International Journal of Modern Achievement in Science, Engineering and Technology (IJSET)
ISSN 3023-459X
DOI: 10.63053/ijset.44

Harnessing the Wind
How Wind Energy Fuels Economic Growth and Progress

Mohammadamin Yarahmadi[1], Pourya Zarshenas[2]

1. Tehran International School, Tehran, Iran
2. Assistant Professor, Ibn Sina University, Georgia,Vice President of the “A.C.Milligram” Intl. Scientific Institute – Switzerland,Universal Scientific Education and Research Network (USERN)

ARTICLE INFO

Keywords:
Wind Energy, Economic Development, Renewable Resources, Sustainability, Policy Analysis.

ABSTRACT

This comprehensive study delves into the intricate relationship between the utilization of wind energy and the economic development of nations around the world. By examining a diverse dataset that spans across various countries over the past two decades, we focus our analysis on several critical economic indicators. These indicators include, but are not limited to, gross domestic product (GDP) growth, employment rates within the renewable energy sectors, and patterns of energy consumption. Our findings reveal a notable positive correlation between the widespread adoption of wind energy technologies and sustainable economic growth, suggesting that countries harnessing wind energy are likely to experience enhanced economic performance. This relationship extends beyond mere statistical correlation; it underscores the vital importance of integrating renewable energy into national energy strategies. Furthermore, the research emphasizes the significant role played by government incentives and policy frameworks in fostering the growth of the wind energy sector. Through the provision of subsidies, tax breaks, and supportive legislation, governments can stimulate investment in renewable technologies, thereby propelling not only the energy sector but the broader economy as well. In addition to government support, our analysis also identifies technological advancements as a crucial factor in the successful deployment of wind energy systems. Innovations in turbine designs, energy storage solutions, and grid integration techniques contribute to the efficiency and reliability of wind energy, making it an increasingly viable option for meeting growing energy demands. Public awareness and education about the benefits of wind energy further amplify its impact on economic development. By fostering a societal understanding of renewable energy, countries can cultivate a culture that prioritizes sustainable practices, leading to increased acceptance and investment in wind technologies. Through our extensive research and analysis, we aim to contribute valuable insights to the ongoing discourse surrounding sustainable development and the integration of renewable energy sources within national economies. The implications of our findings are crucial for policymakers, investors, and stakeholders who are dedicated to promoting wind energy not only as an environmentally friendly alternative but also as a formidable driver of economic growth. In summary, this study reinforces the message that wind energy is not just a means to combat climate change; it is also a vital pathway to achieving sustainable economic development on a global scale.

Introduction

Renewable energy is energy that is collected from renewable resources that are naturally replenished on a human timescale. It includes sources such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy stands in contrast to fossil fuels, which are being used far more quickly than they are being replenished. Although most renewable energy sources are sustainable, some are not. For example, some biomass sources are considered unsustainable at current rates of exploitation. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services. About 20% of humans' global energy consumption is renewables, including almost 30% of electricity. About 8% of energy consumption is traditional biomass, but this is declining. Over 4% of energy consumption is heat energy from modern renewables, such as solar water heating, and over 6% electricity. Globally there are over 10 million jobs associated with the renewable energy industries, with solar photovoltaics being the largest renewable employer. Renewable energy systems are rapidly becoming more efficient and cheaper and their share of total energy consumption is increasing, with a large majority of worldwide newly installed electricity capacity being renewable. In most countries, photovoltaic solar or onshore wind are the cheapest new-build electricity. Many nations around the world already have renewable energy contributing more than 20% of their energy supply, with some generating over half their electricity from renewables. National renewable energy markets are projected to continue to grow strongly in the 2020s and beyond. A few countries generate all their electricity using renewable energy. Renewable energy resources exist over wide geographical areas, in contrast to fossil fuels, which are concentrated in a limited number of countries. Deployment of renewable energy and energy efficiency technologies is resulting in significant energy security, climate change mitigation, and economic benefits. However renewables are being hindered by hundreds of billions of dollars of fossil fuel subsidies. In international public opinion surveys there is strong support for promoting renewable sources such as solar power and wind power.

Renewable energy technology projects are typically large-scale, but they are also suited to rural and remote areas and developing countries, where energy is often crucial in human development. As most of the renewable energy technologies provide electricity, renewable energy is often deployed together with further electrification, which has several benefits: electricity can be converted to heat, can be converted into mechanical energy with high efficiency, and is clean at the point of consumption. In addition, electrification with renewable energy is more efficient and therefore leads to significant reductions in primary energy requirements. In 2021, China accounted for almost half of the increase in renewable electricity. In 2021, Norway, known for its production of hydroelectricity, consumed hydro energy worth 45% of its total energy supply. Renewable power is booming, as innovation brings down costs and starts to deliver on the promise of a clean energy future. American solar and wind generation are breaking records and being integrated into the national electricity grid without compromising reliability. This means that renewables are increasingly displacing “dirty” fossil fuels in the power sector, offering the benefit of lower emissions of carbon and other types of pollution. But not all sources of energy marketed as “renewable” are beneficial to the environment. Biomass and large hydroelectric dams create difficult tradeoffs when considering the impact on wildlife, climate change, and other issues. Here’s what you should know about the different types of renewable energy sources and how you can use these emerging technologies at your own home.

What Is Renewable Energy?

Renewable energy, often referred to as clean energy, comes from natural sources or processes that are constantly replenished. For example, sunlight or wind keep shining and blowing, even if their availability depends on time and weather. While renewable energy is often thought of as a new technology, harnessing nature’s power has long been used for heating, transportation, lighting, and more. Wind has powered boats to sail the seas and windmills to grind grain. The sun has provided warmth during the day and helped kindle fires to last into the evening. But over the past 500 years or so, humans increasingly turned to cheaper, dirtier energy sources such as coal and fracked gas. Now that we have increasingly innovative and less-expensive ways to capture and retain wind and solar energy, renewables are becoming a more important power source, accounting for more than one-eighth of U.S. generation. The expansion in renewables is also happening at scales large and small, from rooftop solar panels on homes that can sell power back to the grid to giant offshore wind farms. Even some entire rural communities rely on renewable energy for heating and lighting. As renewable use continues to grow, a key goal will be to modernize America's electricity grid, making it smarter, more secure, and better integrated across regions.

Dirty energy

Nonrenewable, or "dirty," energy includes fossil fuels such as oil, gas, and coal. Nonrenewable sources of energy are only available in limited amounts and take a long time to replenish. When we pump gas at the station, we're using a finite resource refined from crude oil that's been around since prehistoric times. Nonrenewable energy sources are also typically found in specific parts of the world, making them more plentiful in some nations than others. By contrast, every country has access to sunshine and wind. Prioritizing nonrenewable energy can also improve national security by reducing a country's reliance on exports from fossil fuel–rich nations. Many nonrenewable energy sources can endanger the environment or human health. For example, oil drilling might require strip-mining Canada's boreal forest, the technology associated with fracking can cause earthquakes and water pollution, and coal power plants foul the air. To top it off, all these activities contribute to global warming.

Overview

Coal, oil, and natural gas remain the primary global energy sources even as renewables have begun rapidly increasing. Planet Solar, the world's largest solar-powered boat and the first ever solar electric vehicle to circumnavigate the globe (in 2012). Renewable energy flows involve natural phenomena such as sunlight, wind, tides, plant growth, and geothermal heat, as the International Energy Agency explains: Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources. Renewable energy resources and significant opportunities for energy efficiency exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries. Rapid deployment of renewable energy and energy efficiency, and technological diversification of energy sources, would result in significant energy security and economic benefits. It would also reduce environmental pollution such as air pollution caused by the burning of fossil fuels, and improve public health, reduce premature mortalities due to pollution and save associated health costs that could amount to trillions of dollars annually. Multiple analyses of de-carbonization strategies have found that quantified health benefits can significantly offset the costs of implementing these strategies. Renewable energy sources, that derive their energy from the sun, either directly or indirectly, such as hydro and wind, are expected to be capable of supplying humanity energy for almost another 1 billion years, at which point the predicted increase in heat from the Sun is expected to make the surface of the Earth too hot for liquid water to exist. Climate change and global warming concerns, coupled with the continuing fall in the costs of some renewable energy equipment, such as wind turbines and solar panels, are driving increased use of renewables. New government spending, regulation and policies helped the industry weather the global financial crisis better than many other sectors. As of 2019, however, according to the International Renewable Energy Agency, renewables overall share in the energy mix (including power, heat and transport) needs to grow six times faster, in order to keep the rise in average global temperatures "well below" 2.0 °C (3.6 °F) during the present century, compared to pre-industrial levels. As of 2011, small solar PV systems provide electricity to a few million households, and micro-hydro configured into mini-grids serves many more.[needs update] Over 44 million households use biogas made in household-scale digesters for lighting and/or cooking, and more than

166 million households rely on a new generation of more-efficient biomass cook stoves. United Nations' eighth Secretary-General Ban Ki-moon has said that renewable energy has the ability to lift the poorest nations to new levels of prosperity. At the national level, at least 30 nations around the world already have renewable energy contributing more than 20% of energy supply. National renewable energy markets are projected to continue to grow strongly in the coming decade and beyond, and some 120 countries have various policy targets for longer-term shares of renewable energy, including a 20% target of all electricity generated for the European Union by 2020.[needs update] Some countries have much higher long-term policy targets of up to 100% renewables. Outside Europe, a diverse group of 20 or more other countries targets renewable energy shares in the 2020–2030 time frame that range from 10% to 50%. Renewable energy often displaces conventional fuels in four areas: electricity generation, hot water/space heating, transportation, and rural (off-grid) energy services:

- ✓ **Power generation**

By 2040, renewable energy is projected to equal coal and natural gas electricity generation. Several jurisdictions, including Denmark, Germany, the state of South Australia and some US states have achieved high integration of variable renewables. For example, in 2015 wind power met 42% of electricity demand in Denmark, 23.2% in Portugal and 15.5% in Uruguay. Interconnectors enable countries to balance electricity systems by allowing the import and export of renewable energy. Innovative hybrid systems have emerged between countries and regions.

- ✓ **Heating**

Solar water heating makes an important contribution to renewable heat in many countries, most notably in China, which now has 70% of the global total (180 GWth). Most of these systems are installed on multi-family apartment buildings and meet a portion of the hot water needs of an estimated 50–60 million households in China. Worldwide, total installed solar water heating systems meet a portion of the water heating needs of over 70 million households. The use of biomass for heating continues to grow as well. In Sweden, national use of biomass energy has surpassed that of oil. Direct geothermal for heating is also growing rapidly. The newest addition to heating is from geothermal heat pumps which provide both heating and cooling, and also flatten the electric demand curve and are thus an increasing national priority.

- ✓ **Transportation**

Bioethanol is an alcohol made by fermentation, mostly from carbohydrates produced in sugar or starch crops such as corn, sugarcane, or sweet sorghum. Cellulosic biomass, derived from non-food sources such as trees and grasses is also being developed as a feedstock for ethanol production. Ethanol can be used as a fuel for vehicles in its pure form, but it is usually used as a gasoline additive to increase octane and improve vehicle emissions. Bioethanol is widely used in the USA and in Brazil. Biodiesel can be used as a fuel for vehicles in its pure form, but it is usually used as a diesel additive to reduce levels of particulates, carbon monoxide, and hydrocarbons from diesel-powered vehicles. Biodiesel is produced from oils or fats using trans-esterification and is the most common biofuel in Europe. A solar vehicle is an electric vehicle powered completely or significantly by direct solar energy. Usually, photovoltaic (PV) cells contained in solar panels convert the sun's energy directly into electric energy. The term "solar vehicle" usually implies that solar energy is used to power all or part of a vehicle's propulsion. Solar power may be also used to provide power for communications or controls or other auxiliary functions. Solar vehicles are not sold as practical day-to-day transportation devices at present but are primarily demonstration vehicles and engineering exercises, often sponsored by government agencies. High-profile examples include Planet Solar and Solar Impulse. However, indirectly solar-charged vehicles are widespread and solar boats are available commercially.

History

Prior to the development of coal in the mid-19th century, nearly all energy used was renewable. The oldest known use of renewable energy, in the form of traditional biomass to fuel fires, dates from more than a million years ago. The use of biomass for fire did not become commonplace until many hundreds of thousands of years later. Probably the second oldest usage of renewable energy is harnessing the wind in order to drive ships over water. This practice can be traced back some 7000 years, to ships in the Persian Gulf and on the Nile. From hot springs, geothermal energy has been used for bathing since Paleolithic times and for space heating since ancient Roman times. Moving into the time of recorded history, the primary sources of traditional renewable energy were human labor, animal power, water power, and wind, in grain crushing windmills, and firewood, a traditional biomass. In the 1860s and 1870s, there were already fears that civilization would run out of fossil fuels and the need was felt for a better source. In 1873 Augustin Mouchot wrote: The time will arrive when the industry of Europe will cease to find those natural resources, so necessary for it. Petroleum springs and coal mines are not inexhaustible but are rapidly diminishing in many places. Will man, then, return to the power of water and wind? Or will he emigrate where the most powerful source of heat sends its rays to all? History will show what will come. In 1885, Werner von Siemens, commenting on the discovery of the photovoltaic effect in the solid state, wrote:

In conclusion, I would say that however great the scientific importance of this discovery may be, its practical value will be no less obvious when we reflect that the supply of solar energy is both without limit and without cost, and that it will continue to pour down upon us for countless ages after all the coal deposits of the earth have been exhausted and forgotten.

Max Weber mentioned the end of fossil fuel in the concluding paragraphs of his Die protestantische Ethik und der Geist des Kapitalismus (The Protestant Ethic and the Spirit of Capitalism), published in 1905. Development of solar engines continued until the outbreak of World War I. The importance of solar energy was recognized in a 1911 Scientific American article: "in the far distant future, natural fuels having been exhausted [solar power] will remain as the only means of existence of the human race". The theory of peak oil was published in 1956. In the 1970s environmentalists promoted the development of renewable energy both as a replacement for the eventual depletion of oil, as well as for an escape from dependence on oil, and the first electricity-generating wind turbines appeared. Solar had long been used for heating and cooling, but solar panels were too costly to build solar farms until 1980. Since the 21st century, many parts of the world have transitioned to sources of renewable energy from fossil fuels.

What is zero-carbon or low-carbon energy?

Nuclear-generated electricity isn't renewable but its zero-carbon, which means its generation emits low levels or almost no CO_2, just like renewable energy sources. Nuclear energy has a stable source, which means it's not dependent on the weather and will play a big part in getting Britain to net zero status.

1. Solar energy
2. Wind energy
3. Hydro energy
4. Geothermal energy
5. Biomass energy

Wind power

Wind power or wind energy is the use of wind turbines to generate electricity. Wind power is a popular, sustainable, renewable energy source that has a much smaller impact on the environment than burning fossil fuels. Wind farms consist of many individual wind turbines, which are connected to the electric power transmission network. In 2020, wind supplied almost 1600 TWh of electricity, which was over 5% of worldwide electrical generation and about 2% of energy consumption. With over 100 GW added during 2020, mostly in China, global installed wind power capacity reached more than 730 GW. To help meet the Paris Agreement goals to limit climate change, analysts say it should expand much faster - by over 1% of electricity generation per year. New onshore (on-land) wind farms are cheaper than new coal or gas plants, but expansion of wind power is being hindered by fossil fuel subsidies. Onshore wind farms have a greater visual impact on the landscape than other power stations, as they need to be spread over more land and need to be built in rural areas. Small onshore wind farms can feed some energy into the grid or provide power to isolated off-grid locations. Offshore wind farms provide a steadier and stronger source of energy and have less visual impact. Although there is less offshore wind power at present and construction and maintenance costs are higher, it is expanding. Wind power is variable renewable energy, so power-management techniques are used to match supply and demand, such as: wind hybrid power systems, hydroelectric power or other dispatchable power sources, excess capacity, geographically distributed turbines, exporting and importing power to neighboring areas, or grid storage. As the proportion of wind power in a region increases the grid may need to be upgraded. Weather forecasting allows the electric-power network to be readied for the predictable variations in production that occur.

Wind energy

Wind power in an open air stream is thus proportional to the third power of the wind speed; the available power increases eightfold when the wind speed doubles. Wind turbines for grid electric power, therefore, need to be especially efficient at greater wind speeds. Wind is the movement of air across the surface of the Earth, driven by areas of high and low pressure. The global wind kinetic energy averaged approximately 1.50 MJ/m^2 over the period from 1979 to 2010, 1.31 MJ/m^2 in the Northern Hemisphere with 1.70 MJ/m^2 in the Southern Hemisphere. The atmosphere acts as a thermal engine, absorbing heat at higher temperatures, releasing heat at lower temperatures. The process is responsible for the production of wind kinetic energy at a rate of 2.46 W/m^2 thus sustaining the circulation of the atmosphere against friction. Through wind resource assessment it is possible to estimate wind power potential globally, by country or region, or for a specific site. The Global Wind Atlas provided by the Technical University of Denmark in partnership with the World Bank provides a global assessment of wind power potential. Unlike 'static' wind resource atlases which average estimates of wind speed and power density across multiple years, tools such as Renewables. Ninja provide time-varying simulations of wind speed and power output from different wind turbine models at an hourly resolution. More detailed, site-specific assessments of wind resource potential can be obtained from specialist commercial providers, and many of the larger wind developers have in-house modeling capabilities. The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. The strength of wind varies, and an average value for a given location does not alone indicate the amount of energy a wind turbine could produce there. To assess prospective wind power sites a probability distribution function is often fit to the observed wind speed data. Different locations will have different wind speed distributions. The Weibull model closely mirrors the actual distribution of hourly/ten-minute wind speeds at many locations. The Weibull factor is often close to 2 and therefore a Rayleigh distribution can be used as a less accurate, but simpler model.

Wind farm

Wind farm is a group of wind turbines in the same location. A large wind farm may consist of several hundred individual wind turbines distributed over an extended area. The land between the turbines may be used for agricultural or other purposes. For example, Gansu Wind Farm, the largest wind farm in the world, has several thousand turbines. A wind farm may also be located offshore. Almost all large wind turbines have the same design — a horizontal axis wind turbine having an upwind rotor with 3 blades, attached to a nacelle on top of a tall tubular tower. In a wind farm, individual turbines are interconnected with a medium voltage (often 34.5 kV) power collection system and communications network. In general, a distance of 7D (7 times the rotor diameter of the wind turbine) is set between each turbine in a fully developed wind farm. At a substation, this medium-voltage electric current is increased in voltage with a transformer for connection to the high voltage electric power transmission system.

Generator characteristics and stability

Induction generators, which were often used for wind power projects in the 1980s and 1990s, require reactive power for excitation, so electrical substations used in wind-power collection systems include substantial capacitor banks for power factor correction. Different types of wind turbine generators behave differently during transmission grid disturbances, so extensive modeling of the dynamic electromechanical characteristics of a new wind farm is required by transmission system operators to ensure predictable stable behavior during system faults. In particular, induction generators cannot support the system voltage during faults, unlike steam or hydro turbine-driven synchronous generators. Induction generators are not used in current turbines. Instead, most turbines use variable speed generators combined with either a partial or full-scale power converter between the turbine generator and the collector system, which generally have more desirable properties for grid interconnection and have low voltage ride through-capabilities. Modern turbines use either doubly fed electric machines with partial-scale converters or squirrel-cage induction generators or synchronous generators (both permanently and electrically excited) with full-scale converters. Transmission systems operators will supply a wind farm developer with a grid code to specify the requirements for interconnection to the transmission grid. This will include the power factor, the constancy of frequency, and the dynamic behavior of the wind farm turbines during a system fault. The world's second full-scale floating wind turbine (and first to be installed without the use of heavy-lift vessels), WindFloat, operating at rated capacity (2 MW) approximately 5 km offshore of Póvoa de Varzim, Portugal. Offshore wind power is wind farms in large bodies of water, usually the sea. These installations can utilize the more frequent and powerful winds that are available in these locations and have less visual impact on the landscape than land-based projects. However, the construction and maintenance costs are considerably higher. Siemens and Vestas are the leading turbine suppliers for offshore wind power. Ørsted, Vattenfall, and E.ON are the leading offshore operators. As of November 2021, the Hornsea Wind Farm in the United Kingdom is the largest offshore wind farm in the world at 1,218 MW.

Collection and transmission network

In a wind farm, individual turbines are interconnected with a medium voltage (usually 34.5 kV) power collection system and communications network. At a substation, this medium-voltage electric current is increased in voltage with a transformer for connection to the high voltage electric power transmission system. A transmission line is required to bring the generated power to (often remote) markets. For an offshore station, this may require a submarine cable. Construction of a new high voltage line may be too costly for the wind resource alone, but wind sites may take advantage of lines already installed for conventional fuel generation.Wind power resources are not always located near to high population density. As transmission lines become longer the losses associated with power transmission increase, as modes of losses at lower lengths are exacerbated and new modes of losses are no longer negligible as the length is increased, making it harder to transport large loads over large distances. When the transmission capacity does not meet the generation capacity, wind farms are forced to produce below their full potential or stop running altogether, in a process known as curtailment. While this leads to potential renewable generation left untapped, it prevents possible grid overload or risk to reliable service. One of the biggest current challenges to wind power grid integration in some countries is the necessity of developing new transmission lines to carry power from wind farms, usually in remote lowly populated areas due to availability of wind, to high load locations, usually on the coasts where population density is higher. Any existing transmission lines in remote locations may not have been designed for the transport of large amounts of energy. In particular geographic regions, peak wind speeds may not coincide with peak demand for electrical power, whether offshore or onshore. A possible future option may be to interconnect widely dispersed geographic areas with an HVDC super grid.

Wind power capacity and production

In 2020, wind supplied almost 1600 TWh of electricity, which was over 5% of worldwide electrical generation and about 2% of energy consumption. With over 100 GW added during 2020, mostly in

China, global installed wind power capacity reached more than 730 GW. But to help meet Paris Agreement goals to limit climate change analysts say it should expand much faster by over 1% of electricity generation per year. Expansion of wind power is being hindered by fossil fuel subsidies. The actual amount of electric power that wind can generate is calculated by multiplying the nameplate capacity by the capacity factor, which varies according to equipment and location. Estimates of the capacity factors for wind installations are in the range of 35% to 44%.Capacity factor since wind speed is not constant, a wind farm's annual energy production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. The ratio of actual productivity in a year to this theoretical maximum is called the capacity factor. Online data is available for some locations, and the capacity factor can be calculated from the yearly output. For example, the German nationwide average wind power capacity factor overall of 2012 was just under 17.5% (45,867 GW·h/yr / (29.9 GW × 24 × 366) = 0.1746) and the capacity factor for Scottish wind farms averaged 24% between 2008 and 2010. Unlike fueled generating plants, the capacity factor is affected by several parameters, including the variability of the wind at the site and the size of the generator relative to the turbine's swept area. A small generator would be cheaper and achieve a higher capacity factor but would produce less electric power (and thus less profit) in high winds. Conversely, a large generator would cost more but generate little extra power and, depending on the type, may stall out at low wind speed. Thus an optimum capacity factor of around 40–50% would be aimed for. Wind energy penetration is the fraction of energy produced by wind compared with the total generation. Wind power's share of worldwide electricity usage in 2021 was almost 7%, up from 3.5% in 2015. There is no generally accepted maximum level of wind penetration. The limit for a particular grid will depend on the existing generating plants, pricing mechanisms, capacity for energy storage, demand management, and other factors. An interconnected electric power grid will already include reserve generating and transmission capacity to allow for equipment failures. This reserve capacity can also serve to compensate for the varying power generation produced by wind stations. Studies have indicated that 20% of the total annual electrical energy consumption may be incorporated with minimal difficulty. These studies have been for locations with geographically dispersed wind farms, some degree of dispatchable energy or hydropower with storage capacity, demand management, and interconnected to a large grid area enabling the export of electric power when needed. Beyond the 20% level, there are few technical limits, but the economic implications become more significant. Electrical utilities continue to study the effects of large-scale penetration of wind generation on system stability and economics. A wind energy penetration figure can be specified for different duration of time but is often quoted annually. To obtain 100% from wind annually requires substantial long-term storage or substantial interconnection to other systems that may already have substantial storage. On a monthly, weekly, daily, or hourly basis -or less- wind might supply as much as or more than 100% of current use, with the rest stored, exported or curtailed. The seasonal industry might then take advantage of high wind and low usage times such as at night when wind output can exceed normal demand. Such industry might include the production of silicon, aluminum, steel, or natural gas, and hydrogen, and using future long-term storage to facilitate 100% energy from variable renewable energy. Homes can also be programmed to accept extra electric power on demand, for example by remotely turning up water heater thermostats.

Variability

Wind power is variable, and during low wind periods, it must be replaced by other power sources. Transmission networks presently cope with outages of other generation plants and daily changes in electrical demand, but the variability of intermittent power sources such as wind power is more frequent than those of conventional power generation plants which, when scheduled to be operating, may be able to deliver their nameplate capacity around 95% of the time. Electric power generated from wind power can be highly variable at several different timescales: hourly, daily, or seasonally. Annual variation also exists but is not as significant. Because instantaneous electrical generation and consumption must remain in balance to maintain grid stability, this variability can present substantial challenges to incorporating large amounts of wind power into a grid system.

Intermittency and the non-dispatchable nature of wind energy production can raise costs for regulation, incremental operating reserve, and (at high penetration levels) could require an increase in the already existing energy demand management, load shedding, storage solutions, or system interconnection with HVDC cables. Fluctuations in load and allowance for the failure of large fossil-fuel generating units require operating reserve capacity, which can be increased to compensate for the variability of wind generation. Presently, grid systems with large wind penetration require a small increase in the frequency of usage of natural gas spinning reserve power plants to prevent a loss of electric power if there is no wind. At low wind power penetration, this is less of an issue. Utility-scale batteries are often used to balance hourly and shorter timescale variation, but car batteries may gain ground from the mid-2020s. Wind power advocates argue that periods of low wind can be dealt with by simply restarting existing power stations that have been held in readiness, or interlinking with HVDC. Electrical grids with slow-responding thermal power plants and without ties to networks with hydroelectric generation may have to limit the use of wind power. Conversely, on particularly windy days, even with penetration levels of 16%, wind power generation can surpass all other electric power sources in a country. In Denmark, which had a power market penetration of 30% in 2013, over 90 hours, wind power generated 100% of the country's power, peaking at 122% of the country's demand at 2 am on 28 October. The combination of diversifying variable renewables by type and location, forecasting their variation, and integrating them with dispatchable renewables, flexible fueled generators, and demand response can create a power system that has the potential to meet power supply needs reliably. Integrating ever-higher levels of renewables is being successfully demonstrated in the real world: In 2009, eight American and three European authorities, writing in the leading electrical engineers' professional journal, didn't find "a credible and firm technical limit to the amount of wind energy that can be accommodated by electric power grids". In fact, not one of more than 200 international studies, nor official studies for the eastern and western U.S. regions, nor the International Energy Agency, has found major costs or technical barriers to reliably integrating up to 30% variable renewable supplies into the grid, and in some studies much more.

Seasonal cycle of capacity factors for wind and photovoltaics in Europe under idealized assumptions. The figure illustrates the balancing effects of wind and solar energy at the seasonal scale (Kaspar et al., 2019). Solar power tends to be complementary to wind. On daily to weekly timescales, high-pressure areas tend to bring clear skies and low surface winds, whereas low-pressure areas tend to be windier and cloudier. On seasonal timescales, solar energy peaks in summer, whereas in many areas wind energy is lower in summer and higher in winter. Thus the seasonal variation of wind and solar power tend to cancel each other somewhat. Wind hybrid power systems are becoming more popular.

Predictability

Wind power forecasting methods are used, but the predictability of any particular wind farm is low for short-term operation. For any particular generator, there is an 80% chance that wind output will change less than 10% in an hour and a 40% chance that it will change 10% or more in 5 hours. In summer 2021 wind power in the United Kingdom fell due to the lowest winds in seventy years-smoothing peaks by producing hydrogen may help in future when wind has a larger share of generation. While the output from a single turbine can vary greatly and rapidly as local wind speeds vary, as more turbines are connected over larger and larger areas the average power output becomes less variable and more predictable. Weather forecasting permits the electric-power network to be readied for the predictable variations in production that occur. Wind power hardly ever suffers major technical failures, since failures of individual wind turbines have hardly any effect on overall power, so that the distributed wind power is reliable and predictable, whereas conventional generators, while far less variable, can suffer major unpredictable outages.

Energy storage

Typically, conventional hydroelectricity complements wind power very well. When the wind is blowing strongly, nearby hydroelectric stations can temporarily hold back their water. When the wind drops they can, provided they have the generation capacity, rapidly increase production to compensate. This gives a very even overall power supply and virtually no loss of energy and uses no more water. Alternatively, where a suitable head of water is not available, pumped-storage hydroelectricity or other forms of grid energy storage such as compressed air energy storage and thermal energy storage can store energy developed by high-wind periods and release it when needed. The type of storage needed depends on the wind penetration level -low penetration requires daily storage, and high penetration requires both short- and long-term storage – as long as a month or more. Stored energy increases the economic value of wind energy since it can be shifted to displace higher-cost generation during peak demand periods. The potential revenue from this arbitrage can offset the cost and losses of storage. Although pumped-storage power systems are only about 75% efficient, and have high installation costs, their low running costs and ability to reduce the required electrical base-load can save both fuel and total electrical generation costs.

Fuel savings and energy payback

According to the American Wind Energy Association, production of wind power in the United States in 2015 avoided consumption of 280 million cubic meters (73 billion US gallons) of water and reduced CO_2 emissions by 132 million meteric tons, while providing US$ 7.3 billion in public health savings. The energy needed to build a wind farm divided into the total output over its life, Energy Return on Energy Invested, of wind power varies but averages about 20–25. Thus, the energy payback time is typically around a year.

Economics

Onshore wind cost per kilowatt-hour between 1983 and 2017. Onshore wind is an inexpensive source of electric power, cheaper than coal plants and new gas plants. According to Business Green, wind turbines reached grid parity (the point at which the cost of wind power matches traditional sources) in some areas of Europe in the mid-2000s, and in the US around the same time. Falling prices continue to drive the Levelized cost down and it has been suggested that it has reached general grid parity in Europe in 2010, and will reach the same point in the US around 2016 due to an expected reduction in capital costs of about 12%. In 2021 the CEO of Siemens Gamesa warned that increased demand for low-cost wind turbines combined with high input costs and high costs of steel result in increased pressure on the manufacturers and decreasing profit margins.

Electric power cost and trends

A turbine blade convoy passing through Edenfield in the U.K. (2008). Even longer 2-piece blades are now manufactured, and then assembled on-site to reduce difficulties in transportation. Wind power is capital intensive but has no fuel costs. The price of wind power is therefore much more stable than the volatile prices of fossil fuel sources. However, the estimated average cost per unit of electric power must incorporate the cost of construction of the turbine and transmission facilities, borrowed funds, return to investors (including the cost of risk), estimated annual production, and other components, and averaged over the projected useful life of the equipment, which may be more than 20 years. Energy cost estimates are highly dependent on these assumptions so published cost figures can differ substantially. The presence of wind energy, even when subsidized, can reduce costs for consumers (€5 billion/year in Germany) by reducing the marginal price, by minimizing the use of expensive peaking power plants. The cost has decreased as wind turbine technology has improved. There are now longer and lighter wind turbine blades, improvements in turbine performance, and increased power generation efficiency. Also, wind project capital expenditure costs and maintenance costs have continued to decline. In 2021 at Lazard study of unsubsidized electricity said that wind power levelized cost of electricity continues to fall but more slowly than before. The study estimated new wind-generated electricity cost from $26 to $50/MWh, compared to new gas power from $45 to $74/MWh. The median cost of fully depreciated existing coal power was $42/MWh, nuclear $29/MWh and gas $24/MWh. The study estimated offshore wind at around $83/MWh. Compound annual growth rate was 4% per year from 2016 to 2021, compared to 10% per year from 2009 to 2021.

Incentives and community benefits

Turbine prices have fallen significantly in recent years due to tougher competitive conditions such as the increased use of energy auctions, and the elimination of subsidies in many markets. As of 2021 subsidies are still often given to offshore wind. But they are generally no longer necessary for onshore wind in countries with even a very low carbon price such as China, provided there are no competing fossil fuel subsidies. Secondary market forces provide incentives for businesses to use wind-generated power, even if there is a premium price for the electricity. For example, socially responsible manufacturers pay utility companies a premium that goes to subsidize and build new wind power infrastructure. Companies use wind-generated power, and in return, they can claim that they are undertaking strong "green" efforts. Wind projects provide local taxes, or payments in place of taxes and strengthen the economy of rural communities by providing income to farmers with wind turbines on their land.

Small-scale wind power

A small Quietrevolution QR5 Gorlov type vertical axis wind turbine on the roof of Colston Hall in Bristol, England. Measuring 3 m in diameter and 5 m high, it has a nameplate rating of 6.5 kW. Small-scale wind power is the name given to wind generation systems with the capacity to produce up to 50 kW of electrical power. Isolated communities that may otherwise rely on diesel generators may use wind turbines as an alternative. Individuals may purchase these systems to reduce or eliminate their dependence on grid electric power for economic reasons, or to reduce their carbon footprint. Wind turbines have been used for household electric power generation in conjunction with battery storage over many decades in remote areas. Examples of small-scale wind power projects in an urban setting can be found in New York City, where, since 2009, several building projects have capped their roofs with Gorlov-type helical wind turbines. Although the energy they generate is small compared to the buildings' overall consumption, they help to reinforce the building's 'green' credentials in ways that "showing people your high-tech boiler" cannot, with some of the projects also receiving the direct support of the New York State Energy Research and Development Authority.Grid-connected domestic wind turbines may use grid energy storage, thus replacing purchased electric power with locally produced power when available. The surplus power produced by domestic microgenerators can, in some jurisdictions, be fed into the network and sold to the utility company, producing a retail credit for the microgenerators' owners to offset their energy costs. Off-grid system users can either adapt to intermittent power or use batteries, photovoltaic, or diesel systems to supplement the wind turbine. Equipment such as parking meters, traffic warning signs, street lighting, or wireless Internet gateways may be powered by a small wind turbine, possibly combined with a photovoltaic system, which charges a small battery replacing the need for a connection to the power grid. Distributed generation from renewable resources is increasing as a consequence of the increased awareness of climate change. The electronic interfaces required to connect renewable generation units with the utility system can include additional functions, such as active filtering to enhance the power quality.

Impact on environment and landscape

The environmental impact of wind power is minor compared to that of fossil fuels. According to the IPCC, in assessments of the life-cycle greenhouse-gas emissions of energy sources, wind turbines have a median value of 12 and 11 (gCO_2eq/kWh) for offshore and onshore turbines, respectively. Compared with other low carbon power sources, wind turbines have some of the lowest global warming potential per unit of electricity generated. Onshore (on-land) wind farms can have a significant visual impact and impact on the landscape. Due to a very low surface power density and spacing requirements, wind farms typically need to be spread over more land than other power stations. Their network of turbines, access roads, transmission lines, and substations can result in "energy sprawl"; although land between the turbines and roads can still be used for agriculture. They also need to be built away from urban areas, which can lead to "industrialization of the countryside". Some wind farms are opposed for potentially spoiling protected scenic areas, archaeological landscapes and heritage sites. A report by the Mountaineering Council of Scotland concluded that wind farms harmed tourism in areas known for natural landscapes and panoramic views. Habitat loss and fragmentation are the greatest potential impacts on wildlife of onshore wind farms. But the worldwide ecological impact is minimal. Wind farm construction near wetlands has been linked to several bog landslides in Ireland that have polluted rivers, such as at Derrybrien (2003) and Meenbog (2020).Such incidents could be prevented with stricter planning procedures and siting guidelines. Thousands of birds and bats, including rare species, have been killed by wind turbine blades, though wind turbines are responsible for far fewer bird deaths than fossil-fueled power stations. This can be mitigated with proper wildlife monitoring. Many wind turbine blades are made of fiberglass and only have a lifetime of 10 to 20 years. Previously, there was no market for recycling these old blades, and they are commonly disposed of in landfills. Because blades are hollow, they take up a large volume compared to their mass. Since 2019, some landfill operators have begun requiring blades to be crushes before being landfilled. Wind turbines also generate noise. At a distance of 300 meters (980 ft) this may be around 45 dB, which is slightly louder than a refrigerator. At 1.5 km (1 mi) distance they become inaudible. There are anecdotal reports of negative health effects on people who live very close to wind turbines. Peer-reviewed research has generally not supported these claims. The United States Air Force and Navy have expressed concern that siting large wind turbines near bases "will negatively impact radar to the point that air traffic controllers will lose the location of aircraft".

Politics

Nuclear power and fossil fuels are subsidized by many governments, and wind power and other forms of renewable energy are also often subsidized. It has been suggested that a subsidy shift would help to level the playing field and support growing energy sectors, namely solar power, wind power, and biofuels. History shows that no energy sector was developed without subsidies. According to the International Energy Agency (IEA) (2011), energy subsidies artificially lower the price of energy paid by consumers, raise the price received by producers or lower the cost of production. "Fossil fuels subsidies costs generally outweigh the benefits. Subsidies to renewables and low-carbon energy technologies can bring long-term economic and environmental benefits". Following the 2011 Japanese nuclear accidents, Germany's federal government is working on a new plan for increasing energy efficiency and renewable energy commercialization, with a particular focus on offshore wind farms. Under the plan, large wind turbines will be erected far away from the coastlines, where the wind blows more consistently than it does on land, and where the enormous turbines won't bother the inhabitants. The plan aims to decrease Germany's dependence on energy derived from coal and nuclear power plants.

Public opinion

Surveys of public attitudes across Europe and in many other countries show strong public support for wind power. In 2008, surveys found about 80% of EU citizens supported wind power. Bakker et al. (2012) found in their study that residents who did not want turbines built near them suffered significantly more stress than those who "benefited economically from wind turbines". Although wind power is a popular form of energy generation, onshore or near offshore wind farms are sometimes opposed for their impact on the landscape (especially scenic areas, heritage areas and archaeological landscapes), as well as noise, and impact on tourism. In a 2007 survey of wind power in Canada, 89% of respondents said that using renewable energy sources like wind or solar power was positive for Canada because these sources were better for the environment. Only 4 percent considered using renewable sources as negative since they could be unreliable and expensive. Another 2007 survey concluded that wind power was the alternative energy source most likely to gain public support for future development in Canada, with only 16% opposed to this type of energy. By contrast, 3 out of 4 Canadians opposed nuclear power developments. In other cases, there is direct community ownership of wind farms. The hundreds of thousands of people who have become involved in Germany's small and medium-sized wind farms demonstrate such support there. A 2010 Harris Poll found strong support for wind power in Germany, other European countries, and the

United States. In China, Shen et al. (2019) found that Chinese city-dwellers may be resistant to building wind turbines in urban areas, with a surprisingly high proportion of people citing an unfounded fear of radiation as driving their concerns. Also, the study finds that like their counterparts in OECD countries, urban Chinese respondents are sensitive to direct costs and wildlife externalities. Distributing relevant information about turbines to the public may alleviate resistance.

Community

Wind turbines such as these, in Cumbria, England, have been opposed for a number of reasons, including aesthetics, by some sectors of the population. Many wind power companies work with local communities to reduce environmental and other concerns associated with particular wind farms. In other cases there is direct community ownership of wind farm projects. Appropriate government consultation, planning and approval procedures also help to minimize environmental risks. Some may still object to wind farms but The Australia Institute says their concerns should be weighed against the need to address the threats posed by climate change and the opinions of the broader community. In the US, wind power projects are reported to boost local tax bases, helping to pay for schools, roads, and hospitals, and to revitalize the economies of rural communities by providing steady income to farmers and other landowners. In the UK, both the National Trust and the Campaign to Protect Rural England have expressed concerns about the effects on the rural landscape caused by inappropriately sited wind turbines and wind farms. Some wind farms have become tourist attractions. The Whitelee Wind Farm Visitor Centre has an exhibition room, a learning hub, a café with a viewing deck and also a shop. It is run by the Glasgow Science Centre. In Denmark, a loss-of-value scheme gives people the right to claim compensation for loss of value of their property if it is caused by proximity to a wind turbine. The loss must be at least 1% of the property's value. Despite this general support for the concept of wind power in the public at large, local opposition often exists and has delayed or aborted a number of projects. As well as concerns about the landscape, there are concerns that some installations can negatively affect TV and radio reception and Doppler weather radar, as well as produce excessive sound and vibration levels leading to a decrease in property values. Potential broadcast-reception solutions include predictive interference modeling as a component of site selection. A study of 50,000 home sales near wind turbines found no statistical evidence that prices were affected. While aesthetic issues are subjective and some find wind farms pleasant and optimistic, or symbols of energy independence and local prosperity, protest groups are often formed to attempt to block some wind power stations for various reasons. Some opposition to wind farms is dismissed as NIMBYism, but research carried out in 2009 found that there is little evidence to support the belief that residents only object to wind farms because of a "Not in my Back Yard" attitude.

Geopolitics

It has been argued that expanding the use of wind power will lead to increasing geopolitical competition over critical materials for wind turbines such as rare earth elements neodymium, praseodymium, and dysprosium. But this perspective has been criticized for failing to recognize that most wind turbines do not use permanent magnets and for underestimating the power of economic incentives for expanded production of these minerals.-

Turbine design

Wind turbines are devices that convert the wind's kinetic energy into electrical power. The result of over a millennium of windmill development and modern engineering, today's wind turbines are manufactured in a wide range of horizontal axis and vertical axis types. The smallest turbines are used for applications such as battery charging for auxiliary power. Slightly larger turbines can be used for making small contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. Arrays of large turbines, known as wind farms, have become an increasingly important source of renewable energy and are used in many countries as part of a strategy to reduce their reliance on fossil fuels. Wind turbine design is the process of defining the form and specifications of a wind turbine to extract energy from the wind. A wind turbine installation consists of the necessary systems needed to capture the wind's energy, point the turbine into the wind, convert mechanical rotation into electrical power, and other systems to start, stop, and control the turbine. In 1919 the German physicist Albert Betz showed that for a hypothetical ideal wind-energy extraction machine, the fundamental laws of conservation of mass and energy allowed no more than 16/27 (59%) of the kinetic energy of the wind to be captured. This Betz limit can be approached in modern turbine designs, which may reach 70 to 80% of the theoretical Betz limit. The aerodynamics of a wind turbine are not straightforward. The airflow at the blades is not the same as the airflow far away from the turbine. The very nature of how energy is extracted from the air also causes air to be deflected by the turbine. This affects the objects or other turbines downstream, which is known as Wake effect. Also, the aerodynamics of a wind turbine at the rotor surface exhibit phenomena that are rarely seen in other aerodynamic fields. The shape and dimensions of the blades of the wind turbine are determined by the aerodynamic performance required to efficiently extract energy from the wind, and by the strength required to resist the forces on the blade. In addition to the aerodynamic design of the blades, the design of a complete wind power system must also address the design of the installation's rotor hub, nacelle, tower structure, generator, controls, and foundation.Wind power has been used as long as humans have put sails into the wind. King Hammurabi's Codex (reign 1792 - 1750 BC) already mentioned windmills for generating mechanical energy. Wind-powered machines used to grind grain and pump water, the windmill and wind pump, were developed in what is now Iran, Afghanistan, and Pakistan by the 9th century. Wind power was widely available and not confined to the banks of fast-flowing streams, or later, requiring sources of fuel. Wind-powered pumps drained the polders of the Netherlands, and in arid regions such as the American mid-west or the Australian outback, wind pumps provided water for livestock and steam engines. The first windmill used for the production of electric power was built in Scotland in July 1887 by Prof James Blyth of Anderson's College, Glasgow (the precursor of Strathclyde University). Blyth's 10 meters (33 ft) high cloth-sailed wind turbine was installed in the garden of his holiday cottage at Marykirk in Kincardineshire, and was used to charge accumulators developed by the Frenchman Camille Alphonse Faure, to power the lighting in the cottage, thus making it the first house in the world to have its electric power supplied by wind power. Blyth offered the surplus electric power to the people of Marykirk for lighting the main street, however, they turned down the offer as they thought electric power was "the work of the devil." Although he later built a wind turbine to supply emergency power to the local Lunatic Asylum, Infirmary, and Dispensary of Montrose, the invention never really caught on as the technology was not considered to be economically viable. Across the Atlantic, in Cleveland, Ohio, a larger and heavily engineered machine was designed and constructed in the winter of 1887–1888 by Charles F. Brush. This was built by his engineering company at his home and operated from 1886 until 1900. The Brush wind turbine had a rotor 17 meters (56 ft) in diameter and was mounted on an 18 meters (59 ft) tower. Although large by today's standards, the machine was only rated at 12 kW. The connected dynamo was used either to charge a bank of batteries or to operate up to 100 incandescent light bulbs, three arc lamps, and various motors in Brush's laboratory. With the development of electric power, wind power found new applications in lighting buildings remote from centrally generated power. Throughout the 20th century parallel paths developed small wind stations suitable for farms or residences. The 1973 oil crisis triggered the investigation in Denmark and the United States that led to larger utility-scale wind generators that could be connected to electric power grids for remote use of power. By 2008, the U.S. installed capacity had reached 25.4 gigawatts, and by 2012 the installed capacity was 60 gigawatts. Today, wind-powered generators operate in every size range between tiny stations for battery charging at isolated residences, up to gigawatt-sized offshore wind farms that provide electric power to national electrical networks.

Advantages of Wind Power

- ✓ **Wind power is cost-effective.** Land-based utility-scale wind is one of the lowest-priced energy sources available today, costing 1–2 cents per kilowatt-hour after the production tax credit. Because the electricity from wind farms is sold at a fixed price over a long period of time (e.g. 20+ years) and its fuel is free, wind energy mitigates the price uncertainty that fuel costs add to traditional sources of energy.

- ✓ **Wind creates jobs.** The U.S. wind sector employs more than 100,000 workers, and wind turbine technician is one of the fastest growing American jobs. According to the *Wind Vision Report*, wind has the potential to support more than 600,000 jobs in manufacturing, installation, maintenance, and supporting services by 2050.
- ✓ **Wind enables U.S. industry growth and U.S. competitiveness.** New wind projects account for annual investments of over $10 billion in the U.S. economy. The United States has a vast domestic resources and a highly-skilled workforce, and can compete globally in the clean energy economy.
- ✓ **It's a clean fuel source.** Wind energy doesn't pollute the air like power plants that rely on combustion of fossil fuels, such as coal or natural gas, which emit particulate matter, nitrogen oxides, and sulfur dioxide—causing human health problems and economic damages. Wind turbines don't produce atmospheric emissions that cause acid rain, smog, or greenhouse gases.
- ✓ **Wind is a domestic source of energy.** The nation's wind supply is abundant and inexhaustible. Over the past 10 years, U.S. wind power capacity has grown 15% per year, and wind is now the largest source of renewable power in the United States.
- ✓ **It's sustainable.** Wind is actually a form of solar energy. Winds are caused by the heating of the atmosphere by the sun, the rotation of the Earth, and the Earth's surface irregularities. For as long as the sun shines and the wind blows, the energy produced can be harnessed to send power across the grid.
- ✓ **Wind turbines can be built on existing farms or ranches.** This greatly benefits the economy in rural areas, where most of the best wind sites are found. Farmers and ranchers can continue to work the land because the wind turbines use only a fraction of the land. Wind power plant owners make rent payments to the farmer or rancher for the use of the land, providing landowners with additional income.

Challenges of Wind Power

- ❖ **Wind power must still compete with conventional generation sources on a cost basis.** Even though the cost of wind power has decreased dramatically in the past several decades, wind projects must be able to compete economically with the lowest-cost source of electricity, and some locations may not be windy enough to be cost competitive.
- ❖ **Good land-based wind sites are often located in remote locations, far from cities where the electricity is needed.** Transmission lines must be built to bring the electricity from the wind farm to the city. However, building just a few already-proposed transmission lines could significantly reduce the costs of expanding wind energy.
- ❖ **Wind resource development might not be the most profitable use of the land.** Land suitable for wind-turbine installation must compete with alternative uses for the land, which might be more highly valued than electricity generation.
- ❖ **Turbines might cause noise and aesthetic pollution.** Although wind power plants have relatively little impact on the environment compared to conventional power plants, concern exists over the noise produced by the turbine blades and visual impacts to the landscape.
- ❖ **Wind plants can impact local wildlife.** Birds have been killed by flying into spinning turbine blades. Most of these problems have been resolved or greatly reduced through technology development or by properly siting wind plants. Bats have also been killed by turbine blades, and research is ongoing to develop and improve solutions to reduce the impact of wind turbines on these species. Like all energy sources, wind projects can alter the habitat on which they are built, which may alter the suitability of that habitat for certain species.

How Do Wind Turbines Work?

Wind turbines work on a simple principle: instead of using electricity to make wind -like a fan- wind turbines use wind to make electricity. Wind turns the propeller-like blades of a turbine around a rotor, which spins a generator, which creates electricity.

Explore a Wind Turbine
Wind is a form of solar energy caused by a combination of three concurrent events:

1. The sun unevenly heating the atmosphere
2. Irregularities of the earth's surface
3. The rotation of the earth.

Wind flow patterns and speeds vary greatly across the United States and are modified by bodies of water, vegetation, and differences in terrain. Humans use this wind flow, or motion energy, for many purposes: sailing, flying a kite, and even generating electricity. The terms "wind energy" and "wind power" both describe the process by which the wind is used to generate mechanical power or electricity. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity. A wind turbine turns wind energy into electricity using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade. When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this causes the rotor to spin. The rotor connects to the generator, either directly (if it's a direct drive turbine) or through a shaft and a series of gears (a gearbox) that speed up the rotation and allow for a physically smaller generator. This translation of aerodynamic force to rotation of a generator creates electricity.

Types of Wind Turbines

The majority of wind turbines fall into two basic types:

- ✓ **Horizontal-axis turbines**
- ✓ **Vertical-axis turbines**

Wind turbines can be built on land or offshore in large bodies of water like oceans and lakes. The U.S. Department of Energy is currently funding projects to facilitate offshore wind deployment in U.S. waters.

Relationship between the amount of wind energy use and the rate of increase in progress and economic development

In an era characterized by rapid technological advancements and pressing environmental challenges, the exploration of renewable energy resources has taken center stage. Among these, wind energy has emerged as a leading player, contributing not only to a sustainable energy future but also catalyzing various socioeconomic benefits. The relationship between the utilization of wind energy and its impact on economic development is particularly significant, warranting close examination. The global shift towards renewable energy sources has intensified as societies confront the dual challenges of climate change and energy security. Policymakers and economists alike recognize that meeting the energy demands of the future necessitates a fundamental transformation of the energy landscape. Wind energy, with its vast potential and relatively low operational costs, offers an attractive solution. This renewable resource has the capacity to power communities, industries, and economies while simultaneously reducing carbon emissions. Evidence has shown that countries investing in wind energy infrastructure experience accelerated economic growth. As governments prioritize sustainable practices, the integration of wind energy not only creates job opportunities in manufacturing, installation, and maintenance but also stimulates local economies. The direct relationship between wind energy adoption and economic development can be observed in regions that have harnessed this resource effectively, leading to improved living standards and economic resilience. To comprehend the dynamics of this relationship, it is essential to delve into the multifaceted benefits of wind energy. Beyond generating electricity, wind energy projects have been associated with increased investment in rural communities where these farms are primarily located. This infusion of capital often leads to the enhancement of local infrastructures, including schools, healthcare facilities, and transportation networks, ultimately fostering an environment conducive to economic growth.

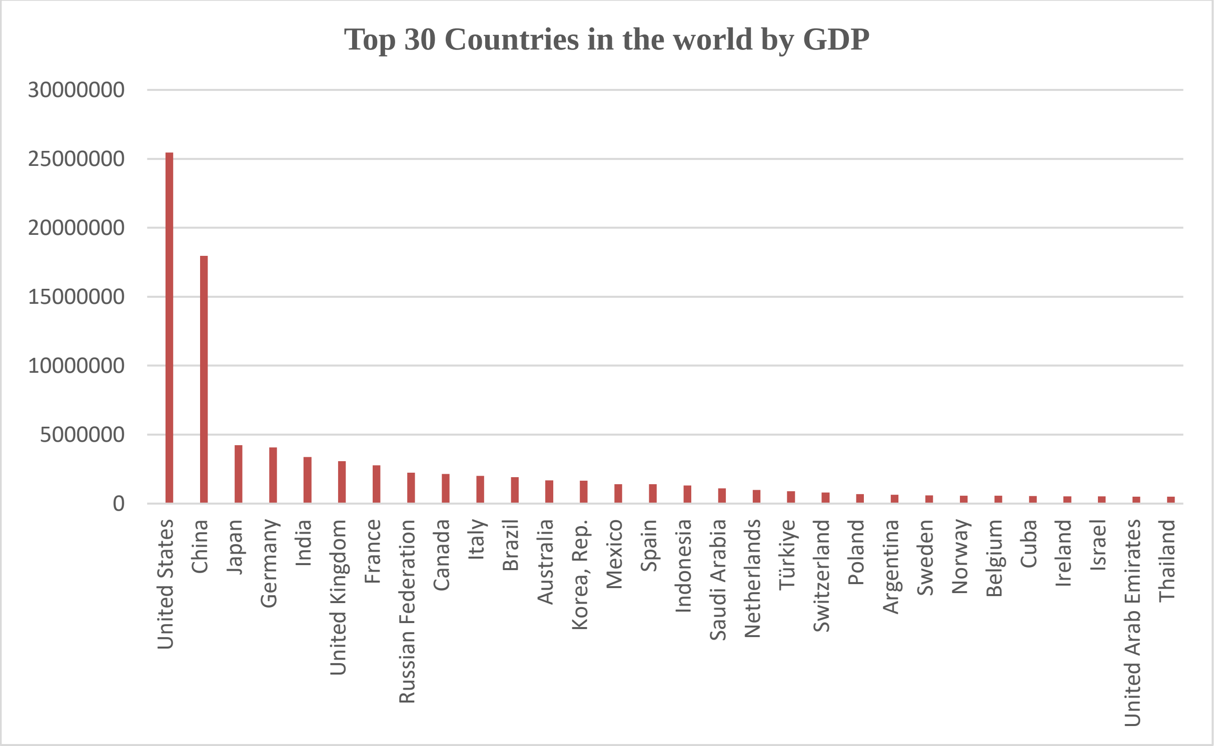

Table1. The USA and China are the two giants in terms of GDP. They also rank top two in terms of total win energy produced. However, in terms of wind penetration and SDG they aren't necessarily the highest, showing how other factors play a role too. Nevertheless, out of the top 10 countries by wind penetration, only 3 countries are not present in this chart of countries with the highest GDP; therefore, again this shows that Wind Energy can positively affect the economic situation of a country.

Moreover, the wind energy sector is a beacon for innovation and technological development. As the industry has evolved, so too have the techniques and technologies employed in harnessing wind power. Advancements in turbine design, energy storage solutions, and smart grid technology have contributed significantly to the efficiency and reliability of wind energy systems. These innovations not only enhance energy production but also create a ripple effect throughout the economy by inspiring further research and development activities.

The health of local economies is also intricately linked to the energy landscape. As communities transition away from fossil fuels and towards cleaner energy sources, the job market evolves to prioritize skills in renewable energy technologies. In addition to direct employment, there is often a surge in ancillary services, including manufacturing, logistics, and service industries, which further solidify the economic benefits derived from wind energy investments.

The energy transition also has profound implications for energy independence and security. Countries that invest heavily in domestic wind energy production reduce their reliance on imported fuels, insulating themselves from volatility in global energy markets. This newfound energy autonomy not only fosters national security but also encourages a stable economic environment where businesses can thrive without the unpredictability associated with fluctuating fossil fuel prices.

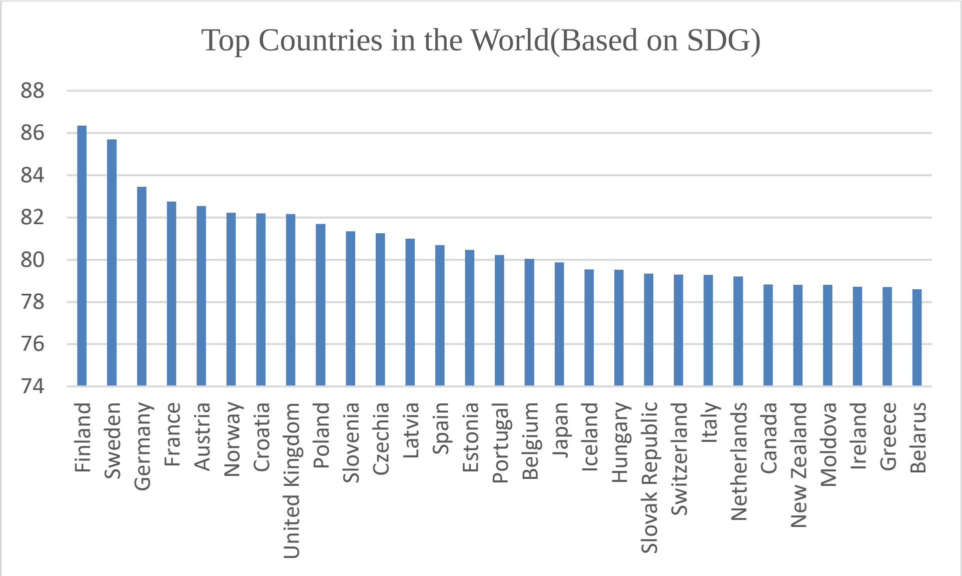

Table2. The top 30 countries in the world shown on the graph based on SDG. All countries that place in the top 10 ranking based on wind penetration are found in this Chart, showcasing the effect wind energy penetration has on a Country's Sustainable Development Index.

However, the successful integration of wind energy into the economic framework is not without its challenges. Regulatory hurdles, infrastructure limitations, and public perception can impede the growth of this sector. Therefore, understanding and addressing these barriers is essential for maximizing the potential benefits of wind energy adoption for economic development. As we explore the intricate connections between wind energy usage and economic progress, it becomes evident that this relationship is not merely theoretical. Numerous case studies from around the globe depict a clear narrative: regions that have embraced wind energy demonstrate robust economic indicators, including job creation, GDP growth, and improved quality of life metrics.

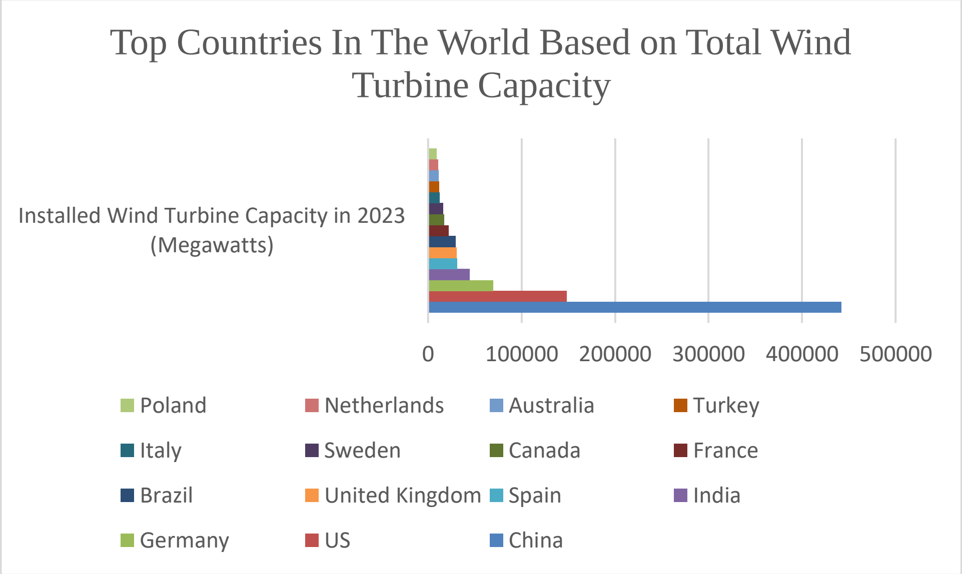

Table3. Countries do not necessarily have more wind turbine capacity if they have higher penetration. As seen in the above chart, only 4(Spain, UK, Germany, & Sweden) countries are seen in both Top Countries based on Wind Energy Penetration and Top Countries in The World Based on Total Wind Turbine Capacity charts.

The transition to wind energy represents more than a mere shift in technology; it embodies a transition in thinking about our energy systems and their roles in society and the economy. By prioritizing renewable energy sources, we pave the way for a more sustainable and equitable future, where progress and development are no longer at odds with environmental stewardship. As we embark on a thorough analysis of this relationship, it is crucial to appreciate the complexity and interdependence of various factors contributing to both wind energy utilization and economic development. The forthcoming sections will delve deeper into the statistics, case studies, and potential pathways for leveraging wind energy as a driving force for economic advancement.

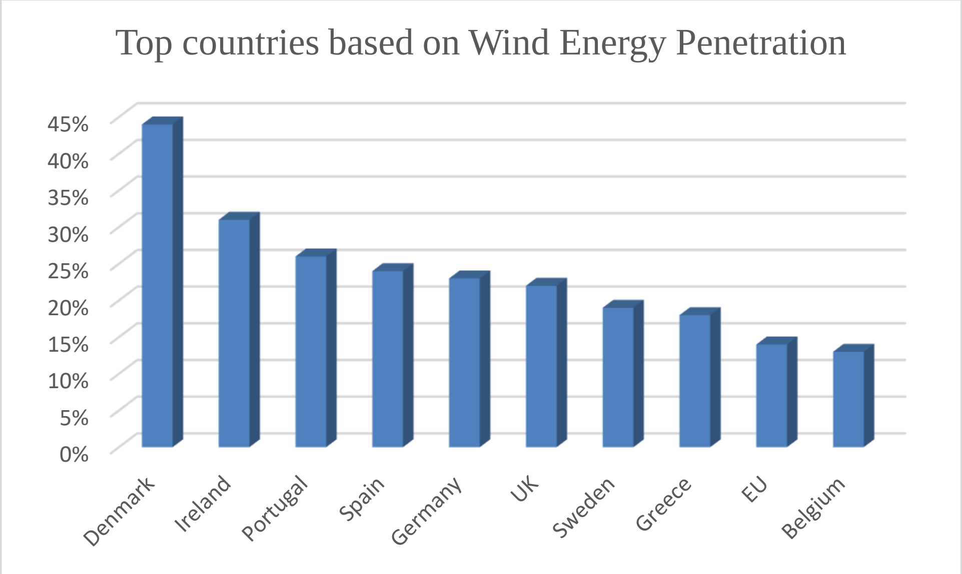

Table4. Top 10 Areas in terms of Wind Penetration. Denmark ranks first, highest of any country with 44%.

We are using portion of total electric demand which is from wind power rather than total megawatts due to the major differences in the total power created by countries. though the US is ranked second in total Energy produced by wind energy, it ranks 46th by SDG, showing that the wind energy penetration is more important than total wind energy produced. However, both are important to understand the full scope of this situation.

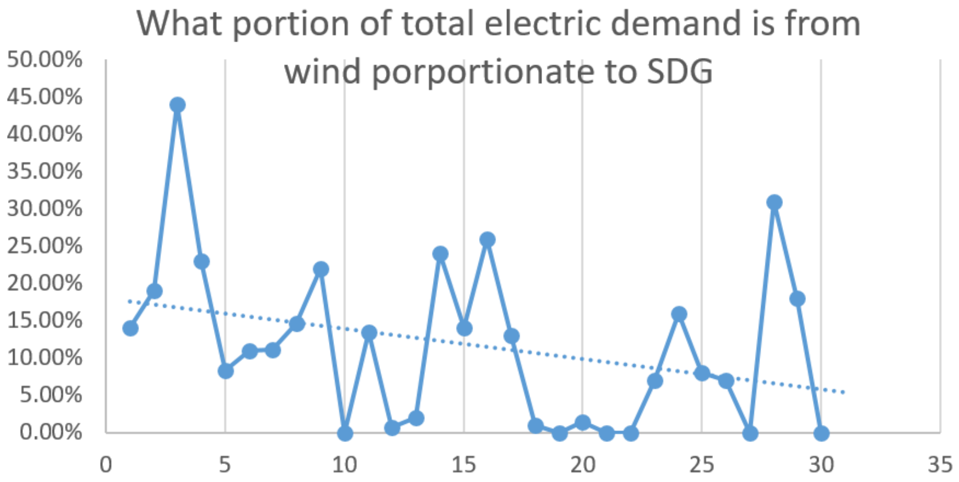

Table5. Despite The Graph having a downwards trend, due to the R of the regression being 0.362335, we cannot say with certainty that lower rankings of a nation based on SDG means that lower portion of total electric demand is from wind energy.

While the United States and China lead in GDP and total wind energy produced globally, they do not rank highly in wind penetration or SDG ranking. This exemplifies that although they have large-scale wind energy, a country's GDP, overall energy consumption, economic diversification and sustainable development efforts still contributes to its ability to be successful on the SDG index. Nonetheless, as stated prior, seven of the ten countries ranked in penetration are also represented as high GDP countries. This illustrates how wind can improve and allow for significant growth in overall economy. Therefore, wind energy capacity alone is not reflective of advancements in sustainability, but will also serve as a vital economic quantity for countries with proper infrastructure on renewable energy into their current energy grids.

Conclusion

The connection between wind energy and economic development is not only viable but essential in our quest for a sustainable future. By examining this direct relationship, we can uncover meaningful insights that encourage innovative policy measures and strategic investments aimed at realizing the full potential of wind power in propelling economies forward. Through this exploration, we aim to contribute to the ongoing dialogue surrounding renewable energy's role in shaping a prosperous and sustainable world for generations to come. When observing the relationship between wind penetration and SDG ranking, it is clear that these countries happen to have high penetration coupled with evaluating the returns and scoring highly on the Sustainable Development Index. Spain, UK, Germany, and Sweden rank high on wind penetration and generation, which illustrates how investments into the wind sector produce sustainable development reporting results. I would also argue that of the 10 countries with high penetration ranking, only three are not in the top 30 SDG these three countries are still classified as high GDP. Therefore, wind energy penetration can likely support or drive sustainability efforts, correlating their wind/tree or visited capacity with less carbon emissions, supporting clean energy goals and promoting resilient energy use in the future. However, high wind energy capacity does not always correlate with wind penetration. As seen in the charts, countries like Spain, the UK, Germany, and Sweden are outliers that manage both high wind energy capacity and penetration. Denmark’s exceptional wind penetration rate of 44% further highlights how smaller countries with focused renewable energy policies can outperform larger economies in terms of energy integration. The weak correlation between SDG ranking and wind penetration (R = 0.362335) suggests that while wind penetration is beneficial, other critical elements of sustainable development, such as social, economic, and institutional factors, also play essential roles.

References

1. Shahbaz, Muhammad, et al. "The effect of renewable energy consumption on economic growth: Evidence from the renewable energy country attractive index." Energy 207 (2020): 118162.
2. Aguirre, Mariana, and Gbenga Ibikunle. "Determinants of renewable energy growth: A global sample analysis." Energy policy 69 (2014): 374-384.
3. Bi, Zhaoming, Renyu Guo, and Rabnawaz Khan. "Renewable Adoption, Energy Reliance, and CO_2 Emissions: A Comparison of Developed and Developing Economies." Energies 17.13 (2024): 3111.
4. Brodny, Jarosław, Magdalena Tutak, and Peter Bindzár. "Assessing the level of renewable energy development in the European Union member states. A 10-year perspective." Energies 14.13 (2021): 3765.
5. Lee, Shun-Chung, and Li-Hsing Shih. "Enhancing renewable and sustainable energy development based on an options-based policy evaluation framework: Case study of wind energy technology in Taiwan." Renewable and Sustainable Energy Reviews 15.5 (2011): 2185-2198.