and wind energy during the use/retail phase. Emissions for coal energy are the greatest during combustion, whereas emissions for wind energy are the lowest for the use/retail phase. Because wind energy does not produce emissions during the use/retail phase, this allows for wind energy to have a lower carbon footprint overall (Wilburn, 2011).

Waste

From the mining and use phases of the coal lifecycle, coal produces a large amount of waste. Mining releases several pollutants into the environment such as carbon dioxide, methane, and mercury. These pollutants create environmental and health hazards for the surrounding habitats. Mining is considered one the most disruptive practices to the environment, and it requires long-term, extensive reclamation plans. Additionally, it is costly to reclaim lands that have been mined and to make them productive again. For the use/retail phase of the coal life cycle, combustion results in coal ash. Coal ash is a pollutant, and sludge ponds are created to keep the fly ash from escaping to the air. Nutrient leaching and potential soil and water contamination are environmental concerns for sludge ponds (Carlson & Adriano, 1993).

In 2014, 129.7 million tons of coal ash was produced (Chemical and Engineering News, 2016). Forty eight percent of the coal ash in 2014 was reused for other purposes in agriculture, construction, and concrete (Chemical and Engineering News, 2016). The other 52% of the coal ash was disposed of in sludge ponds or landfills (Chemical and Engineering News, 2016).

For the wind life cycle, the waste is produced when turbines are dismantled at the end of their lifespan. Most of the steel used for wind turbines can be recycled, and this aids with decreasing further raw materials emissions when constructing new wind turbines. Eighty percent of wind turbines can be recycled (Stavridou et al., 2020). However, there are some materials used for producing wind turbines that are not recycled. This includes blades and the nacelle. The blades are constructed using fiberglass composite (Anderson et al., 2014). When the blades are cut up, a hazardous dust is produced (Anderson et al., 2014). Some blades are recycled, and others enter landfills (Anderson et al., 2014). Disposing of the nacelle can also be a concern because it contains composites and PVC foam (Anderson et al., 2014). Alloys used for the generator and gear box can be recycled (Anderson et al., 2014). Figure 4 shows the percent of coal ash that is recycled versus the materials of a wind turbine that can be recycled.

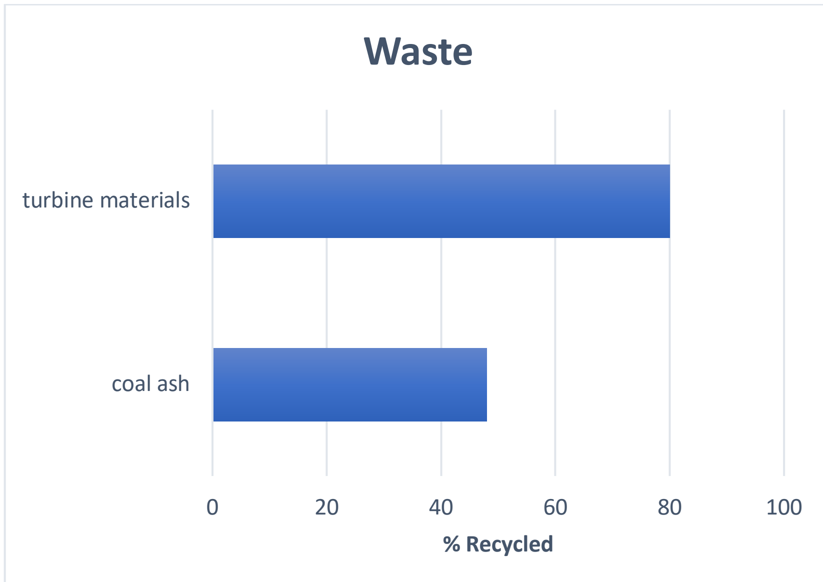

Figure 4: Percent of coal and wind turbine waste that can be recycled.

Other Environmental Impacts

Avian mortality

Avian mortality is a concern for energy systems. Coal power plants produce great amounts of emissions during combustion, and these pollutants can lead to bird deaths over time. Additionally, turbines can kill birds if birds come into contact with the blades. Data from 2006 reported coal plants and wind turbines resulted in a 0.269 deaths per GWh for wind turbines and 5.18 deaths per GWh for coal plants (Figure 5) (Sovacool, 2009). This data was generated by analyzing bird deaths from the total life cycle of coal plants and wind turbines. For wind energy, bird deaths were monitored from wind farms taking into account bird species, location, energy generation from the turbines, and wind technologies (Sovacool, 2009). For coal energy, bird deaths associated with coal mining, collision and electrocution from operating power plants, poisoning from acid rain, mercury pollution, and climate change were recorded and analyzed (Sovacool, 2009). The avian morality data was then synthesized to create a GWh death rate of birds (Sovacool, 2009).

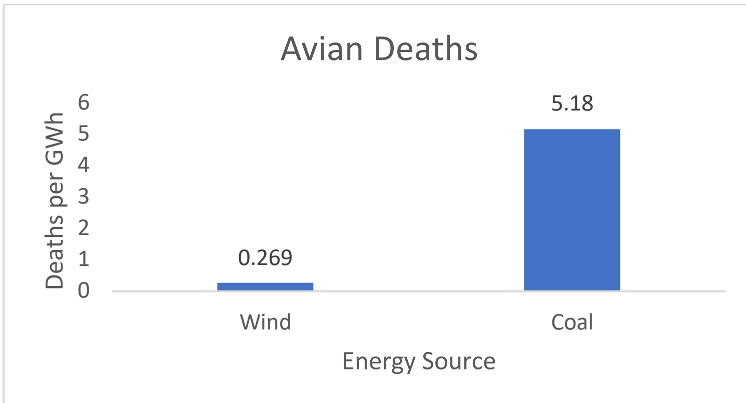

Figure 5: 2006 data of estimated bird deaths based on data from six wind turbines and two coal power plants lifecycles in the United States (Sovacool, 2009).

The 2006 data also includes total bird deaths in the United States (Sovacool, 2009). Seven thousand one hundred ninety-three birds were killed from wind turbines and 14,500,000 birds are estimated to have been killed by all fossil fuels. These numbers were generated in the study by multiplying the GWh from wind energy and fossil fuels in the United States in 2006 by the values in Figure 5. Twenty-five thousand, seven hundred and eighty-one GWh were produced from wind turbines in 2006, and 2.81 million GWh of coal, oil, and natural gas energy was generated in 2006 (Sovacool, 2009).

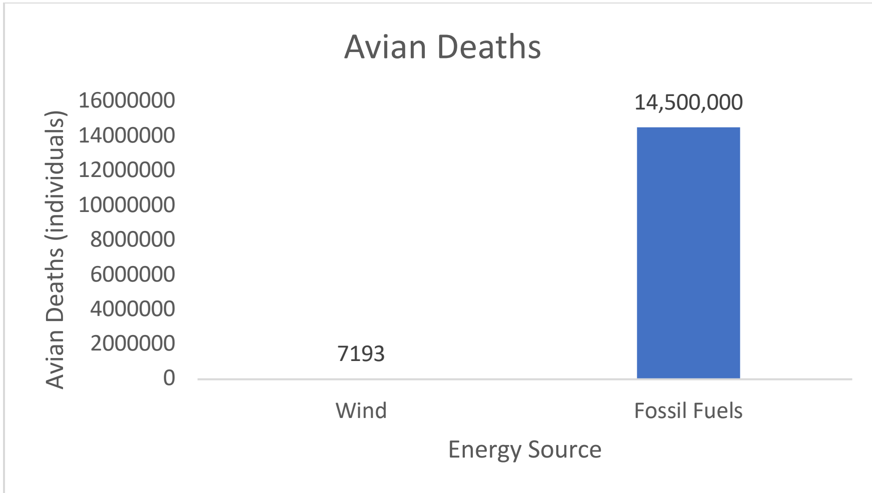

Figure 6: 2006 data of estimated total individual bird deaths by energy source.

Evaluating avian death data is important because one major opposition to building wind farms is the thought that wind turbines significantly increase the number of birds killed in comparison to other energy sources. However, data from Figure 5 show that per GWh, coal energy resulted in 19 times more bird deaths than wind energy. Additionally, it is important to recognize that energy systems are not the only or even the main cause of avian deaths.

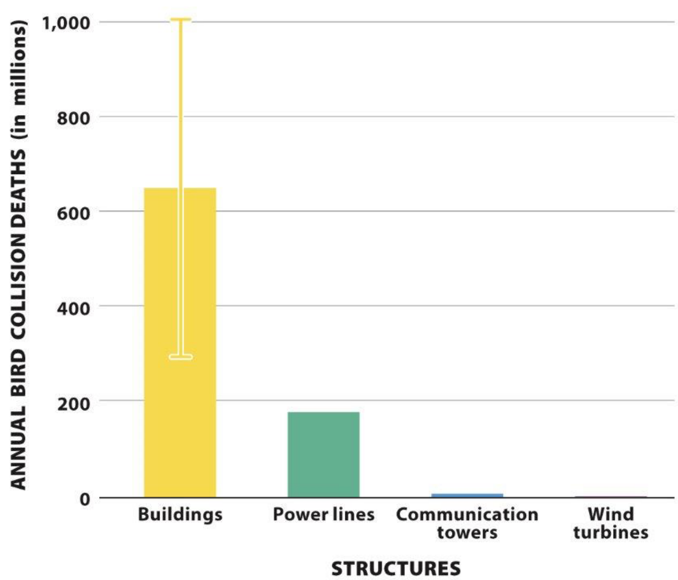

Figure 7: Annual bird collision deaths (Molles & Borrell, 2016).

Figure 7 depicts the main causes of bird deaths. By far, buildings are responsible for bird collisions. Urbanization is also a culprit for avian mortality because of the construction of new buildings. This data estimates bird deaths from buildings, power lines, communication towers, and wind turbines in the United States for 2005 (Molles & Borrell, 2016). It is not specified whether the buildings are in migration paths or not. Although buildings are responsible for a large amount of bird deaths, there are some methods to avoiding it. Physical deterrents on the outside of buildings can "warn" the birds before they collide with glass windows (Molles & Borrell, 2016). Avian deaths are important to consider when determining the environmental impact of energy sources, however, other causes contribute more to avian deaths than energy systems.

Land use

Land use is also an environmental concern for energy sources. Wind energy, in particular, requires large plots of land to accommodate multiple wind turbines. Data from 2008 compared the land requirements of coal and wind energy (Figure 8) (Fthenakis & Kim, 2008).

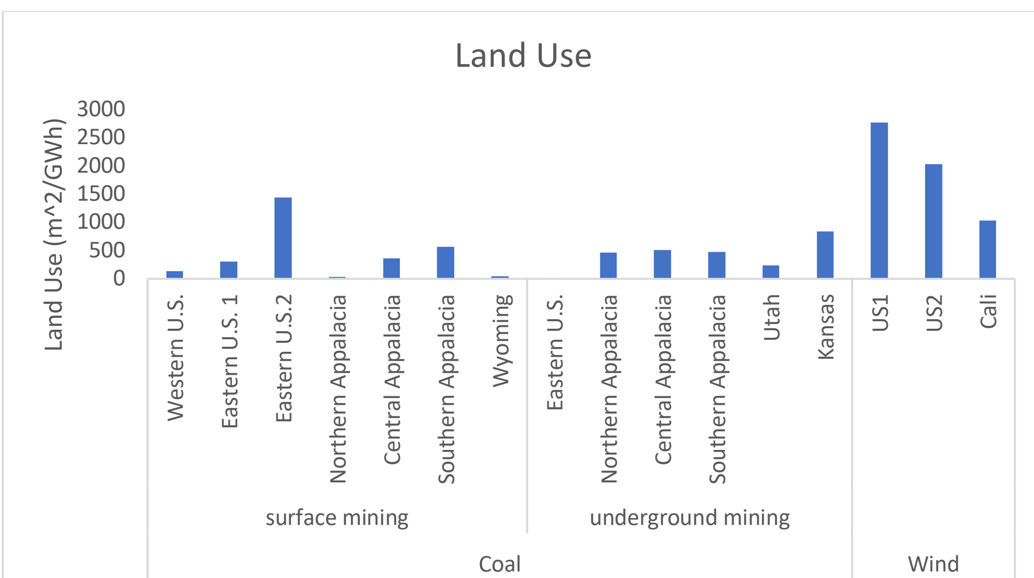

Figure 8: Land use data for coal and wind energy (Fthenakis & Kim, 2008).

Fthenakis & Kim (2008) categorized coal energy by region in the United States. In Figure 8, the second case study of the Eastern U.S. required the greatest amount of land for coal energy production. The U.S. case 1 for wind energy collected data based on a wind speed of class 4 (5.8m/s at 10m), and the U.S. case 2 collected data based on a wind speed of class 6 (6.7 m/s at 10m) (Fthenakis & Kim, 2008). Wind energy required the greatest amount of land for productivity (Fthenakis & Kim, 2008). However, distinctions need to be made about how the land was used. The data for wind energy in Figure 8 consisted of the total amount of land allotted for wind farms. Wind turbines are estimated to only use 1-10% of wind farm areas (Fthenakis & Kim, 2008). The land that remains serves other purposes. This can include animal grazing, agriculture, and recreation (Fthenakis & Kim, 2008). Additionally, land used for coal mining and coal waste are subject to more environmental damage than land allotted to wind farms. Coal mining releases nitrous oxides and sulfur dioxide into the atmosphere, and heavy metals such as mercury are present in the soil (Energy Information Administration, 2020g). Coal waste (ash and sludge) has to be disposed of in sludge ponds to keep the pollutants from entering the air (Fthenakis & Kim, 2008). Lastly, mining reclamation takes years of intensive work to restore the mining area to its original ecosystem functions and productivity (Fthenakis & Kim, 2008).

Assumptions and limitations

It is hard to quantify every aspect of a LCA because of the amount of data that needs to be included. For the raw materials category for wind energy, this study focused on the emissions from steel production because steel is the primary raw material used for turbines and because steel production contributes the most emissions during the raw materials phase. Certainly, wind turbines incorporate other materials. However, the emissions from acquiring these materials are less than the emissions from steel production, and these other materials make up less than 30%

of the wind turbine (Wilburn, 2011). Coal mining releases emissions such as carbon dioxide, methane, and nitrous oxides into the atmosphere. Methane CO_2e emissions were 34.1 million metric tons in 2019 whereas the carbon dioxide and nitrous oxide emissions from mining were 0.1 and under 0.05 million metric tons respectively (Environmental Protection Agency, 2020d). Methane is the primary emission from the raw materials phase for coal, therefore the methane CO_2e amounts are compared to the CO_2e amounts of steel produced.

For transportation, this study did not include import or export data. The transportation data collected focused on the transportation that occurs within the United States from factory to either power plant or wind farm. Therefore, emissions would be greater if import/export data were included due to increased distance.

The avian data were collected from a study that computed an average of bird deaths per GWh for wind and coal energy. Therefore, the number in Figure 6 is an estimate of how many birds were killed in 2006. Specific data on how many birds were actually killed from each power source in 2006 was not listed.

Conclusion

All energy sources create complex environmental problems. Through the use of the life cycle assessment in this study, wind energy creates fewer environmental concerns than coal energy in all phases. The LCA phases used in this study are raw materials, transportation, use/retail, and waste phases. The greatest difference in emissions is in the use phase. Coal combustion creates the greatest amount of emissions for the coal life cycle; whereas, wind energy has the least emissions of its life cycle in the use phase.

Avian mortality is a problem that is often discussed with windfarms. However, the research gathered shows that coal power plants cause more deaths per GWh than wind energy by

19 times. These data are important because avian mortality is often an issue discussed for windfarms but rarely talked about for other energy sources. For land use, wind energy does cause concern for the amount of land used for wind farms. However, even this can be debated because the wind turbines leave the land relatively undisturbed, and the land allocated for windfarms can have multipurpose uses. In contrast, the use of land for coal mining destroys habitats, changes ecosystems, and releases pollutants into the air, water, and soil. In many cases these impacts are irreversible.

Transitioning from fossil fuel energy to renewable energy is imperative for the future of energy because fossil fuels are finite. Renewables provide a sustainable energy alternative. Phasing out coal will be a lengthy process because the United States relies heavily on coal energy. Additionally, wind energy and other renewables do not have the same energy storage capacity as fossil fuel energy. Progress is being made by shutting down coal power plants and installing more wind turbines, but this progress is slow. Alas, all energy decisions have costs. Alternatives must be considered when making decisions about the future of energy systems. There is no perfect option, but some options have fewer costs than others. More research and innovation on renewable energy storage needs to take place before the country can transition to mostly renewable energy.

It is important to quantify environmental impact for energy sources because this provides vital information for the future of energy. Additionally, understanding the environmental impacts specific to each source of energy can pinpoint where the issues occur and lead to developing plans on how to lessen the environmental impact. Energy production is a critical service, but attention to environmental health should also be considered when planning for the future of energy.

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