

Review

The Cost of Wind: Negative Economic Effects of Global Wind Energy Development

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Abstract: This paper provides a structured literature review of the negative economic effects associated with the development of wind energy and synthesized the evidence at an abstract level. We then developed an analytical framework to systematically review economic issues such as volatility, electricity price, housing values, and unemployment in relation to wind energy. Global wind energy development data from the time period from 2000 through 2019 were included for a more robust analysis. This period encompasses the vast majority of total global installed wind energy capacity. After amalgamating evidence from existing studies and data banks, we discuss the policy implications, suggest avenues for future research, and propose solutions to mitigate externalities. By understanding the negative economic impact created by the expansion of wind energy, we can better equip policy makers and developers to create more efficient and sustainable energy policy to benefit citizens and preserve the environment for generations to come.

Keywords: wind; energy; economics; electricity; turbine; policy; employment; market

1. Introduction

Wind energy has grown rapidly since the turn of the century [1–3]. Total global installed wind energy capacity has increased from 18 GW in 2000 to 590 GW by 2019 [4]. This growth in wind energy is primarily driven by the goal of combating climate change [5]. Despite this rapid increase, economic limitations remain a significant barrier to greater wind energy penetration [6–8]. This paper offers an overview of the negative economic implications of wind energy based on peer reviewed scientific literature. We analyzed papers that were published between the years 2000 until 2020 as the vast majority of total installed wind energy capacity was developed during this time period [4]. The growth of wind energy is a global phenomenon [9–12]. As wind energy penetration has increased, the negative economic externalities have become more apparent [13]. Negative economic externalities include unemployment in competing industries [14] and decreased housing values for residential dwellings in close proximity to wind farms [15]. Negative economic impacts can include increased electricity market volatility [16] and higher average energy production costs [17].

A recent report by the World Wind Energy Association (WWEA) provides the current global wind energy capacity totals. By the end of 2018, the global installed wind energy capacity reached nearly 600 gigawatts (GW), see Figure 1, which is an increase of 50 GW from the previous year. Total installed wind energy capacity satisfies approximately 6% of global demand for electricity [4]. Wind energy is the largest non-hydro producer of renewable energy [18].

The WWEA annual report for 2019 [4] analyzed the wind energy by country (see Figure 2). China is currently the world leader for total installed capacity, with a total of 217 GW. The USA ranks second with 96 GW, followed by Germany with 59 GW, India with 35 GW, the United Kingdom with 21 GW, Brazil with 15 GW, and France with 15 GW (see Figure 2). The countries listed in this graph were the world leaders at the beginning of our analysis period where Spain was an early leader in

wind energy but has since been surpassed by other countries in total development. Asian countries such as China and India are currently among the world leaders in annual installed capacity.

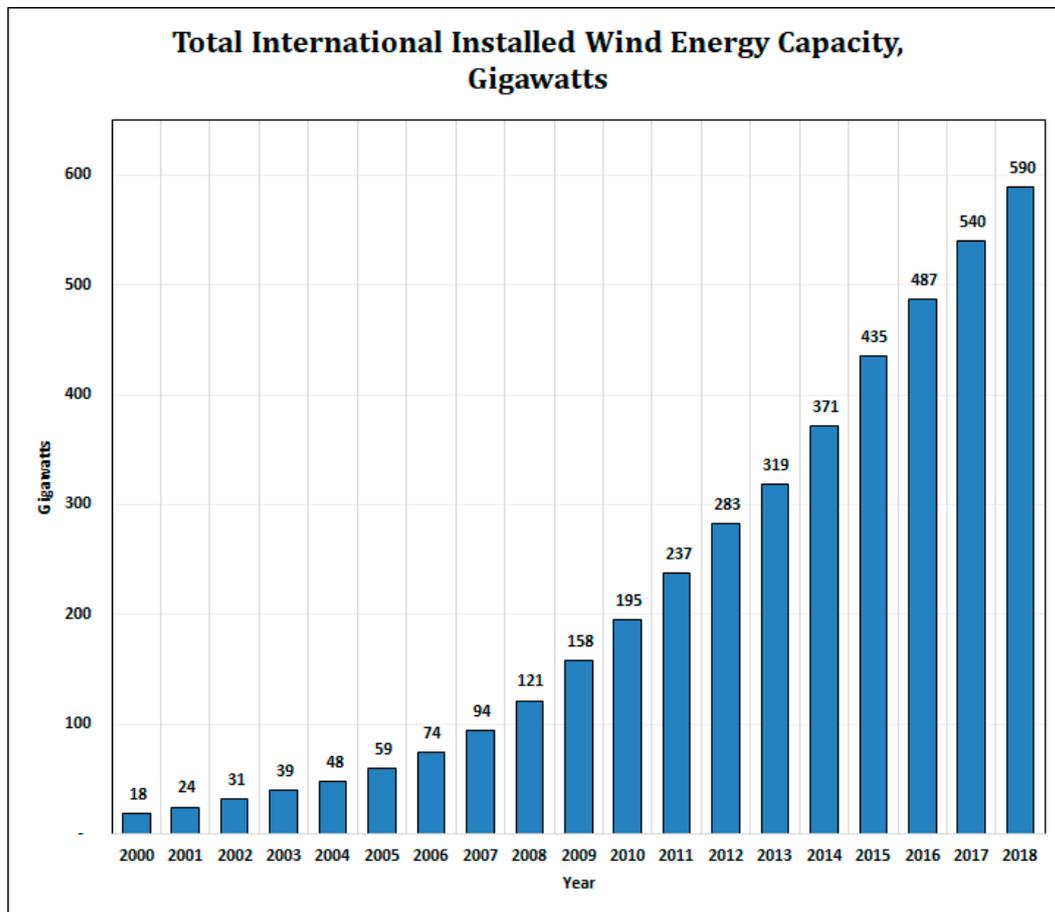


Figure 1. Global wind energy capacity growth. Data source: The Wind Power Statistics [19].

1.1. Development Motivations

The primary motivation for the global expansion of wind energy is the reduction of CO₂ emissions [3,7]. Globally, governments support the development of wind power to mitigate the negative externalities of traditional fossil fuel electricity generation such as CO₂ emissions and greenhouse gasses [20]. Although wind energy has made great advances, coal is still the largest source of electricity in many industrialized countries [21,22]. Fossil fuel power plants are the primary source of greenhouse gases (GHG) in many countries [23]. These facilities can account for approximately 40% of carbon dioxide emissions [18]. Combating climate change and reducing dependence on foreign energy imports are often cited as justification for the expansion of wind energy development [24–26]. Governments around the world have enacted energy policy strategies aimed at the reduction of CO₂ emissions [27,28]. Environmental concerns have been a driving force for the development of wind energy [29]. Wind energy can be beneficial in CO₂ reduction, however, in some regions, there are more efficient means of climate change mitigation. In these cases, wind energy can divert valuable funds and resources away from more effective methods of environmental protection [30].

The global population is expanding rapidly, and the standard of living is rising fast in many industrializing nations. These factors combine to create a growing demand for energy and have given rise to the increased demand for wind energy development. Wind energy is a renewable energy source that has fairly strong support from the general public [1,31–33]. Some consumers not only support wind energy, but are also willing to pay extra for electricity produced by wind farms [34–36]. Citizens are

concerned about the economic impacts of electricity production, and quantitative analysis has revealed that citizens will support wind energy if they believe it will provide net economic benefits to the community [37]. The perceived environmental and economic benefits of wind energy serve to bolster public support, but wind farms are not devoid of negative environmental impacts [38]. These negative externalities include bird fatalities [39,40], the human health impact [24,41], bat deaths [42,43], ground animal ecosystem disruption [44], and habitat loss [45].

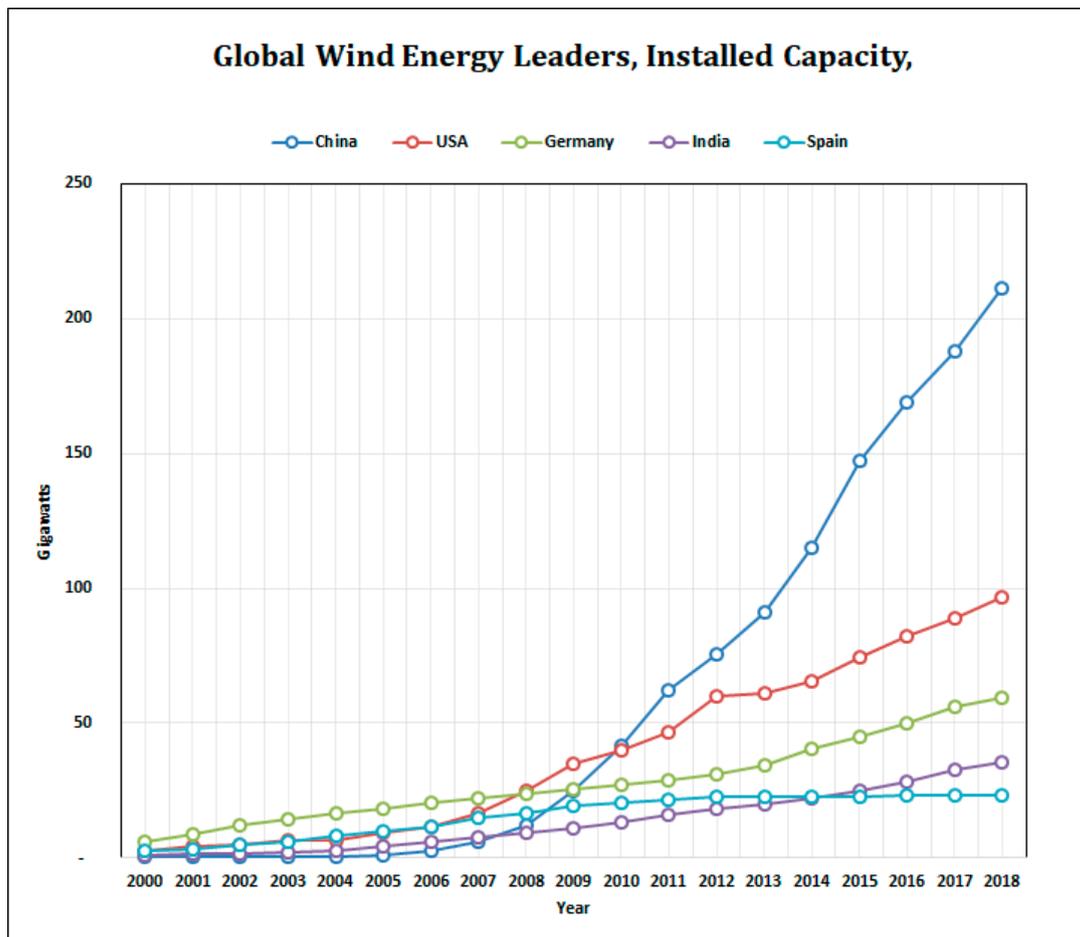


Figure 2. Country level wind energy capacity growth. Data source: The Wind Power, Statistics [19].

Peer reviewed literature has also shown that wind energy generally enjoys public support, but research also shows that wind energy can also produce controversies [46]. Residents who oppose wind energy development are often well informed and motivated. Multiple peer reviewed studies have shown a connection between wind farm proximity and decreased housing values [15,27,31]. It is beneficial for wind energy producers to engage the local community to promote wind energy projects that benefit all affected parties [33]. A better understanding of the negative externalities of wind power is also beneficial to wind energy supporters, because it allows them to overcome these issues. In order to effectively engage local residents, developers must be open and honest about the negative aspects of wind farms and propose solutions to overcome them.

1.2. Purpose of Research

Research gaps remain with regard to the economic effects of wind energy [24]. Given the importance of energy issues, this paper contributes to make the field slightly more comprehensive. Klain [47] writes that more research needs to be devoted to the perceived risks and benefits associated with emerging energy technologies. This manuscript focuses on the negative externalities to help bring balance to the existing

literature in the field of wind energy. We do not seek to support or oppose the development of wind energy, but simply strive to create a more comprehensive perspective. The issue is complex and multifaceted. This paper presents readers with a condensed analysis of the primary negative economic costs as discussed in today's scientific literature. In our study of hundreds of peer reviewed articles, we found four topics to be a recurring theme in the area: electricity market volatility, increased cost of electricity production, housing value impact, and loss of employment in competing industries. Additionally, in our survey of the body of academic literature, we were unable to find a systematic literature review covering these four issues.

This structured review is helpful to legislators, wind energy producers, and citizens. Better understanding of the public economics of wind energy is essential for the effective design and evaluation of energy policies [24]. Policy makers benefit from reading this paper by having access to an analysis of the big picture externalities of wind energy to make informed decisions for the energy future of their constituents. Wind energy developers need impartial outside analysis to better solve issues within their own industry. Those promoting positive attitudes toward alternative energy need to be aware of the persuasive influences in the literature about wind energy [5]. Furthermore, citizens need clear information on the negative impact of wind energy to weigh against positive effects in order to make more informed decisions about potential projects in their localities. Our research benefits all three of these affected parties.

Wind energy is still a relatively new player to the large-scale energy market [48]. The lifespan of wind turbines is approximately 20 years [49]. Given that the vast majority of total global wind energy capacity has been installed within the past 20 years [50], we have only recently been able to offer a comprehensive life cycle analysis of the environmental impact of industrial wind energy and the economic effect over the full course of wind farms through their stages of use, which are manufacturing, construction, maintenance, and decommissioning [51]. Wind energy is a field that is developing rapidly and therefore requires consistent updates in the literature.

Wind energy is currently experiencing significant growth worldwide [9–12]. This recent rise means that more up to date research is needed to analyze the full impact of the technology. Potential negative externalities of alternative energy sources are sometimes overlooked [52]. Decision makers must find energy solutions that offer the best balance of economic feasibility and environmental sustainability. Our research offers suggestions for future studies in underserved areas of wind energy research, along with policy implications in order to provide legislators with the knowledge to create sustainable energy futures. We offer a condensed assessment of the international impact of wind energy with a current perspective.

1.3. Economics of Wind Energy

Economic limitations are a primary barrier to wind energy market penetration [7,8]. These constraints necessitate government intervention for the continued expansion of wind energy. Government policies, not natural market forces, are the primary driver of wind energy [53]. The economic support for international wind energy development is justified by the mitigation of negative externalities associated with fossil fuels, however, there are also negative externalities created by wind energy [8,24]. Wind power receives considerable public financial support via governmental support programs, therefore, it is important to understand who receives the benefits [54].

The economic success of wind energy is impacted by technological advances, availability of prime locations, and wind speed. Once the wind farm is constructed, the efficiency of electricity production is entirely dependent on wind speed [23]. The financing of wind energy projects is significantly different than traditional fossil fuel burning power plants. In some cases, renewable energy can create socio-economic and environmental benefits [55], but the negative externalities must also be factored in. Wind energy requires a large capital outlay at the beginning, and relatively low operating expense [56]. Once the farm is running, the marginal cost of energy is affordable. The fixed costs of wind farms are significant, but the marginal costs are quite small in comparison [57]. Comprehensive financial decisions

must account for the economic and environmental benefits, along with the economic and environmental costs of wind energy. In some cases, wind energy can absorb funding that could otherwise be devoted to more effective forms of environmental protection [30]. Qualifying the indirect costs of wind energy helps policy makers, engineers, and developers to create better policy and technology to create wind energy projects that are more economically competitive and environmentally friendly.

The remainder of this paper is arranged as follows. Section 2 presents the methodology, Section 3 are the results, Section 4 presents the discussion, and Section 5 discusses our conclusions.

2. Methodology

The research methods for this paper involved a rigorous and structured approach to the reviewed scientific journal articles. We first constructed the theoretical basis for questions involving the negative economic externalities of wind energy development and then defined a methodology to refine our search. After formulating specific guidelines for the overall direction of our work, we then proceeded to collect research on wind energy and externalities. A comprehensive literature survey was initiated to locate articles relevant to the topic. Our search was conducted on Science Direct, MDPI, JSTOR, Google Scholar, and The Institute of Electrical and Electronics Engineers (IEEE). Renewable energy data banks and reference lists were utilized. The primary keywords were “wind energy”, “externalities”, “renewable energy”, “economics”, “volatility”, “housing”, “energy employment”, and combinations of these words. These keywords were input into search engines to produce the optimal results. Special attention was applied to journals with high impact factors. The material was sourced from leading international peer reviewed journals. Scientific articles were collected and organized before we initiated a cross check to isolate and remove any duplicate texts, which helped us to analyze the existing aggregated knowledge for this systematic literature review.

The next step in the process was to remove any studies that did not fit within the scope of the topic based on title and abstract. References were taken from papers both supporting and disapproving of wind energy to provide a more balanced perspective and minimize bias. Supporting papers were helpful to provide wind energy statistics, technical attributes, CO₂ effects, government energy policy, and growth data. Bias is possible in any individual paper, and to counteract this, we included a large sample size to improve the scope of this study. Each additional step of the process involved a more in-depth study of the sources, in order to remove superfluous content. The primary focus of these articles related to the major topics within our paper: the development of wind energy, the economics of wind energy, housing price impact, volatility, unemployment, price increase, and renewable energy policy. Wind energy panel time series data were sourced from renewable energy associations in order to construct visuals for context. By the end of this multifaceted process, we were left with over 120 citations in which to conduct a comprehensive assessment of negative externalities of wind energy. A visual representation of the process is presented in Figure 3.

The vast majority of wind energy systems have been installed this century, therefore we selected this time period for up to date research to analyze the current state of wind energy. The synthesis of results from these articles provides a clear and relevant overview of the negative economic effects associated with the expansion of wind energy. The scientific articles for this paper were sourced from the years 2000–2020 (see Figure 4). Before 2000, installed wind energy capacity was relatively insignificant, making scientific analysis of economic negative externalities difficult given the small sample size and lack of global penetration. Therefore, date of publication was a primary eligibility criterion for inclusion in this review.

After collecting information from these journal articles, we then proceeded to create four categories to display the primary issues as presented by the leading experts in the field. These four categories include electricity market volatility, increased costs to generate power, job losses in competing energy industries, and housing value impact.

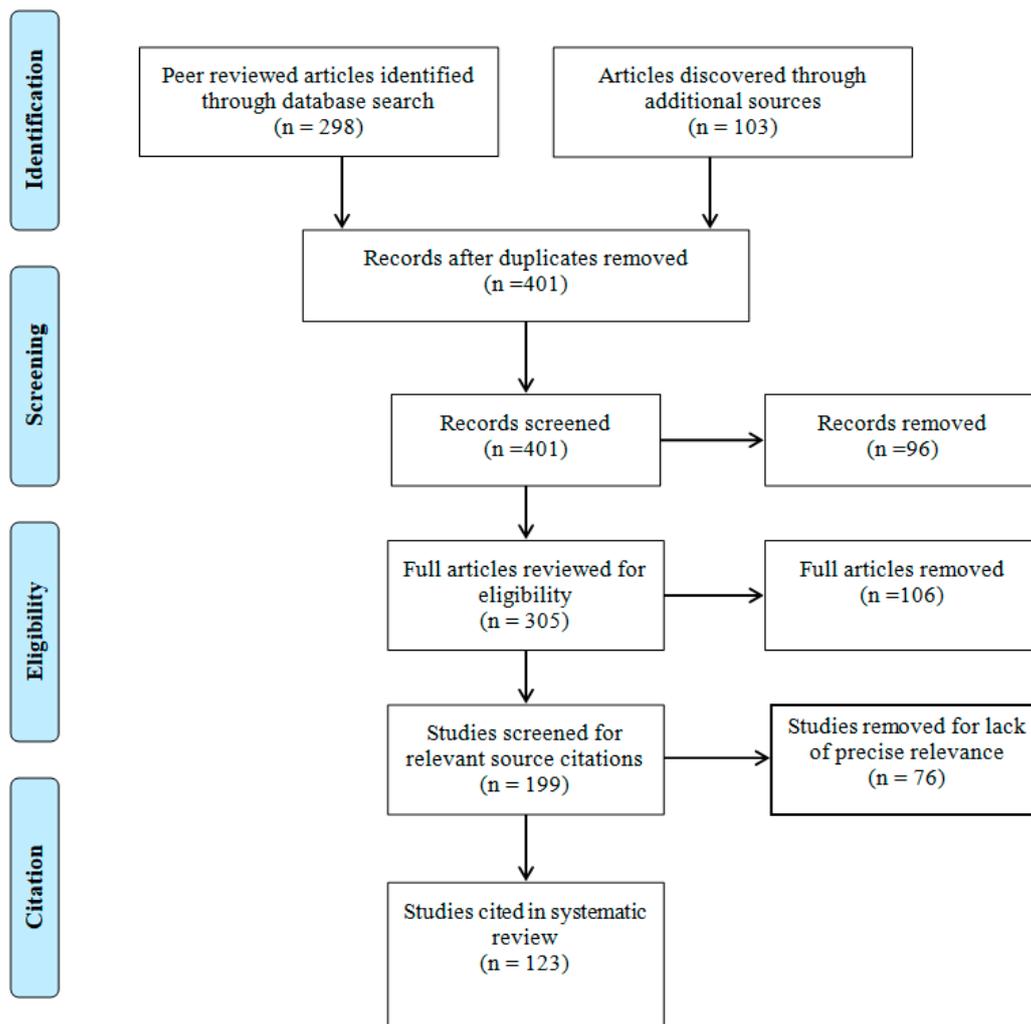


Figure 3. Article selection process flow chart.

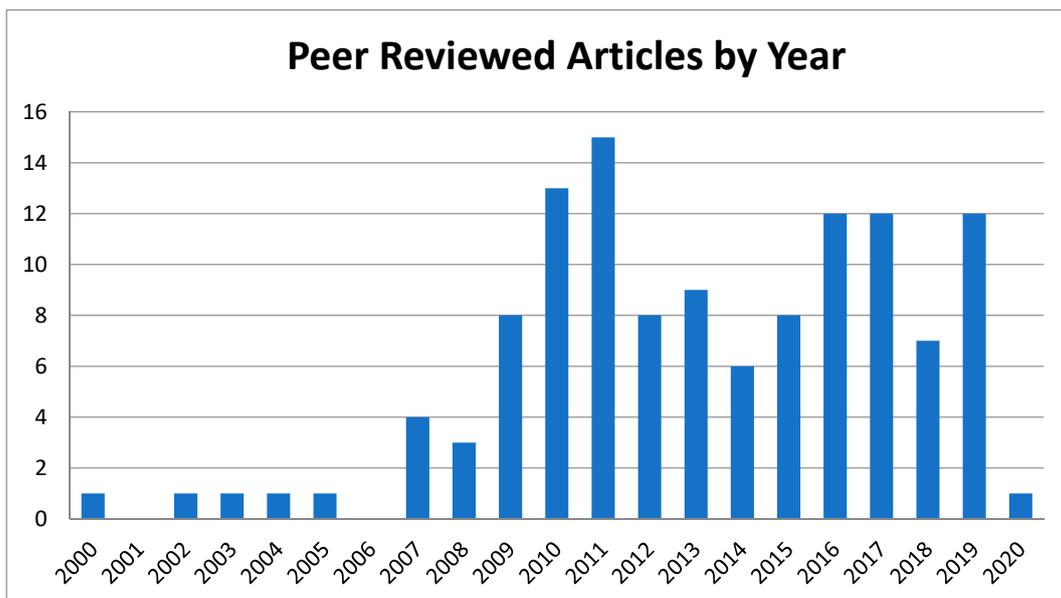


Figure 4. Research papers by date.

3. Results of the Negative Economic Impacts of Wind Energy

3.1. Volatility

The intermittency of wind energy creates additional volatility in electricity markets [16,58]. Intermittency means that the rate of energy produced by the wind turbines and delivered to market is not a constant. This creates volatility of the electricity supply. The volatility inherent in wind energy presents unique challenges [59]. In times of high wind energy output, the total energy supply in the system is increased, therefore lowering short term spot prices, but increasing system volatility [60]. Wind energy is by nature an intermittent generation technology [61], and as wind farms have increased, so has the overall intermittency of electricity supply [62]. Intermittent supply leads to higher levels of volatility in the electricity market, and market stability is also beneficial to consumers and governments.

Intermittency is the primary technical constraint for the development of wind power [3,29,39]. Wind turbines are not capable of producing electricity 24/7 [63]. Quite simply, the wind does not always blow [64]. Until wind velocity reaches a certain level (cut in speed), the wind turbine will not produce any amount of electricity. On the opposite side of the spectrum, during extreme conditions where wind speeds reach high velocities, the wind turbine can shut off to minimize damage risk for the turbine blades. In between these extremes, the wind turbine will produce electricity (Figure 5). This chart is based off a typical power curve for an industrial grade 5 MW turbine. Power generation begins at wind speeds of 3.5 m/s, levels off around 12 m/s, and shuts off at approximately 24 m/s [65]. The problem is that consumer demand does not match the intermittent supply of wind energy.

The electricity generated from wind energy fluctuates significantly based on wind speeds, and is therefore impossible to predict with absolute certainty. A basic characteristic of wind energy is variability of supply [24]. The volatility of production is a major issue because industrial scale electricity is not storable yet [66]. The supply must be constantly balanced to meet demand [24]. In the future, technology may be developed that enables large-scale energy storage, but currently the technologies are not economically feasible on a grid-wide scale [53]. The volatility of the energy generated by wind turbines necessitates conventional backup power plants to ensure supply base load capacity [63]. In order to bridge the gap in production shortages, other energy sources are necessary such as gas and coal fired plants, which are capable of running practically full time [67]. These traditional power sources such as fossil fuels and hydropower can supply electricity during times of low wind speed [53]. Research suggests that governments should not be overly optimistic that industrial-scale wind projects will totally overcome our dependence on fossil fuels [3]. Any energy policy that seeks to rely solely on wind energy would be unrealistic due to volatility of supply.

One possible solution to moderate dependence on fossil fuel backup plants is the use of pumped storage hydro stations. These stations can help increase the penetration of wind energy [68] by accounting for intermittency, and potentially reducing system costs [69]. This technology can help guard wind power systems against disruptions [70] and supply a relatively consistent amount of electricity for the power grid [71].

Wind energy power generation is dependent on wind speed. The power generated by a wind turbine is directly proportional to the cube of the wind speed, therefore doubling wind speed causes the power produced to increase by a factor of eight [72]. After wind speed, consistency and reliability are the most important factors. A typical operational range for wind plants is to be active 65% to 90% of the time, but not at the level of full capacity [72]. These technical aspects of wind turbines are the basis of any economic payback calculations; therefore policy makers and stake holders need an understanding of both energy economics and the mechanical side of wind energy. Wind resource potential is often overstated [73], creating a difficult task of accurately forecasting the net financial cost of wind energy. The basic mathematical equation for wind energy production is listed here:

$$P = \frac{1}{2}C_p\rho AV^3$$

where P is the wind power produced; C_p is the power coefficient; ρ is the density of air (kg/m^3); A is the area of the wind turbine blade in m^2 ; and V is the velocity of wind in m/s .

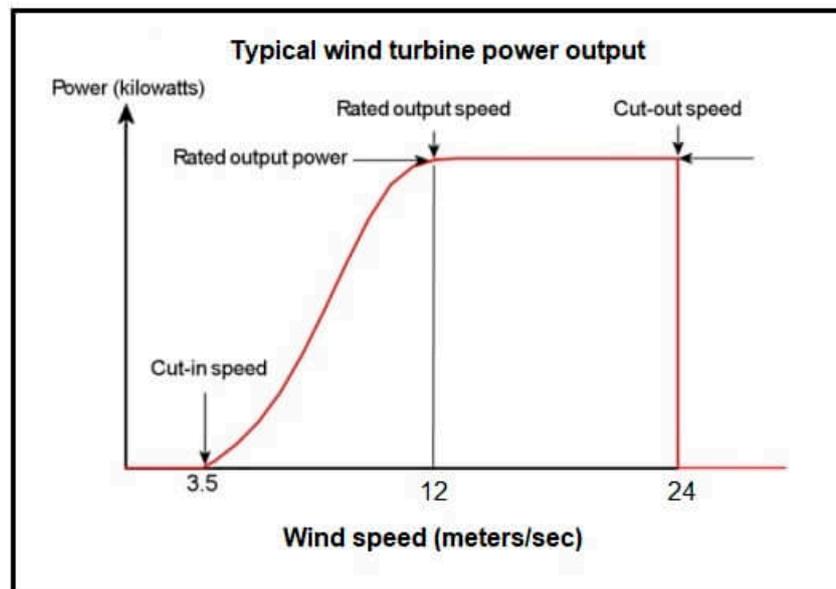


Figure 5. Electricity production based on wind speed. Source: Wind Power Engineering [65].

Electricity markets are further distorted by government interventions to subsidize wind energy. Government support of wind energy development creates market distortions and long-run price volatility [74]. These interventions can create artificial price points in the market by artificially lowering electricity short term prices, but increases prices in the long term [60]. This can hurt traditional electricity producers and consumers as well as lowering long-run economic growth [75]. Electricity markets are complex, and well-meaning policy can lead to unintended consequences. Energy companies often understand the impact of government energy policy better than the legislators themselves. Dominant energy firms can manipulate emissions markets to their advantage, in order to raise electricity prices without inflating emissions prices, and at times of peak energy demand, artificially suppressing emissions prices [76]. Careful energy planning to promote long term stability by minimizing volatility is beneficial to consumers, energy producers, and local governments.

Wind farm electricity production depends on wind speed, which is a variable that fluctuates greatly [77]. Accurate prediction of future wind speed enables better market planning to balance supply and minimize volatility. Wind supply varies highly [78], and therefore wind availability is difficult to forecast precisely [79]. Even advanced forecasting methods cannot guarantee the accurate prediction of short-term wind energy generation [80]. Crafting comprehensive energy policy that produces stable market conditions creates efficiency and long-term sustainability. Creating a balanced energy portfolio with an efficient mix of wind energy, other forms of renewable energy sources [81], and traditional energy sources are essential to a sustainable electricity supply. The cost of wind energy is predicted based on annual wind potential estimates, but because wind speed is a change significantly based on weather, electricity production costs can vary significantly [67].

Developing wind farms in prime locations maximizes energy output. The best wind farm sites are those with relatively flat terrain and consistent wind speeds. The optimal development site would also be devoid of trees and manmade structures such as buildings, airports, hospitals, and houses [82]. Proximity to existing electricity transmission lines is another important variable in wind farm siting [8]. Many of these prime locations have already been developed, meaning that future wind farm development will most likely occur closer to residential communities or vulnerable natural habitats [1]. This follows the classical economic principals developed by David Ricardo on the theory of rent [83]. Wind energy can be beneficial, but the decreasing amount of prime locations limits productivity.

The declining efficiency of wind turbines over the course of their lifetime is an additional issue. Diminishing output adds another factor to determine the proper energy mix. Degradation can reduce a wind farm's output by 12% over their twenty-year lifetime [78]. This is an important aspect of wind energy that should be researched further in order to improve wind energy technology and renewable energy production.

3.2. Increased Costs

Electricity produced from wind energy is generally more expensive than electricity generated by traditional sources [3,17,75,84,85]. The increased cost is ultimately passed on to the consumer [53,63] for which there are a number of reasons. These reasons differ by country depending on the structure of government subsidies and energy. Governments throughout the world use economic incentives to promote the expansion of wind energy with the end goal of reducing CO₂ emissions [20,86]. Governments often tax fossil electricity producers in order to reduce greenhouse gas emissions [87]. These taxes can raise the price of electricity as a whole. Government policies are a primary driver of international wind energy growth, and development is also promoted by financial support programs such as renewable energy certificates, feed-in tariffs (FIT), grants, and taxation benefits [88]. Wind energy production requires proper geographic characteristics for the wind farm site [82] and sufficient wind speeds for generation of electricity, but these factors do not explain the capacity differential between nations [89]. Resource potential is essential, but not necessarily the primary driver for development [90]. Federal support mechanisms are a major factor in the increased price to the consumer, but the technical aspects of intermittency are also a contributing factor. The overall price of electricity is also impacted by volatility of wind energy production [58]. Wind energy receives such significant levels of federal support that it is important to understand who receives these financial benefits and who pays the costs [54].

Legislative bodies around the world have devoted significant budget resources to the promotion of renewable energy development [84]. As subsidies have increased, the wind energy has grown to become dependent on the government for mandates and financial support [53]. Billions of dollars of subsidies from tax revenues have gone to private wind energy producers [53]. Policy makers promote the construction of wind farms by contracting private firms not only with subsidies, but also with regulatory support, energy credits, and quotas that require electricity producers to purchase a certain amount of their supply from wind farms [91]. These wind energy promotion policies are essential to the growth and increase in market share [92]. Tax credits are a large part of the wind energy support structure [93]. An example of this is the federal production tax credit (PTC) in the USA. The PTC is a program that provides tax credits to qualifying renewable energy builders [94]. It is a primary driver of wind energy development in the U.S. [72]. As Westwood [95] states, the PTC provides economic stability for wind energy producers. A number of peer reviewed publications have studied the impact of the PTC on wind power development [56,75,94], which have concluded that there is a positive relationship between wind energy development and these kinds of public energy programs. The structure of these government provided incentive programs varies in different countries, but in the majority of cases, the increase in cost is ultimately passed on to the consumer or tax payer [53].

Wind energy faces various barriers to entry such as financial disadvantages [7] and technical limitations. In order to overcome these challenges, governments have instituted instruments such as feed-in-tariffs, financial subsidies, tradable energy certificates, and regulatory support [3]. Many governments operate by the economic rationale that the solution is for society to subsidize wind-power generation [3] to reduce CO₂ emissions [27]. The goals of these policies are to enhance the public good by protecting the natural environment through financial programs like environmental taxation [96]. The intentions of the lawmakers creating these support policies may be noble, but the reality is that many of these decisions have subverted existing incentives in electricity markets, creating long term economic negative externalities [17]. In the process, energy policy creators have at times inefficiently used tax revenue [53], and many of these governments have a poor track record for allocating federal funds [91]. Lesser [75]

goes as far as to say that there is no economic rationale for governmental subsidization of wind energy development. We take a slightly more neutral stance in our analysis of wind energy, which is aligned much closer to the recommendation of Zerrahn [24], where a wind policy design should be for optimum efficiency and guided by sound public economics. The economics of wind energy ultimately comes down to price. The final cost to consumers should be forefront in the thought process of any policy maker responsibly representing the financial interests of their constituents. The goal should be to create green energy solutions that are not too costly for consumers.

Germany is an excellent case study in wind energy impact on consumer energy prices because it was an early adopter of wind turbine technology [12]. The country has a significant wind energy saturation. Unfortunately, the massive wind energy focus has produced significant negative externalities for German citizens, who pay the highest electricity prices in the entire European Union [63]. The German model has not produced cost effective results because of a failure to harness market incentives [17]. The national energy transition has almost doubled the price of electricity in just 15 years, which has had a disproportionately negative impact on vulnerable households living close to the poverty line who have to devote a greater percentage of income to utility expenses [63].

The increased cost to consumers resulting from expanded wind energy subsidization is not limited to Germany. Upton and Snyder [85] found that in the USA, energy prices increased by as much as 10.9%–11.4%. Staffell and Green [78] also found an increase of 9% in the levelized cost of electricity from wind turbines. Carbon taxes to combat climate change and support renewable energy can increase electricity costs by as much as 19% [97]. The amount of price increase varies drastically from country to country. The generation of electricity from renewable sources causes a significant drain on household income with regressive distributive effects [98]. Economically prudent energy plans should protect the most vulnerable households in their districts. Electricity is a necessary good, so it is beneficial to households to keep prices lower [99]. The regressive impact of increased electricity prices is a topic that deserves additional legislative and academic attention.

Electricity markets are extremely complex, and prices fluctuate dramatically over time [100]. There are many factors to consider when assessing wind energy prices. If wind energy is “expensive” or “inexpensive”, these terms are only in relation to competing sources of energy. In times of increased electricity prices, wind energy development becomes more economically feasible [94]. Fluctuating oil and natural gas prices can make wind energy more or less affordable in comparison [101]. Even competing renewable sources of energy can fluctuate in price based on materials used in manufacturing products such as solar panels. The price premium is further extenuated by offshore wind farm electricity generation [102]. Subsidies can further distort markets, reduce competition, and remove the incentives to innovate and improve efficiency [75]. Energy produced from wind turbines is still more expensive [84] and requires government support in many cases. Therefore, improved innovation and planning are necessary to increase cost competitiveness.

Wind energy cost is also of importance to wind farm developers. Return on investment and payback periods determine if projects will begin development. Wind turbines have a projected lifespan of approximately 20 years [49]. The major challenge in the financing of renewable energy is the lower rate of return of green projects when compared to traditional fossil fuel sources [99]. Texas is the state with most installed wind power capacity in the United States as the state has the most optimal conditions for developing wind energy. The payback period for a wind farm in Texas including federal tax credits is approximately 13 years [103]. The issue with this projection is that it includes the federal tax credits, and therefore cannot be applied to other projects that would have different levels of government funding.

Connecting wind farms to the existing electricity grid is a practical aspect of wind energy that is often overlooked. Prime locations are often situated in remote areas far from existing power grid infrastructure. The ability to generate wind energy is growing faster than the ability to transmit it, meaning that infrastructure improvements are essential for continued growth [53]. Massive infrastructure

investment is required for industrial scale electricity transmission lines, driving up the electricity supply cost [8]. To meet growing demand, these projects will require billions of dollars in capital investment [75].

The task of connection to the electricity grid is even more of a challenge for off shore wind farms [104]. Ocean depths and distance from the shore combine to drive up construction expenditures. The connection costs of offshore wind farms are even higher than traditional wind farms, requiring even more government assistance [104]. Specialized equipment and labor are required for these difficult installations. Water depth and distance from shore can require up to 50% more front end capital for grid connection [104]. Whether onshore or offshore, grid connection remains a barrier to wind energy that must be realistically considered in the early planning phases of wind energy development. Continued innovation and improved design is essential for the continued growth of the energy source [105]. More research should be conducted on topics such as grid connection costs and the declining rate of wind production over the life cycle of wind turbines.

The continued subsidization of the wind energy market can create drains on overall Gross Domestic Product (GDP) [75] by staining tax budgets and decreasing expendable household income [17]. Böhringer et al [96] states that at the macroeconomic level, the aggregate losses in economies of scale are greater than the aggregate gains. Energy supply that works together for the overall economy to produce greater growth and efficiency is best for economic development. Certain research touting the benefits of wind energy states that wind is free, therefore the energy produced from wind will be economically efficient [82]. Simplistic analysis such as this lacks acknowledgement of the basic economic realities of such costs to create the turbines themselves in order to harness the wind power, and then the expenses involved in maintenance and grid connection. Realistic economic evaluation of the benefits and limitations of wind energy is necessary for sustainable energy planning.

3.3. Unemployment

Employment in wind energy often comes at the expense of employment in competing industries due to a crowding out effect [14]. There is little debate about this, but the net employment impact is still an area of contention in the field of peer reviewed articles on the topic of wind energy. Macroeconomic research from Borenstein [106] and Edenhofer et al. [11] indicates that there is scant evidence of a net increase in employment from the increase in renewable energy share. The majority of wind energy scenarios lead to an increase in the level of equilibrium unemployment [107]. The initial phase of wind energy introduction leads to an increase in overall employment, but the later stages result in a contractive effect where job losses in competing industries begin to mount, leading to an overall slightly negative net employment balance [64].

Politicians from across the spectrum are hopeful over the prospect of green job growth from wind energy [96], but the total employment impact is often negative for the economy as a whole [107]. Wind energy is promoted as having positive effects on employment, but a minimal amount of research has systematically dealt with the net employment impact [108]. The total socioeconomic impact of wind energy is still unresolved [24]. Net employment impact is not entirely straightforward and results often differ based on the methods and assumptions of research [14]. Energy sector employment is a significant driver of GDP at a national level [109], therefore the economic effect of wind power on employment is of importance for the economy as a whole.

The employment effect of wind energy creates employment tradeoffs with competing energy sources, both renewables and fossil fuels. Employment in the coal industry has been hit especially hard. Haerer and Pratson [110] conducted thorough research analyzing the coal industry impact in the United States, which revealed that this industry lost over 49,000 (12%) jobs in the five-year time period of 2008–2012. The same study found that a percentage of these job losses were caused by the tightening of regulations on coal burning power plants to increase the market share of alternative electricity sources. While some of these losses in employment were offset by wind energy employment to lessen the net impact, the jobs were not in the same geographical regions [110]. This creates socioeconomic issues involving the retraining of the labor force to avoid the negative impacts associated with long

term chronic unemployment in affected areas. Wind energy does provide employment, especially in the manufacturing phase, which makes up the majority of the employment created by wind energy [108], but the debate centers around the net employment effect, and how to repurpose displaced workers from other energy sectors. The coal industry in the U.S. has experienced a drastic economic decline over recent decades, which has culminated in job losses and severe economic hardships in many communities [111]. Gains in employment from wind energy are not in the same geographic locations as the displaced labor force, therefore transitioning workers from one energy industry to the other is often not possible based on proximity and skillset. In areas where the coal industry is a dominant employer such as Appalachia, fewer employment alternatives exist outside of mining [112]. Throughout history, job losses from disruptive technology have been commonplace. The issue in this specific case is the negative economic impact from geographically concentrated levels of high unemployment causing significant societal issues for these communities. As energy portfolios become more based on renewable energy sources, innovative solutions need to be implemented in order to deal with unemployment in competing industries.

Louie and Pearce [21] stated that “a relatively minor investment in retraining would allow the vast majority of coal workers to switch to PV-related positions even in the event of the elimination of the coal industry”. Simplistic statements such as this are unrealistic and unhelpful in solving this complex issue. Retraining entire industries of workers for completely new skill sets is a drastic undertaking, not to mention the fact that the coal jobs are not in the same locations as the renewable energy jobs that can replace them. This is the case for both PV and wind energy as wind energy employment displacement does not only affect fossil fuels. Alternative forms of energy can also be impacted by the crowding out effect [14]. Prudent energy development should consist of a portfolio containing a diversified mix of renewable electricity sources [81].

The employment aspect of wind energy is not limited to the energy industry as the effects are wide ranging. As technology has advanced, the geographic options for wind energy have also increased. Offshore wind energy has added a new set of externalities to research. Wind farms located in oceans create disruptions for various marine based operations such as fishing, aquaculture farms, shipping routes, and naval exercises [49]. The scale of wind turbines is so immense that wind farms can have economic impact miles from the farm. Broekel and Alfken [113] utilized spatial panel regression methods to discover a negative relationship between wind farms and tourism. This is especially concerning for countries where tourism accounts for a significant share of GDP.

Wind energy creates jobs, especially in the manufacturing industry [108], but after factoring in losses in competing industries, the net employment impact for the economy as a whole is slightly negative [64]. These job tradeoffs are highly significant in the coal industry [110,111], but also affect other alternative sources of electricity production [14]. Although the net employment effect of wind energy on employment is still a contentious issue that has not been empirically resolved [24], research has shown that if the wind energy development is subsidized from labor taxes, the employment impact will be negative [96]. Given the minimal number of systematic empirical studies dealing with this topic [108], we recommend that more research be conducted on specific employment relationships between wind energy development and competing energy production industries. These studies should focus on net employment effects, geographic implications, and the retraining of the displaced labor force.

3.4. Housing Values

Peer reviewed empirical research has found that wind farms can decrease the value of homes anywhere from a low of 1.4% [27], a median of 3–6% [114], or a high of 17% [31]. This value decrease is affected by the proximity and visibility of the wind farm [114]. The wind turbine effect on housing values is a contentious issue in the wind turbine debate. As wind energy has expanded, the potential negative externalities have become more apparent [13]. Residents living close to proposed wind farms can be quite vocal in their concerns over property devaluation [115]. This is understandable

considering that home equity makes up the largest percentage of net worth for the average citizen [116]. In 2015, home equity accounted for approximately 35% of the net worth of the average home owner in the U.S. [117]. Local home owner concern is not unfounded; a minor negative change in home percentage of home value can impact the home owner for thousands of dollars. *Ceteris paribus*, wind farms should be constructed as far away from residential housing as possible [15].

The causes of the wind turbine impact on housing values are multifaceted. Issues such as noise, visual obstruction [13], shadow flicker, and even electromagnetic fields [118,119] can impact those living within close proximity to wind farms. These particular types of issues are even more evident to those living in the country side near wind farms [120], where manmade wind farms can interfere with the natural landscape aesthetics of rural communities [20]. Part of this is because houses located in the countryside are less accustomed to large manmade structures dominating the landscape than urban environments. The construction phase of wind farm development has also been found to cause significant detrimental effects on residential well-being [20]. The impact of wind turbines on housing values decreases as the distance from the turbines increases. Additionally, additional turbines in the wind farm increase the negative impact, although at a marginally declining rate for each additional turbine [15]. In order to better understand how wind turbines could impact housing value, it is important to comprehend the immense scale of modern wind turbines. Figure 6 provides a perspective for how wind farms can affect homeowners in a large proximity.

The overall effect of wind turbines on housing values is still highly controversial [13], but a closer look at the sources of the research helps to bring clarity to the subject. Wind energy associations report that there is no definitive causal connection between wind turbines and decreased housing values. The American Wind Energy Association reports that there are no studies to its knowledge that conclude that wind farms have a negative impact on housing values [122]. The Canadian Wind Energy Association commissioned a study by Canning and Simmons [123] that supported their position that there is no clear statistical proof that rural property values are negatively impacted by the presence of wind turbines [124]. Conversely, organizations that oppose wind energy development report that there is a strong relationship between wind energy and decreased housing values. National Wind Watch reports that the negative relationship between wind farms and housing values is indisputable [125]. Similarly, Wind Concerns Ontario [126] reports that there is a devaluation effect on local housing due to the presence of wind turbines. Certain papers have come to the conclusion that there is no causal relationship, or that the relationship is not statistically significant [55,127,128]. However, it is also important to note that a lack of statistical significance does not necessarily equate to no effect [13]. It is possible that individual houses or small numbers of houses could be affected negatively [128]. Research conducted by property appraisers has found that wind farms have a negative impact on housing values [129,130]. There are also credibility issues with regard to the methods used by certain studies that reported no impact [131]. Much of the debate comes down to the empirical methodology employed and the funding sources. This issue is extremely important to both wind energy developers and local homeowners.

During our review of the scientific literature, we did not find a consensus on this issue. This finding is supported by Gulden [13], who reports that there is still significant disagreement regarding the effect of wind farms on local housing values. We found studies that reported a significant decrease in house value [15,27,31,129,130,132], and studies that were inconclusive, or found no significant effect [55,127,128], but we did not find any studies that reported a significant increase in home value caused by wind farms. Proximity is a primary factor, and the radius for housing value impact is approximately 3 km [114]. Instead of continued debate on the topic, the interests of governments, homeowners, wind energy developers, and stakeholders may be better served by acknowledging that in some cases, property devaluations are inevitable and provide compensation to affected homeowners [13]. Fostering cooperation between local home owners and wind energy producers is more conducive to progress than continued debate on the topic of wind turbines and housing values.

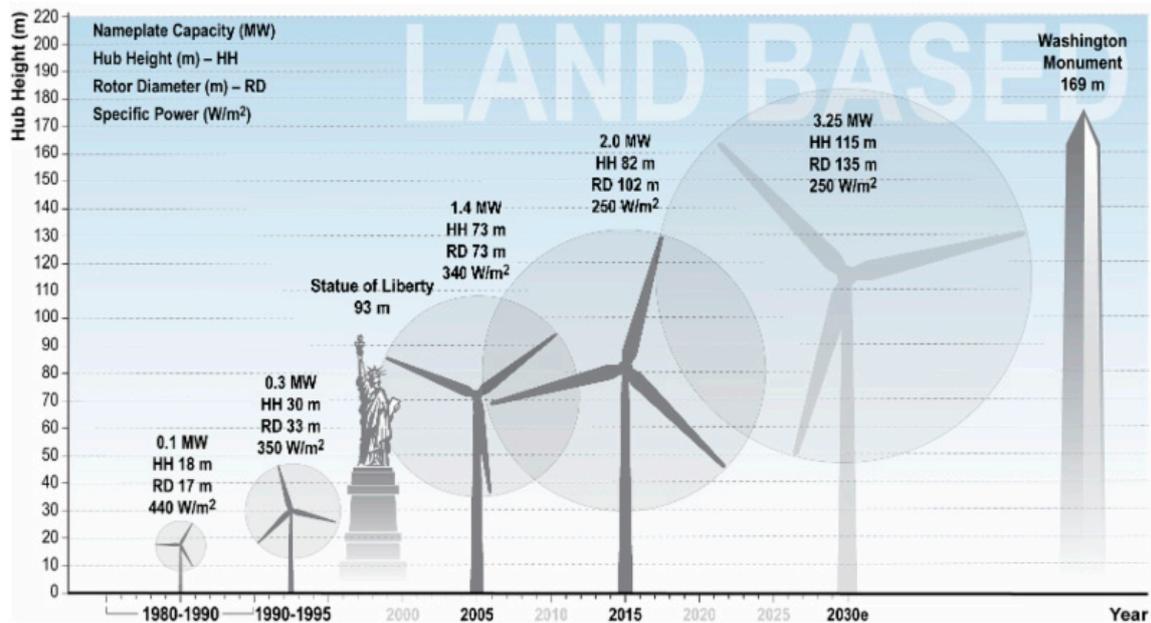


Figure 6. Wind turbine historical height and future projections. Source: Berkeley National Laboratory [121].

3.5. Summary of Results

The development of wind power is economically limited by the intermittency that is inherent to the technology [3,29,39,61]. This intermittency of wind energy leads to additional volatility in electricity markets [16,58]. Volatility of the electricity generated from wind turbines creates a scenario where fossil fuel backup power plants are required to ensure stable base load electricity supply [63,67]. This volatility of supply in the system leads to long term electricity market price increases. Electricity produced from wind energy is more expensive than electricity generated by traditional sources [3,17,75,84,85]. The cost increased is ultimately passed through to the consumer [53,63]. Considering the amount of tax payer dollars spent by governments on wind energy support programs, it is essential to quantify who receives the benefits and who bears the cost of wind energy development [54].

Wind energy can lead to growth in the “green jobs” industries, but these jobs come at the expense of jobs in competing energy sectors due to a crowding out effect [14]. Analysis has found that wind energy can lead to an increase in equilibrium unemployment [107], creating an overall slightly negative net employment balance [64]. On a local level, perhaps the most significant cause of concern over wind energy is the negative effect on housing values. This negative externality has been verified by several studies [15,27,31,129,130,132]. Creating cooperation between local home owners and wind energy developers is more conducive to progress than continued debate on the issue of wind turbines and housing values. We recommend that more research is conducted by teams of researchers with experts in the fields of both renewable energy and property appraisal to produce more comprehensive results. The primary results are displayed below in Table 1.

Table 1. Summary of results.

Section	Subsection	Key Sources	Central Findings
Introduction	Growth	AWEA (2019), Rand and Hoen (2017), Brown, et al. (2012)	<ul style="list-style-type: none"> •Majority of growth occurred since 2000 •China and India experiencing growth
	Economic Limitations	Otsuki (2017), Frondel, et al. (2014), El-Kordy, et al. (2002), Xia & Song (2017), Winkler, et al., 2016	<ul style="list-style-type: none"> •Can potentially divert funding from other forms of environmental protection •Requires government funding
Volatility	Intermediacy	Steggals, et al. (2011), Timilsina, et al. (2013), Twomey & Neuhoff (2010)	<ul style="list-style-type: none"> •Intermittent wind supply creates electricity market volatility
	Market Distortions	Chao (2011), Lesser (2013), Upton & Snyder (2017)	<ul style="list-style-type: none"> •Market volatility leads to long term price increase
	Policy and Subsidies	Palmer, et al. (2011), Westwood (2007), Lesser, (2013), Winkler, et al. (2016)	<ul style="list-style-type: none"> •Government incentives are a driving factor of growth
Increased Costs	Price of Electricity	Frondel, et al. (2015), Upton & Snyder (2017), Tobben (2017) Ghaith & Epplin (2017), Staffell & Green (2014)	<ul style="list-style-type: none"> •Increased price of energy •Potential regressive financial impact •Costs are passed to consumers
	Grid connection	Lofthouse et al. (2015), Green & Vasilakos (2010), Otsuki (2017)	<ul style="list-style-type: none"> •Significant costs often overlooked •Wind farms often in remote locations
Unemployment	Job Losses	Borenstein (2012), Rivers (2013) Meyer & Sommer (2016) Haerer & Preston (2015), Lobao et al. (2016) Roach (2015), Hartley et al. (2015)	<ul style="list-style-type: none"> •Crowding out effect •Net loss in employment •Gains not in same locations as losses •Coal mining regions hit hard •Retraining workforce is not simple
	Employment Gains	Blanco & Rodrigues (2009)	<ul style="list-style-type: none"> •Manufacturing encompasses the largest % of wind energy jobs
House Values	Housing Devaluation	Dröes, et al. (2014), Sunak & Madlener (2016), Jensen et al. (2014)	<ul style="list-style-type: none"> •Significant value losses ranging from 1.4%, 3–6%, 17%
	Negative Relationship	Kielisch (2009), McCann (2010), Canning et al. (2010)	<ul style="list-style-type: none"> •Significant relationship within 3 km

4. Discussion

4.1. Policy Implications

Wind power expansion has broad implications for energy legislators across the globe [62]. This research can better equip decision makers to create more optimal energy systems for their citizens. Extreme positions in absolute support of or in total opposition to wind energy are unhelpful. With increasing levels of environmental and socio-economic awareness, governments across the globe are reconsidering the pollution-related challenges that influence the energy paradigm [25]. Strategic energy policy is vital to the mitigation of negative externalities produced by fossil fuel electricity generation [133]. Wind energy is one option for CO₂ reduction, but in many cases, the externalities outweigh the benefits [75]. The technology faces many barriers that traditional fossil fuels do not [134]. Sustainable energy planning should consider the employment, housing value, volatility, and price impacts of wind energy.

Although wind energy has been increasing rapidly this century, the vast majority of electricity is still produced from fossil fuels. Fossil fuels produce approximately 80% of global energy supplies, and this percentage is not expected to change significantly if current trajectories hold [3]. Even though these traditional fuel sources still have a dominant market share in many countries, they still suffer from economic limitations. They also face issues such as a decreasing supply that renewables do not face. The increased volume of wind energy has to be measured against the rising population and standards of living statistics, which increase the demand for electricity. Elected officials should be realistic when planning for the energy future of their citizens. The current trends and technological limitations of wind energy dictate that as a society, we should not be overly optimistic about the ability of wind farms to overcome the need for fossil fuels [3]. The externalities discussed in this paper differ in impact from country to country. In certain locations, wind energy can be economically viable, based on factors such as resource supply and wind farm proximity to existing power grids. In other locations, wind energy is impractical. In these cases, wind energy development can divert capital and energy away from more effective means of environmental protection [135]. A balanced energy portfolio containing both wind power and other energy sources should be the goal for national energy policy to protect from volatility and supply distortions.

In many nations, it is now time to redesign government support strategies for renewable energy [136]. The amount of life cycle data have reached a point where developers and policy makers can clearly see the cost benefits analysis on a country by country basis across the globe. Considering the significant amount of public financial support going toward wind energy subsidization, it is important to understand who receives the benefits and who bears the costs [54]. This paper highlights the external impacts often overlooked by legislators.

4.2. Suggestions for Future Research

Although a significant amount of peer reviewed research papers has been published on the overall topic of wind energy, the field is expanding so rapidly [11,12] that the body of research needs to be updated frequently. Comprehensive analysis of the economic impacts of wind energy is still relatively minimal in the field. There are a number of areas where further research would prove beneficial.

Wind energy has the potential to create a regressive pricing impact [98], which is because of the higher price of wind energy compared to traditional fossil fuels [17,84,85], combined with the fact that households at the lower end of the economic spectrum feel a greater effect from higher electricity prices. These lower income households must devote a higher percentage of their total income to electricity bills. Econometric analysis of the price impact of wind energy is essential to clearly quantify the impact on lower income households. Currently research on this topic has been conducted in Germany, which has one of the most mature and extensive wind energy portfolios in the world. The country also pays the highest electricity rates in Europe [63]. Conducting research to quantify the impact of wind energy on lower income households would help to advance the cause of energy justice. Future studies should

be conducted in more countries to determine if the regressive impact is an international phenomenon. These studies would be of great importance to countries such as India and China because of their development of wind power and focus on raising the standards of living for their citizens.

The rural communities that produce wind energy are often located significant distances away from the urban centers that consume the electricity [8]. Although the energy is produced in these rural areas, they often do not receive the benefits of this production. Researchers can create studies that highlight the rural urban divide between the producers and consumers of wind energy and propose options to solve this inequality. Strategies for financially compensating rural communities where the turbines are located would advance economic justice, and potentially decrease local resistance to the development of wind farms. These research papers could highlight solutions that would benefit both wind farm builders and local residents.

Renewable energy resource potential varies significantly from country to country. Any energy policy that seeks to rely solely on wind energy would be unrealistic because of intermittency [3]. A diverse mix of energy resources to meet the electricity of the nation is essential [81]. In order to reduce climate change, a multifaceted energy strategy must be employed to best utilize the available resources of individual countries. Wind energy may be environmentally beneficial and economically feasible in some countries and not in others. A mixed method research employing empirical methodology should be applied to study panel datasets to determine the best renewable energy mix on an individual national level.

Comprehensive economic life cycle analysis is also a promising area of future research. A more in depth understanding of the life cycle of renewable energy technologies is essential [137]. The primary economic characteristics of wind energy are a heavy capital outlay at the beginning, low operating expenses over the life span of the turbine, and additional capital outlays for the decommissioning phase. Once operational, wind farms require minimal financial investment, but the upstream processes such as the extraction of raw materials, production of finished materials and components, transportation, and manufacturing as well as the downstream activities such as decommissioning require massive amounts of capital. In order to understand the entire assessment of economic performance, the entire life cycle of production from use to disposal has to be understood [138]. The decommissioning stage is where the blades are removed from the site and is recycled as much as possible [139]. Most of the total installed global wind energy capacity has been built this century, meaning that we are just now reaching the end of the decommissioning phase of many turbines. Building wind turbines in factories is a major undertaking. Accounting for the economic cost over the life cycle of the turbine is necessary to accurately compare the full expenses of wind energy to other sources of renewable energy such as hydro or solar. Economic life cycle analysis can also provide insight into the best options for renewable energy to match a country's financial profile.

Wind energy is promoted based on its environmental qualities as a way to reduce negative externalities from fossil fuels, but it is not completely free of negative impacts [38]. Wind energy creates negative externalities for birds [39,40], humans [24,41] bats [42,43] ground animals [44], habitats [45], and even aquatic environments in the case of offshore wind power [51,112]. Authors should conduct research comparing the environmental negative externalities of different forms of renewable energy sources from an international perspective to provide comprehensive analysis of which energy sources would provide the greatest environmental benefits in their location.

5. Conclusions

This paper provides a systematic literature review of the negative economic effects associated with the development of wind energy. We place these issues in context by providing international growth data and the basic wind production equation to explain the expansion of wind energy and the basic technical aspects of wind turbines. This study has limitations inherent to any structured literature review. It is impossible to collect and review all relevant wind energy externality literature, but we conducted a broad and detailed search to incorporate a large sample size of studies from top

international journals in order to minimize these limitations. Additionally, there are more than four economic effects produced by wind energy, however, this paper presents four major categories as sourced from the body of literature in the field. The large sample size of papers analyzed also serves to minimize bias. After collecting >400 articles for review, and screening and incorporating >120 of these studies as citations for this paper, we believe that we have accomplished our initial aim of providing a condensed overview of the negative externalities of wind energy.

As wind energy has expanded, the negative impacts have become more evident [13]. Our paper presents the primary negative externalities produced by wind energy according to the field of peer reviewed scientific research. The impact of wind energy is certainly not entirely negative and there are also significant positive externalities. We focused on the negative aspects to bring balance to the current literature. We recommend that policy makers also read positivist literature on the benefits of wind energy for a more holistic view of wind energy. An efficient electricity supply is essential to modern economies and is therefore fundamentally linked together with human development [140]. Electricity has a significant impact on the economy as a whole, therefore efficient energy production is necessary for the well-being of society [131]. Wind energy offers benefits in many ways, but the negative externalities must also be taken into account to produce effective energy policy.

Wind energy has a place in the future of energy development, but a more realistic approach must be implemented for economically sustainable growth that will produce the best outcomes for all parties. We acknowledge that in many cases, the costs of wind power exceed the benefits [66], and that the financial costs often make wind energy development economically inefficient [53], but balanced energy policy containing a mix of wind energy and other renewables can provide a sustainable energy future [81]. A realistic and pragmatic approach to wind energy development offers the best chance for optimal outcomes for all parties involved. The middle ground provides a chance for climate change mitigation policies that will be broadly accepted by society [141]. Wind energy can be helpful in certain communities, but in many situations, it can divert resources away from other more efficient sources of green energy [30]. The challenge is to develop an energy strategy that minimizes environmental negative externalities while providing financially feasible energy to citizens. By understanding the negative effects of wind energy on the surrounding areas, policy makers, engineers, and developers can develop better policy and wind energy technology. This will help create wind energy projects that are more economically efficient and environmentally sustainable for future generations.

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