Photo of Kentucky's first utility wind turbine installed in February 2024 at Kentucky Utilities' Renewable Integration Research Facility

Rethinking Wind in Kentucky

by Larry Holloway, Aron Patrick, and Dan Ionel

April 4, 2024

A joint research project with the University of Kentucky College of Engineering, Kentucky Utilities, and PPL Corporation Research & Development

Stanley and Karen Pigman College of Engineering

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Advancing technology, changing economics, and new analyses point to increased wind energy potential for Kentucky's future.

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1 Executive Summary

Recent analyses and developments suggest that wind energy could play a role in Kentucky's future power generation mix. This recent change in outlook for Kentucky wind has been driven by three factors: (1) improved wind turbine technologies, (2) improved economics, and (3) recent analyses showing improved grid reliability due to wind's complementarity to solar power generation.

Recent developments in wind turbine technology, new wind resource data, and new federal tax credits for renewable energy are increasing the suitability of wind electricity generation in Kentucky. In 2022, Kentucky was one of only eight states in the US that had no utility-scale wind power generation,[4] due to relatively low wind resources, low electricity prices,[5] and the absence of state policies encouraging the local development of renewable energy. Recent analyses referenced in this report suggest that the situations for most of these eight states are changing, even under conservative assumptions of renewable energy adoption; wind is becoming a more attractive generation option for most of these states, including Kentucky.[6]

Even with new advances in turbines and new federal tax credits, there are still challenges for wind development in Kentucky due to cost and intermittency. Among low-carbon energy sources, solar PV is typically the cheapest new generation, ahead of wind as second cheapest [1]. Both are more cost effective than new geothermal, hydrogen, advanced nuclear, or carbon capture coal plants. However, when considering the capital cost of building new wind projects vs. maintaining and fueling existing high-utilization fossil-fueled plants, the argument for wind is less clear. Wind power has no fuel costs when generating, so has a lower marginal cost of generation in comparison to fuel-based generation relying on coal or natural gas. However, the savings in avoiding fuel costs can be offset when considering the cost of building new wind power facilities vs. maintaining and fueling existing coal fired plants. 3ith very low natural gas prices and high efficiencies of natural gas combined cycle plants, even building a new natural gas combined cycle plant can have lower lifetime cost vs. a new wind facility for some areas of the US, including the area covering Kentucky [2][7]. Of course, such levelized (lifetime) estimates of cost rely on predictions of future costs for natural gas and other factors.

[4] States without any utility-scale wind generation for 2022 were Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, and South Carolina. See Table 3.18 of [47]

[5] Tables T5.a, T5.b, T5.c of [47]

[6] Each of these eight states with no current wind generation are predicted to have some wind power by 2050 under the cost-based analyses in the National Renewable Energy Agency's Standard Scenarios 2023. This growth is even in the cases of "Conservative Renewable Energy assumptions, current policies" and also under assumed "Reduced renewable energy resources, current policies". However, it should be noted that Florida's gain in wind is almost negligible in this last scenario. Scenarios are available at [48]. As of March 2024, the following states in this list had active requests for wind project development in their interconnect queues: Arkansas, Kentucky, Louisiana, and Mississippi [49]

[7] The US EIA estimates that for the NERC/ISO region which includes Kentucky, a new advanced natural gas combined cycle plant would be \$41.04 per MWh LCOE, vs. \$45.65 per MWh for onshore wind.

Another challenge with wind power is that it is not dispatchable – no power can be generated if there is not sufficient wind. This challenge can be mitigated by either pairing wind with energy storage or by including wind as part of a broad portfolio of energy generation facilities that can complement and supplement each other. Even considering a future scenario of a highly decarbonized energy mix, pairing wind with solar and storage can result in higher reliability and lower cost than achieving similar carbon emissions reductions with only solar and storage [3].

The remainder of this document examines factors contributing to the changing opportunity of wind in Kentucky. Below we highlight and summarize these factors.

1.) **Changing technologies for wind power generation:** Advancing wind turbine technologies allow capture of more consistent higher-speed winds higher above the ground and allow more effective capture of power from a wider range of wind speeds. The average hub height for installations in the US has climbed from less than 80 meters in 2010 to close to 100 meters in 2022. These wind turbines with greater hub heights are able to capture higher speed and more consistent wind with less interference from the landscape below. Similarly, turbines with longer rotors can capture a larger area of wind, allowing power generation even under slower wind conditions. Section 2 of this paper looks at how these technologies are opening up the potential for wind across different areas of the state.
2.) **Improving economics of wind:** Nationally, wind is ranked second after solar for the lowest levelized cost (lifetime cost per unit of energy) of electricity generation for new power plants, with even less cost per unit of energy than new coal plants or natural gas plants. The price of wind installations per unit of energy generated has fallen due to several reasons outlined in Sections 2 and3 of this report. These reasons include:
    a. **Better technologies allow wind turbines to generate more energy more consistently,** reducing the cost per unit generated. Also, **installation costs for wind projects have fallen** as the wind market has matured.
    b. **The 2022 federal Inflation Reduction Act provides generous tax credits for clean electricity generation** methods like wind. The IRA extended and expanded the federal production tax credits and investment tax credits for wind and provided bonus incentives for domestically sourced key components and for installations in "energy communities". Many areas of Kentucky qualify as "energy communities" due to past relation to coal industry.
    c. **The Value-Cost ratio of new wind energy projects in Kentucky's region of the US is high, particularly because the region's grid has so little existing wind power already.** Out of 25 grid regions in the continental US (NERC/ISO subregions), the region that covers most of Kentucky is ranked by the US Energy Information Agency as third highest for the Value-Cost ratio of new wind projects [2]. Wind does not have fuel costs, so has almost no marginal cost when it is generating power. Thus, when the wind is blowing, wind turbines add power to the grid without the expense of fuel-based plants, especially expensive peaking plants. Furthermore, for a grid region with little wind power and mostly fuel-based power (coal or natural gas), curtailment of wind power becomes less likely, leading to more energy from a wind project onto the power grid.
    d. **New analyses identify Kentucky for economic potential of behind-the-meter non-utility wind generation.** A recent analysis has ranked Kentucky as second in the nation

for potential for use of smaller commercial-sized (non-utility) turbines [4]. The same analysis ranked Kentucky as 10th among all states for economic potential for installations by commercial, industrial, and residential consumers for onsite generation.

e. **Low-carbon energy such as from wind will become a competitive necessity for manufacturers competing in international markets with carbon regulation**. Kentucky's economy is heavy in manufacturing, and Kentucky's industries make products that are either exported directly or indirectly. Without low-carbon energy such as solar or wind, Kentucky's companies will be at an economic disadvantage under Europe's Carbon Borders Adjustment Mechanism (CBAM). The availability in the state of low-carbon energy sources like wind becomes important for retaining and supporting Kentucky's manufacturers as they compete in consumer markets or international markets that prioritize clean energy.

3.) **The value of the complementarity of wind:** Renewable energy sources such as solar and wind (and even to some extent hydro) have their power output vary over time based on time of day, season, weather, and other reasons. Power sources are considered complimentary when they vary in different ways from each other. Wind and solar are considered complimentary because wind blows more in seasons such as winter when there is less daylight, on cloudy or stormy days when the sun is less bright, and also overnight when the sun is not shining. Recent studies have recognized that a mix of wind and solar together can improve the reliability of the grid and reduce the need for backup power from batteries or fossil fuels. Research focusing on Kentucky's power grid found that reaching different targets of decarbonization can be done for less cost when using solar and wind generation together vs. solar alone [3].

Together, these recent developments suggest an opportunity for wind energy to be a part of Kentucky's future electricity generation mix and a need for more serious consideration of the potential environmental, economic, and reliability benefits of including wind as a part of our state's energy portfolio. To help evaluate the potential for wind energy as part of the state's energy mix, a new PPL Corporation Research and Development project at Kentucky Utilities (KU) Renewable Integration Research Facility has installed Kentucky's first utility wind turbine alongside Kentucky's largest lithium-ion battery storage and multiple types of solar photovoltaics. In addition to testing wind power and gathering wind resource data from the top of a 125 foot tower, the project intends to show how multiple types of renewable resources can work together in tandem to provide more reliable and lower cost low-carbon electricity generation options than solar alone.

2 Changing Technologies for Wind Power Generation and New Opportunities for Kentucky

This section looks at developments in wind turbines that allow the more effective capture of energy from the wind in a wider range of locations. These developments include wind turbines at higher distances above the ground. We look at maps of wind speeds across Kentucky at these greater heights. These maps identify areas of the state with the strongest potential for capturing wind energy.

2.1 Advances in Wind Turbine Technologies: National Trends

Wind turbine heights are increasing, allowing new turbine designs to access stronger and more consistent winds higher above the ground. Also, wind turbine rotors have increased in length, allowing turbines to effectively capture more energy from lower wind speeds.

Two important factors influencing the ability of a turbine design to capture wind are the height of the turbine hub above the ground and the diameter of the area swept by the turbine rotors. In the last two decades, these dimensions have dramatically improved. The improvement in these two factors is evident in the graph in Figure 1. In this subsection, we briefly consider these trends in the US market.

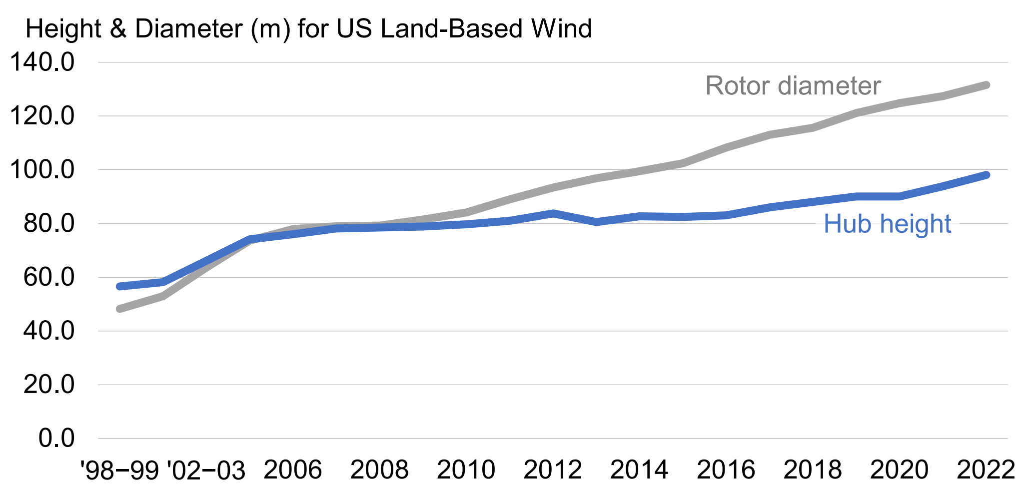

Figure 1: Average turbine hub height and rotor diameter for land-based wind (from data from [5]).

Wind speeds generally are better at higher distances from the ground. Lower to the ground, wind is more likely to experience interference of buildings, trees, and lower terrain features. Higher from the ground, these interferences are reduced, so wind is more consistent and has higher average wind speeds. Thus, turbines that are built at these higher distances from the ground will generally be able to capture more energy from the wind.

Wind turbine heights increased over the last two decades, so they can better reach faster and more consistent winds. The average hub height for installations in the US in 2000 was under 60 meters. It increased to be just below 80 meters by 2010, and in 2022 was 98.1 meters, with 43% of installations in 2022 being over 100m in height. (Details available from the data file available at [5]). Hub heights for land-based wind are expected to continue to increase through this decade. The National Renewable Energy Lab (NREL) in their 2023 Annual Technology Baseline report consider four representative wind turbine technologies anticipated as common in the market in 2030 [6]. Each of these turbine technologies is considered representative of turbines for different wind regimes and market segments. These four representative technologies for 2030 market have hub heights expected to range from 100-140 meters in height.

Wind turbines have increased in the diameter of the rotors, allowing them to have a greater cross-section area to capture more wind. The ability of a wind turbine to capture energy from the wind depends on the cross-section area that its rotors sweep. Thus, longer rotors give a larger diameter of the circle swept by the rotors, and thus more area of wind that is captured. Figure 1 shows the increase in the diameters over time. In 1998-1999 installations, the average rotor diameter was only 48 meters [5]. This increased to 84 in 2010, and to 131.6 in 2022, a remarkable 274% increase from the 1998-1999 installations. The improvement in the ability of capturing the wind is even more dramatic when considering the increasing swept area with these larger diameters. The area swept by an average turbine in 1998-1999 was approximately 3600 square meters. By 2022, the average turbine had a swept area of over 27,000 square meters, an increase of over seven times. This represents more area from which the turbine can capture wind energy.

Wind turbines have also increased in power rating. A third advance in wind turbine design is the nameplate rating for the power capacity of the turbine. This is the maximum amount of power that the turbine equipment can generate. Thus, a 3MW turbine could generate at most 3MW of power under sufficiently strong winds but will generate less power than the rated capacity in lower speed winds. A larger capacity for a turbine in a given location allows it to generate more power given sufficiently strong winds. However, the average amount of power generated depends not only on the capacity of the turbine, but also the wind characteristics (the distribution of different wind speeds over time at the site at the installed height) of the site where it is installed, since the site may only sometimes have sufficient winds for the full nameplate capacity output. The average nameplate capacity of turbines in the US was below 1 MW in 2000, reached 1.79 MW in 2010, and in 2022 is now 3.23MW, more than tripling [5].

The advances in turbine height and rotor diameter allow a turbine to average more power generation vs its nameplate capacity. The ability of a turbine to effectively tap wind energy resources at a given site is typically characterized by its *capacity factor*. The capacity factor is the ratio of the amount of power generated on average to its nameplate rated capacity. Thus, for example, a 3MW rated turbine that on average over a year only generates 1MW of power would have a 33% capacity factor. Higher turbines reaching better winds with larger rotor diameters typically will have better capacity factors, meaning they are more effective at capturing the wind and generating power. A turbine's capacity factor at a site depends on the distribution of different wind speeds over time at the site at the installed height as well as the turbine power curve which indicates what power the turbine will generate over the range of wind speeds.

Wind turbines designed for low wind speeds are now available in the market. The international standard IEC 61400 defines turbine design standards for operation in four different classes of winds. Class 1 is for high wind, with an average wind speed at hub height of 10 meters per second. Class 2 is for medium wind corresponding to average wind speeds of 8.5 m/s, class 3 for low wind speeds of averaging 7.5 m/s, and class 4 for very low winds averaging 6 m/s. Low wind speed turbines, such as those designed for the IIIB IEC 61400 classification (low wind speed, low turbulence) are now available or announced by manufacturers (for example [7], [8], [9] [10]). Wind farms are being developed in other states with low wind speed conditions, such as Mississippi [11].

2.2 Reassessing Kentucky Wind Resources

Areas in Kentucky have reasonable wind that can now be accessed by newer wind turbine designs. This section looks at wind speed characteristics across the state, showing that some areas are better than the national average.

Estimating wind energy generation potential depends on a variety of factors, including the wind resources in a region, the availability of technologies to harvest the wind resources, and the economic feasibility compared to market factors. In this subsection, we focus on estimates of the availability of wind, looking at the geographic distribution of wind speeds across the state.

The trend in higher hub heights for wind turbines allows a reassessment of the power potential at higher elevations off the ground. Our wind resource data for Kentucky relies on the 2023 land-based wind supply curves from NREL, the National Renewable Energy Laboratory [12]. The wind resource data from NREL is based on a map grid of 11.5km by 11.5km map cells, subdividing the continental US into 57,000 map grid points [13]. NREL's "Reference Access" data set excludes potential siting of turbines on urban lands, land with inappropriate terrain, or land with certain other exclusions such as certain federal lands. There are 728 map grid cells identified in Kentucky as having some available land for wind development. We consider wind characteristics at 115 meters above the ground for each grid-cell in Kentucky with land potentially available for development (i.e. not excluded due to terrain, buildings, or other exclusions). Much of the discussion in this section relies on a data file available at [12] looking at a Reference Access scenario (regarding potential siting restrictions) and only moderate technology development in turbines. This data was then filtered for Kentucky map grid cells for our state-level analysis and discussion.

The average wind speed at 115 meters height across Kentucky grid cells is 6.53 meters per second, approximately 14.6 miles per hour. Some areas of the state have considerably higher speeds. The state average of 6.53 meters/second is not far from the average of 6.85 m/s for the map grid cells across the entire US. The histogram below shows the distribution of average wind speeds across the map grid cells, and the map diagram below shows this average wind speed for each available map grid point in

Kentucky. More important than the average, however, is that there are pockets of higher average wind speed in the state. There are forty-nine grid cells with average wind speed above 7.00 m/s.

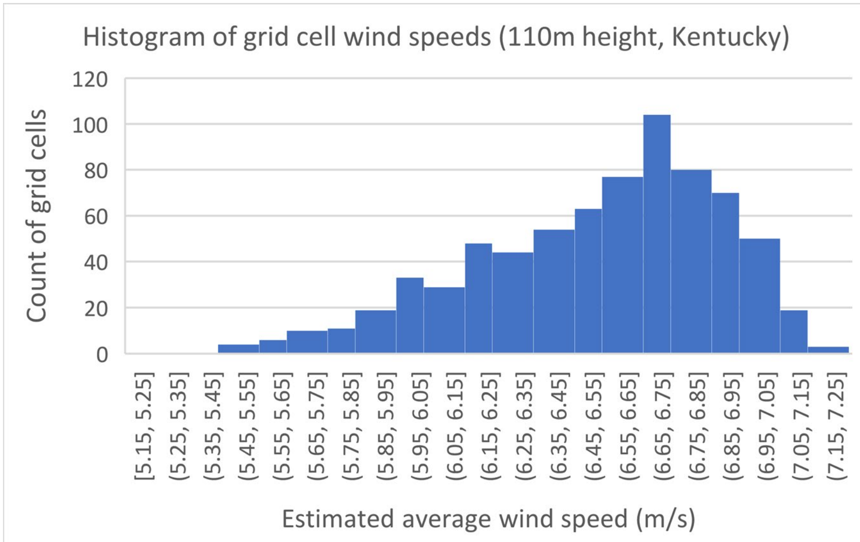

Figure 2. Distribution of average wind speed among all Kentucky map cells. The speed shown is in meters per second. Data download from [12], Reference Access, moderate technology baseline scenario 2023.

Generally, areas in far western Kentucky and in the Bluegrass region of central Kentucky have the highest wind speeds, although an area in far southeastern Kentucky has the highest average speed in the state. The geographic distribution of the average wind speeds across the state can be seen from the map below. As can be seen, counties with the highest average (average over the grid points within them) are Bourbon, Meade, Carlisle, Scott, and Graves. Bourbon and Scott counties are considered central Kentucky, north of Lexington. Carlisle and Graves are considered far west Kentucky, near Missouri. The mountains of East Kentucky generally have the poorest wind speeds, with the worst average wind speed of 5.15 m/s in Pike County. However, the single grid cell with the highest average wind speed is also in the eastern part of the state, in Harlan County, with an estimated average windspeed of the map grid cell at 7.24 m/s. Although Kentucky’s best pockets of wind resources have wind speeds around 7 m/s, this is notably lower than the wind speeds of installations across the US during the last decade, with those wind farms averaging 8 m/s [5].

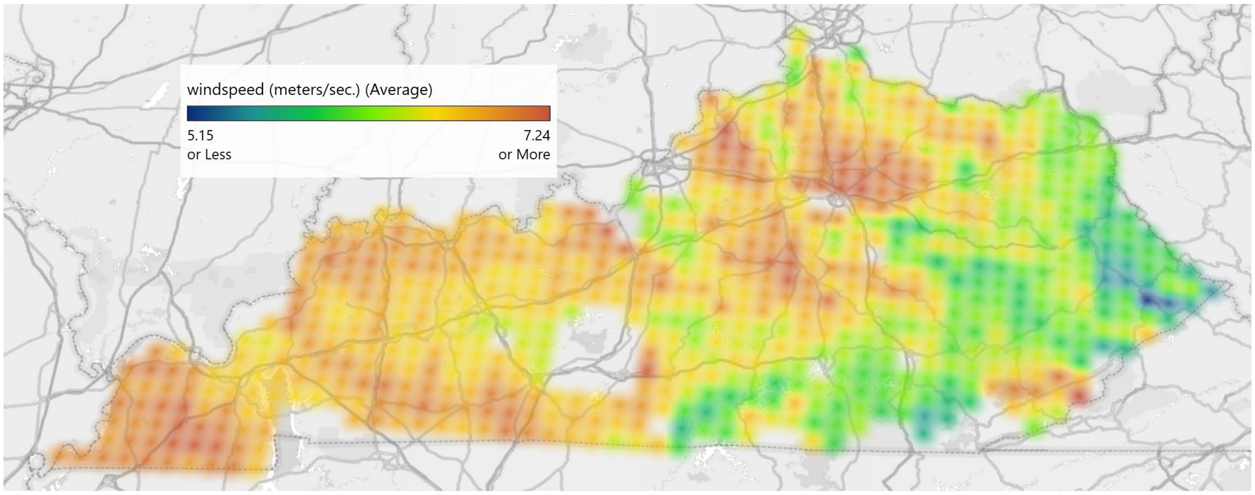

Figure 3. Windspeed variation across Kentucky, 115 meter hub height. Graphic developed from NREL "Reference Access", moderate technology baseline scenario 2023 file downloaded from [7].

The *capacity factor* of a wind turbine at a given location is a measure of the average power a turbine will generate vs. its rated power generation capacity. As defined in the prior section, the capacity factor is the ratio of the average amount of power generated by a turbine at a given location to its nameplate rated capacity. NREL estimates the capacity factor achievable across the map grid cells in Kentucky for the 115 meter hub height. The data file we consider looks at a 2030 projected turbine technology, and specifically a projected available turbine technology category identified as T1. Technology T1 assumes a turbine rating of 6MW, a rotor diameter of 170m, a hub height of 115 meters, and a specific power of 264. Note that a potential drawback of this available NREL dataset is that turbine T1 is better suited for strong wind resource sites. In contrast, NREL's representative turbine technology models T3 and T4 would be better suited to capture wind power in lower wind quality sites such as in many areas of Kentucky. In this sense, the data that we are presenting from NREL could be considered an underestimate of wind power potential and capacity factor versus considering other model turbine technologies.

Out of 120 Kentucky counties, 56 of them are estimated to have sites with very competitive capacity factors. These 56 counties have map grid cells with estimated capacity factor of 40% or higher for a turbine technology class T1 operating at 115 meters hub height. For comparison, wind projects installed across the US and completed in 2021, the average capacity factor was 36%. As noted already, technology class T1 is targeted for higher quality wind sites and is less appropriate for Kentucky's moderate winds than class T3 or T4, and so capacity factors for T3 or T4 turbines are expected to be even better. Fayette, Bourbon, McCracken, and Henry Counties have some of the best estimated potential capacity factors, ranging up to 43% for T1 technologies at 115 meters above the ground.

3 The Improved Economics of Wind

In this section, we consider national trends in the cost of wind power and look at some key factors to be considered in the overall cost of wind energy development. This includes the available tax credits in the 2022 Inflation Reduction Act. We then look more specifically at cost factors for Kentucky, and especially how Kentucky can take advantage of some of the special bonus tax provisions in the Inflation Reduction Act. Finally, we mention the broader importance of having low-carbon energy such as from wind to support Kentucky's manufacturing industries that export to areas of the world with carbon tariffs.

3.1 National Trends on the Cost of Wind Energy Generation

The levelized costs for onshore wind have declined by over 60% since 2000. This has resulted from advancing technologies that have improved the amount of power generated, as well as important tax incentives from the 2022 Inflation Reduction Act.

A common way to evaluate costs of an energy generation project is by considering its Levelized Cost of Electricity (LCOE). LCOE can be used for any energy generation project, whether it be wind, solar, coal, natural gas, or other. The LCOE for a project is calculated as the present value of its lifetime costs divided by its energy production, where energy is commonly measured as megawatt-hours, abbreviated MWh. The lifetime costs include the project's capital expenses (CAPEX) and its operating expenses (OPEX). For an onshore wind facility, the CAPEX includes site acquisition and preparation, engineering and installation, the turbine and other generation equipment and infrastructure, the electrical infrastructure and interconnection, and other owner costs. The OPEX includes fuel (such as if the plant burns coal or natural gas), operation, insurance, taxes, management, expected replacements of large components, maintenance, and consumables. For a wind project, the CAPEX and OPEX costs can vary based on the size of the wind site, with an understanding that projects with more wind turbines are able to distribute some costs over more turbines and thus result in a lower LCOE.

Levelized Cost calculations use estimates of future costs and also situation-specific assumptions. Thus, LCOE estimates can vary, so we focus on comparing LCOE across different projects (using similar underlying assumptions) and the trends over time of LCOE estimates to provide insight when comparing alternative generation projects. The LCOE calculation considers the expected lifetime energy generation of the project and estimates of the future costs for the plant operation. Since the future costs in the LCOE are estimated, and since all costs are brought to the present value, the LCOE considers a time value of money which often reflects inflation estimates and importantly considers the cost of capital which may vary across different companies. Since LCOE estimates will vary based on these estimates and company-specific and site-specific factors, we do not focus on a specific LCOE value. Instead, we focus on comparison of Levelized Cost estimates between generation choices and the changes in estimates over time.

The LCOE for a wind project will depend on the energy generated, so projects with higher capacity factor generally have lower levelized costs. Since LCOE is calculated as the lifetime costs over the lifetime energy generated, the LCOE of a project is reduced for projects with more lifetime energy production. Thus, a turbine installed in good wind resources and having a higher capacity factor will have more lifetime energy production and lower LCOE than a project with the same CAPEX and OPEX installed in poorer wind resources.

The US Department of Energy estimates that the LCOE of wind has fallen almost 70% since 1998-1999 [5] [8]**. Two major factors contributed to the falling cost of wind over the last decade: improving wind turbine designs and tax credits from the 2022 Inflation Reduction Act.** The developments in turbines that allow them to reach stronger winds higher above the ground have been complemented by advances that permit effective capture of lower quality winds and by installation costs that have been generally declining. Since LCOE is levelized per unit of energy, the more energy that a specific wind turbine generates for a given capital cost and operational cost, the lower its levelized cost will be.

Tax incentives from the 2022 Inflation Reduction Act are also a big factor in reducing the cost of wind. As noted already, the national estimates for the LCOE of onshore wind is reduced significantly due to tax incentives which are expected to cut from 30% to 50% of the capital cost of a project [1]. There are generally two types of tax credits that are used for encouraging renewable energy projects: *Production Tax Credits* and *Investment Tax Credits*. Production tax credits provide a tax credit per unit of energy produced. Investment tax credits provide a tax credit as a percentage of the investment basis in the renewable energy project. The Inflation Reduction Act (US code sections 45 and 48) extended and expanded some prior credits for solar and wind projects started through 2024. For projects starting service after 2024 (but before either 2032 or a threshold drop in emissions is met), the credits are more generally applicable to any generation source that does not emit greenhouse gasses. These are called *Clean Electricity Production Credits (section 45Y,* [14]*)* and *Clean Electricity Investment Credits* (section 48E, [15]). Projects may choose to take the Clean Electricity Production Tax Credit or the Clean Electricity Investment Tax Credit, but not both.[9]

The Clean Electricity Production Credits and Clean Electricity Investment Credit in the 2022 Inflation Reduction Act have several bonus provisions that can increase the tax credits even more, with "energy-community" bonuses particularly benefiting Kentucky. If prevailing wage and apprenticeship criteria are met for the project, the investment tax credit increases to 30% of the qualified project basis and the production credit increases to 1.5 cents per kWh of energy produced (subject to inflation adjustment) [16]. If the project also meets certain domestic content requirements, the credits are increased by an additional 10%, and if the project is located in an "energy community" the credits are increased by an additional 10% [17]. In the next section, we examine how these bonus provisions could affect projects in Kentucky, especially the "energy community" provision.

[Note that the Clean Electricity Production Credit and Clean Electricity Investment Credit do have a phase out provision, phasing out in 2032 or before if US greenhouse gas emissions from electricity production drop below 25 percent of the 2022 emissions level.]

Two other concepts must be mentioned when considering cost of wind projects:

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[8] From [5], the 1998-1999 average LCOE of wind was $106/MWh vs. $32/MWh as the average for 2022.

[9] Note that there are also separate tax credits discussed in tax code sections 48(e) and 48E(h) related to energy investments in low-income communities. However, these are only for projects that begin before 2025 and are of limited size. We do not consider these low-income community incentives further in this document.

- ***Additional transmission infrastructure may be necessary to carry wind power from a remote generating site to consumers:*** A large-scale power generating project must be connected to electrical transmission infrastructure to carry the generated power to consumers. A location that might have strong wind resources could be in a remote area where transmission infrastructure is limited. If transmission infrastructure is insufficient to carry the generated power, then new transmission must be built or upgraded, adding to the eventual total cost. However, this cost often is not considered a part of LCOE.
- ***Curtailment of wind may be necessary if generated wind energy cannot be immediately transmitted, used, or stored:*** Curtailment is when a generating resource (such as solar or wind) will intentionally reduce its energy output during a period of time because it is not needed by the power grid during that time. This may be due to insufficient transmission capacity. Alternatively, it may be due to more generation during a time than is needed. For example, a day that is windy and sunny and has low electricity demand (such as from mild temperatures) may not require all the possible electricity that could be provided by wind resources, solar resources, and other generation resources. For a wind plant, curtailment will mean less electricity generated and thus a higher levelized cost. During such times when energy availability exceeds energy demand, the curtailment of wind, solar, or other energy resources will be based on government policies, utility policies, and other factors. Curtailment typically becomes a larger factor as the amount of renewable energy resources on the power grid increases.

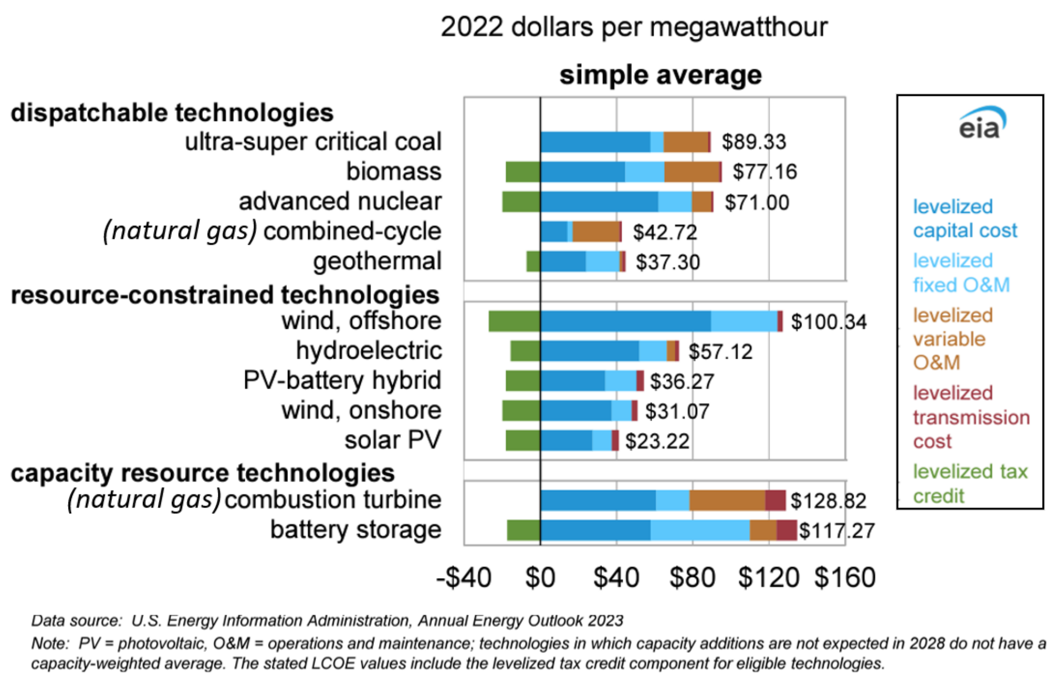

Figure 4. Estimated Levelized Cost of Electricity (LCOE) for new resources entering services in 2028 [2].

The US Energy Information Agency's Annual Energy Outlook (AEO) each year develops national estimates of the LCOE of different energy generation options for energy projects [2]. In the AEO2023, estimates are for new generation sources to enter service in 2028. The results of their 2023 analysis are in Figure 4. The figure shows the contribution of different costs towards the levelized costs. The higher operating cost shown for coal, natural gas, and biomass reflects the costs of fuel, which is not a factor for wind or solar. The negative costs (shown in green) show the significance of the tax credits from the 2022 Inflation Reduction Act in reducing the overall cost of "clean electricity" sources.

At a national level, the Levelized Cost of Electricity (LCOE) for onshore wind energy generation is the second lowest cost of generation after solar PV [2]**. New onshore wind generation resources are estimated to be lower than new coal, natural gas, or nuclear plants on a per energy basis of energy.** The US Energy Information Administration (EIA) regularly reports LCOE across all generation resources for planned new generation. For the US Energy Information Agency's 2023 Annual Energy Outlook report, the estimates of LCOE are for plants to be built for service beginning in 2028. The summary diagram from that report is shown in Figure 4. The onshore wind estimate is for plants with an expected average capacity factor of 40% and is estimated as the average across all projects and regions of the US, with significant regional variations. These regional variations are discussed more specifically for Kentucky in the next section.

3.2 Benefits from the 2022 Inflation Reduction Act for Kentucky Wind Projects

The levelized cost for wind power will vary across Kentucky. Portions of the state with good wind will generally experience lower cost than those areas with poorer wind. Also important to consider are regions of Kentucky eligible for enhanced tax credits under the 2022 Inflation Reduction Act. Many areas of Kentucky qualify as "energy communities" which means wind facilities in these areas are eligible for additional 10% bonus tax credits on the investment costs or on the energy production.

The levelized cost of electricity from wind in Kentucky varies across the state based on wind quality and on specific location bonus credits from the 2022 Inflation Reduction Act. In section 2.2 above, we considered advancements in wind turbines that allow turbines to capture better winds higher above the ground and to capture energy from a wider range of wind speeds. However, since wind speeds vary by location, the energy generation from a turbine will also vary by location. Thus, areas in Kentucky with better wind resources will more closely match the national average than those areas with poorer wind resources. Figure 2 illustrated the range of average wind speeds in Kentucky.

The 2022 Inflation Reduction Act (IRA) includes several incentives that benefit specific regions of Kentucky. The 2022 Inflation Reduction Act Clean Electricity Production Credits and the Clean Electricity Investment Credits include 10% bonuses for facilities located in "energy communities" [18]. An energy community is defined as (1) a brownfield site, (2) a metropolitan statistical area or non-metropolitan statistical area that meets certain thresholds of unemployment and had past employment or tax revenues related to coal, oil, or natural gas, or (3) a census tract (or adjoining tract) which has had a coal mine closure since 1999 or in which a coal-fired electric generating unit was retired after 2009.[10]

The first category of "energy community" specified in the IRA is brownfields. The IRS definition of brownfields for the Inflation Reduction Act tax credits is narrower than the definition used in the EPA Brownfield Program Site [19] Many of the identified brownfield sites across Kentucky are small and are not appropriate for wind development. However, EPA's RE-Powering screening tool identifies 9 potentially qualifying "brownfield" sites within the state with sufficient area and sufficient windspeed to be suitable for utility-scale or community-scale wind [20]. The RE-Powering tool identifies an additional 53 brownfield potential sites that are deemed to be suitable for smaller facility-scale wind power generation. (Note: The IRS claims that not all sites listed in RE-powering mapper tool may qualify for the IRA definition of brownfields [19].)

The second category of "energy community" is associated with areas meeting a threshold of fossil-fuel employment or tax revenues and also meeting an unemployment rate threshold. Most of Kentucky is covered by this definition, with at least 94 of the state's 120 counties meeting the criteria based on 2022 data. A location meeting this definition of energy community is "*a "metropolitan statistical area" [MSA] or "non-metropolitan statistical area" [NMSA] that has (or had at any time after 2009) (a.) a 0.17% or greater direct employment or 25% or greater local tax revenues related to the extraction, processing, transport, or storage of coal, oil, or natural gas, and (b.) has an unemployment rate at or above the national average unemployment rate for the previous year*" [18] Of Kentucky's 120 counties, 101 of these are in MSAs or NMSAs identified by the IRA as meeting the first criteria on current or past fossil fuel employment. Of these 101 counties, 94 of them also meet the threshold of having an unemployment rate for 2022 that is equal to or greater than the national average unemployment rate for 2022. As noted by the IRS, the unemployment rate qualification will be reassessed each year based on the prior year's unemployment data. Figure 5 shows the counties meeting this second definition of energy communities, based on current or past fossil-fuel employment threshold and the 2022 unemployment rate data. Note that we do not yet show counties meeting the alternative criteria of local tax revenues from fossil fuels – the IRS has not yet issued (as of Feb 2024) guidance on this alternative criteria, as it notes there are currently "data challenges" in identifying local tax revenue sources [21].

The third category of "energy communities" is associated with coal mines that have been closed or coal power generating facilities that have been retired. This covers a large area corresponding to the eastern Kentucky coal fields and also an area corresponding to the western Kentucky coal fields. This category of energy communities is defined as census tracts or directly adjoining census tracts in which a coal mine has closed after 1999 or in which a coal-fired electric generating unit has been retired after 2009 [18].Figure 6 below shows those census tracts that meet the criteria of a coal mine closure, a coal generating facility retirement, or adjacency to either.

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[10] This discussion of the Inflation Reduction Act tax credits is intended for informational purposes. Companies, communities, or individuals considering investments in clean energy projects should consult with a tax attorney regarding the specific eligibility of their project.

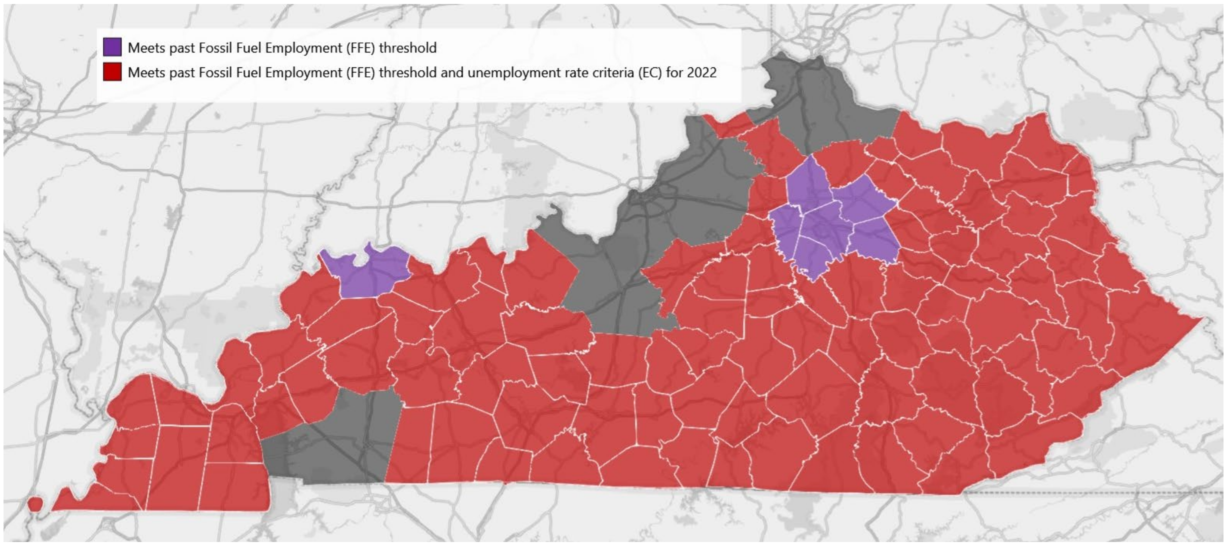

Figure 5: Counties meeting the second "energy communities" definition based on fossil fuel employment and latest available unemployment data.

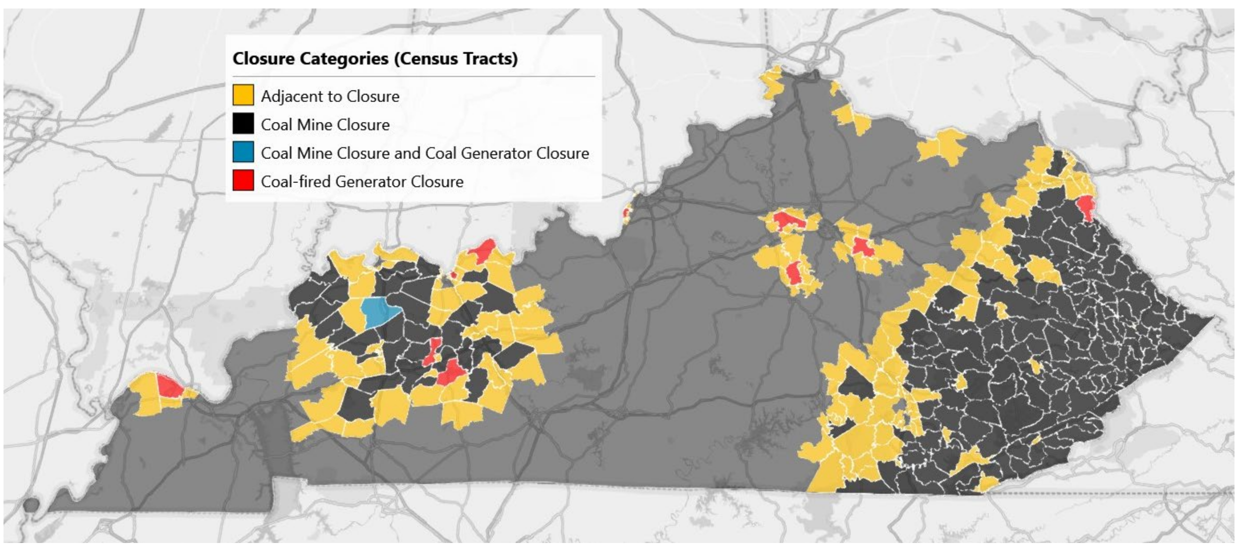

Figure 6: Kentucky census tracks qualifying as "energy communities" through qualifying coal mine closures, coal generation closures, or adjacent to such mining or generation closures. (Data from https://energycommunities.gov/energy-community-tax-credit-bonus/)

The Clean Electricity Investment Tax Credit can reduce the investment cost of wind projects by up to 50%. Alternatively, the Clean Electricity Production Tax Credit can be used to offset up to 2.25 cents per kWh produced if wage and apprenticeship requirements are met, and up to 2.85 if domestic

content and "energy community" bonus provisions are met.[11] Wind projects in most regions of Kentucky could potentially qualify for these maximum tax credits because so much of the state qualifies as an Energy Community under the 2022 IRA. The maximum tax credit comes from satisfying wage and apprenticeship data, meeting domestic content ("made in USA") requirements, and by being located in an area classified as an Energy Community. Most areas of Kentucky qualify under the Energy Community designations. To put the production tax credit amount of 2.85 cents per kWh into context, we note that the average retail price of power in Kentucky in 2022 was 10.51 cents per kWh [22].

3.3 The Value-Cost Ratio of Wind for Kentucky

The Value-Cost ratio of a project compares the value of the energy generated to the cost of the project. The project's value is its avoided cost, which is the cost that would have occurred if the project did not occur. Kentucky is in a region that is ranked among the top three in the continental US for its Value-Cost ratio for wind energy. This is partly because there is so little wind generation capacity in the region, meaning that the power generated by wind offsets the fuel costs of natural gas and coal, and what wind power is generated is unlikely to be curtailed from the grid.

Levelized Avoided Cost of Electricity (LACE) is a way of representing the *value* of the energy to be generated by a project. LACE basically considers what the cost of the energy from a project would be if the project didn't exist, where this energy would otherwise have to come from other generation sources or storage. LACE considers variation in daily and seasonal electricity demand. The demand variation over these different daily and seasonal periods results in different marginal prices of energy during those times. These marginal prices are the fuel and similar operating costs for other generating units that would have to be dispatched to cover the demand. Thus, the LACE for a wind project would represent the fuel and operation cost of other units (or the market energy purchase price if no other units are available) to supply the energy if the wind project didn't exist.

The Value-Cost ratio of a project is the ratio of the project's LACE and the LCOE. If the Value-Cost ratio is greater than one, then the value of the energy produced (represented by LACE) is higher than the cost of the energy produced (represented by LCOE). The project then exceeds the breakeven point of one and is considered to be potentially economically viable.

The value of the generated energy as represented by LACE depends on the mix of available generation sources and when they are generating. For example, for a power grid with very little renewables energy generation and heavy use of natural gas peaking units, a renewable power project may have a high LACE because the power generated by the project can replace the high-cost of the natural gas peaking unit

[11] According to [17], the credit is 2.25 cents per kWh (to be inflation adjusted) before the bonuses for projects >1MW and meeting a wage and apprenticeship requirements. The bonuses are 10% if meeting domestic content criteria and 10% if located in a qualifying energy community. However, according to paragraph 2.04 of [16], the credit for the Clean Electricity Production Credit (section 45Y) is 1.5 cents per kWh for projects meeting the wage and apprenticeship criteria, before bonus provisions are applied.

while the renewable source is generating power (such as when the wind is blowing or when the sun is shining). In contrast, a solar power project in a grid with heavy solar power generation would have a lower LACE, because it is adding to a grid that might already be saturated with solar power during sunny days.

The Energy Information Administration estimates the Value-Cost ratio of different projects in different regions of the US [1]**.** Most of the state of Kentucky is listed in their Region 16, labeled as the SERC Reliability Corporation-Central [23]. Region 16 also includes Tennessee and portions of northern Mississippi, northern Alabama, and a small part of Georgia.

The Value-Cost ratio for wind projects in Kentucky's region is only exceeded by two other regions in the US. There are a total of 25 regions. Of those, Region 16 containing Kentucky has a value-cost ratio for wind only exceeded by Region 13 and Region 15. Region 13 covers most of eastern Virginia and the northeast area of North Carolina. Region 15 includes most of Alabama and Georgia, southeastern Mississippi, and the panhandle of Florida.

The Value-Cost ratio of wind for Region 16 covering Kentucky is considered competitive, in part because there is so little wind generation currently in the region. Similarly, Regions 13 and 15 mentioned above as having higher Value-Cost ratios also have no wind generation and are primarily fuel-based (coal or natural gas) plants. As wind is added to such a grid with little wind, it has the opportunity to replace the energy from energy sources with fuel costs, such as from coal or natural gas, and more specifically has the opportunity to reduce the frequency of the grid's use of expensive natural gas peaking units. Even if the grid has much solar, the wind becomes an offset to the use of expensive peaking units at night or on cloudy days, leading to an increase in LACE. Furthermore, on a grid with the amount of wind generation capacity low, the amount of curtailment of power generated from wind is reduced. Without curtailment, the amount of energy generated to the grid is higher, leading to a lower LCOE. Thus, the lack of wind generating capacity in a grid improves the Value-Cost ratio of wind.

3.4 The Economic Potential in Kentucky for Behind-the-Meter Distributed Wind

A recent national study ranks Kentucky as 10th among states for the economic potential of commercial scale (non-utility) wind turbines, with a total economic potential of 44.6 GW [4]. NREL's term "behind-the meter distributed wind" refers specifically to non-utility installations by commercial, industrial, or residential consumers for onsite generation to offset the consumer's consumption of retail electricity. The study also considered different sized turbines, with Kentucky ranking second (behind Colorado) for potential for use of smaller commercial-size turbines (20-100KW size) in behind-the-meter applications.

3.5 Renewable Energy and its Potential Importance for Kentucky's Exported Products

Countries and regions outside the US are beginning to regulate imported products based on the greenhouse gas emissions from their production, including in the electricity that was used in their production. In some cases, these regulations impose *a tariff associated with the greenhouse gas emissions from the production or manufacture of imported products. Kentucky manufacturers exporting to such countries or regions need to source their electricity from renewables or else be at a price disadvantage due to carbon pricing on their exports.*

Kentucky is a manufacturing state with heavy export activity. There are over 6000 manufacturing facilities in Kentucky with over 250,000 Kentuckians working in a manufacturing facility [24]. In 2023, Kentucky's exports were over $40 billion dollars [25]. Of the total exports for the state, the top ten industry categories are all manufactured products, from chemicals to pharmaceuticals to aerospace products. Kentucky's direct exports specifically to Europe total $11 billion.

Some countries or regions of the world are beginning to impose carbon pricing tariffs on imports. The European Union has developed a *Carbon Border Adjustment Mechanism* (CBAM) rule to recognize greenhouse gas emissions associated with imported materials and products. The goal of CBAM is to ensure imported products do not circumvent the EU climate targets. The CBAM entered into its transitional phase on October 1 2023 and will phase into full operation by 2026 [26] [27]. During the transitional phase, CBAM is initially just tracking materials and products in the categories of cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen, and may later expand its tracking of embedded carbon to other sectors.

Starting in 2026, Kentucky industries that export to the EU will have to pay for the carbon footprint of their products. Industries using renewable energy such as wind and solar will have a reduced carbon footprint, and thus less expense in purchasing carbon certificates for exporting into the EU. Starting in 2026, importers to the EU will have to buy CBAM certificates "corresponding to the carbon price that would have been paid had the goods been produced under the EU's carbon pricing rules".

A company may have reasons other than European rules to want to use renewable-powered electricity. These corporate goals are driven by regulations in different areas of the world, but other times may be based on demands of companies higher in the supply-chain, directives of shareholders, or a brand strategy to position a company's products to appeal to certain consumer market segments. Companies in Kentucky with clean energy goals include:

- Toyota [28]: Toyota plans to match 45% of their purchased power with renewable electricity by 2026, and has a goal of being carbon neutral at all global manufacturing facilities by 2035. Toyota employs 8200 people in Kentucky [29].
- Ford Motor Company [30] [31]: Ford has a goal of reaching carbon neutrality globally no later than 2050 using 100% locally-sourced renewable energy for all manufacturing plants globally by 2035. As a step towards this goal, they have already announced that all of its electricity supply in its Michigan operations will be attributed to clean energy through a partnership with DTE Energy, which will add 650 megawatts of solar energy. Ford employs 12,000 people in Kentucky [29].
- Lexmark [32]: Lexmark, with headquarters and a manufacturing facility in Lexington Kentucky, has an aim to source 100% renewable energy by 2030 and to become fully carbon neutral by 2035. Lexmark employs over 3000 people in Kentucky [29].

- Mersen Inc [33]: Mersen Group in 2022 already has 68% of its global operations using renewable energy. They have a larger goal of reduction of greenhouse gas emissions by 20% (on a 2018 baseline) by 2025. Mersen's operations in Louisville Kentucky employ 5000 people [29].
- Metalsa [34]: The company has a goal to be a Net Zero emissions company by 2050. They have committed to a reduction of 46% of Scope 1 greenhouse gasses with a commitment to provide 62% of renewable energy to their facilities. Metalsa employs 2000 people in Elizabethtown Kentucky [29].
- Logan Aluminum [35]: Aluminum manufacturing is very energy intensive. Logan Aluminum's sustainability goals for their carbon footprint are directly tied to their electricity supply through TVA. Logan Aluminum's sustainability report notes that TVA has a 30-year decarbonization plan to reduce their carbon emissions by 80%, with an eventual goal to be net-zero by 2050. Logan Aluminum specifically notes the recent reductions in carbon intensity by TVA as helping it move towards its own corporate sustainability goals. Logan Aluminum's Russellville Kentucky facility employs 1500 people [29].
- Bowling Green Metalforming LLC: Bowling Green Metalforming is a division of Cosma International, a division of Magna. Magna has pledged to use 100% renewable electricity at their facilities in Europe by 2025 and globally by 2030 [36]. Bowling Green Metalforming employs 1,800 in Bowling Green Kentucky.
- L'Oreal [37]: The beauty company L'Oreal has a manufacturing facility in Northern Kentucky. The company has a corporate goal of using 100% renewable energy for its sites by 2025. Furthermore, the company has a goal that its strategic suppliers will reduce their direct emissions by 50% (compared to 2016) by 2030.
- North American Stainless [38]: North American Stainless (NAS) operates a production facility in Ghent Kentucky. NAS is the largest, fully integrated stainless steel producer in the US and is part of the Acerinox group. NAS has established a set of carbon targets for 2030, comprising a 20% reduction in the direct and indirect carbon emissions intensity with respect to 2015 levels.

Companies that do not have access to renewable energy directly but want to claim renewable energy use can purchase Renewable Energy Certificates, either from their utility or from projects in other states. Some companies with renewable energy goals, whether corporate goals or mandates based on their customers or regulations, are unable to achieve these goals or mandates using the mix of electricity sources available from their utility grid. In such a case, these companies can offset their carbon emissions footprint by purchasing Renewable Energy Certificates (RECs) [39]. By 2022, 9.6 million customers participated in the US voluntary green power market, procuring about 272 million MWh [40]. This represents about 6% of all retail electricity sales. The renewable energy certificate purchases can occur through a company's electric utility provider or through other suppliers or arrangements. These certificates may even come from renewable energy projects in other states. (For example, see [41].)

4 Benefits to Grid Reliability and Cost from the Complementarity of Wind and Solar Power

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Wind and solar are complementary in that they vary differently through the day and through the year. Having wind power and solar power both together on a power grid can improve the reliability of power supply with less reliance on batteries or on fossil fuel power generation.

Solar and wind power can be intermittent, with energy production depending on the time of day, the time of year, and the weather. One of the challenges of renewable energy sources like solar and wind is that they can be intermittent based on time of day and weather: when the sun sets, there is no solar power generated, and when the wind stops blowing, there is no wind power generation. However, power customers depend on their power through all times of the day and through all weather situations.

It is important that a power system be *resilient*, so that the power system can provide sufficient power to cover critical demand load at all times, even when there is a loss of generation due to the variability of sun and wind or an adverse event with other generation sources. There are several ways to achieve resilience in electricity supply. One way is through energy storage, so that excess energy can be stored when not needed and released when demanded. A second way to achieve resilience is with diversity of generation sources. This diversity can take many forms, including as a diversity in generation mix, using a mix of dispatchable sources (such as coal, gas or nuclear) or with a mix of intermittent sources such as solar and wind that vary in different ways and times. Relying on coal or natural gas for providing backup power for the grid may currently be appropriate or necessary but is counter to long-term national and international efforts to reduce greenhouse gas emissions such as CO_2 [42].

One way to achieve resilience in a power system with heavy reliance on intermittent renewable energy sources is by achieving diversity of supply through renewable sources that are *complementary*. Two energy sources are considered *complementary* if they are negatively correlated in some way, so that they do not necessarily experience loss of power at the same time. For example, they may be complementary if they are geographically distant, so that weather patterns and daylight patterns at the distant sites act with some independence, such that it may be windy at a distant site even when a closer site is calm. Two energy sources can also be considered complementary if they fluctuate differently over the day, such as wind blowing even when the solar power declines due to night or during stormy weather. Further resilience is achieved in such a system with the use of energy storage (batteries, pumped storage, or hydrogen), so that energy stored at times when solar or wind are abundant can then be drawn upon during times when solar and wind power subside.

The complementarity of wind to solar can easily be seen in the graphs in Figure 7 below: in most months, wind blows stronger at night and also blows strongly in winter months when days are short. The System Advisor Module (SAM) from the National Renewable Energy Laboratory allows analysis of potential wind installations by location, historical weather patterns, and turbine characteristics [43]. The graphs in Figure 7 were generated by the NREL System Advisor Module and represent the hourly average wind speed at 100 meters height for each month of the year. The data corresponds to the weather during 2014 and a location of latitude 37.78 and longitude 84.71, which roughly is at the E.W. Brown power generating station near Harrodsburg, Kentucky. As can be seen from the graphs, the month with the highest average wind speed in 2014 at this location was January when days are short and solar power would be low. The horizontal axis on each monthly graph is the hour of the day. As can be seen in the graphs, for most months, the average wind power by hour is higher early in the morning and late in the evening, when the sun would be down and no solar power would be generated.

Figure 7: Average wind speed by hour of the day for each month of the year for the example Kentucky site for 2014 weather.

Figure 8 shows the Kentucky statewide average of estimated solar PV (a) and wind generation (b) capacity factors simulated by each minute of every day for a year. As can be seen at the very bottom and very top of the wind graph, wind is stronger in the winter months, while solar is strongest in the summer months.

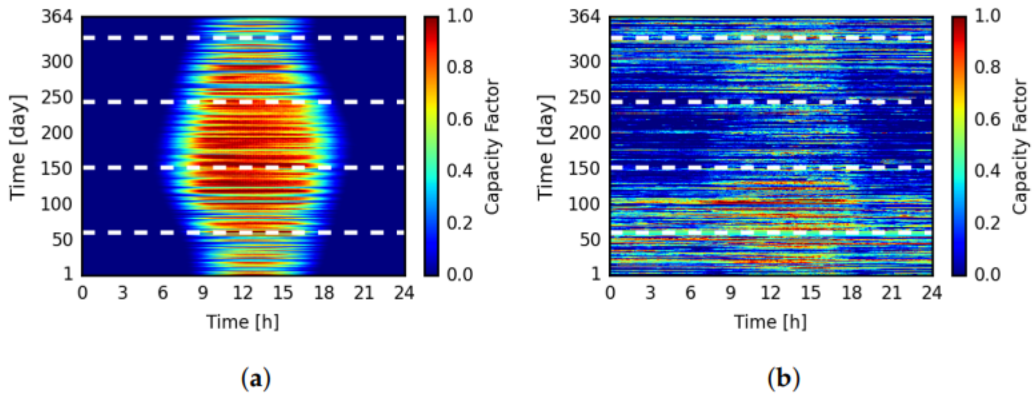

Figure 8. Kentucky state-wide utility solar PV (a) and land-based wind (b) aggregated minutely generation capacity factor across the year with white dotted lines differentiating meteorological seasons. From [3].

Wind and solar power are temporally complementary across most of Kentucky, but with the least complementarity in the mountains of Eastern Kentucky. Clark et al have shown that solar power and wind power are temporally complementary in much of the US [cite: Clark et al]. In short, in much of the US, wind often blows when the sun is down, on cloudy or stormy days, and in the winter when days are short. The degree of this complementarity varies over seasons and also geographically, with the flatter areas of the Great Plains, the Midwest and the Southeast noted as having solar and wind power as highly complementary, and mountainous areas such as the Rocky Mountains and Appalachian Mountains being less complementary.

Recent studies have shown that using complementary wind and solar power can provide some resilience to the power grid while minimizing reliance on coal and gas generation. (For examples, see various chapters of [44].). One example is an NREL study by Clark et al which evaluates a potential system near Memphis, Tennessee USA [45]. Average wind speeds in the Memphis area are very comparable to wind speeds found in Kentucky. The case study example considered ensuring energy supply of a microgrid (10MW critical load, 12 MW peak) such that the microgrid could be resilient even detached from any external power grid. Two cases were considered: renewable generation satisfying 90% of critical load with the remaining supplemented by a diesel generator, and a second case of renewable generation satisfying 100% of critical load. In both cases, when wind and solar are both strong and more power is generated than is required by the load, excess power from the sun or the wind is either stored or just curtailed.

The analysis for the Memphis-area microgrid concludes that including wind power generation in the microgrid *"enables smoother power output and decreased storage capacity requirements"*, and is also able to meet demands on cloudy days by heavier reliance on the wind generation. In both cases considered (with renewable generation satisfying 90% of critical load supplemented by diesel generator or renewable generation satisfying 100% of critical load), a system of wind, solar, and battery storage was designed to ensure that the critical load supply requirements would be met, and the results are compared to using only solar with battery (no wind generation). The solar plus battery (no wind) case is viewed as unsatisfactory due to the large and expensive battery storage capacity required to ensure power demand is met overnight.

A combined solar/wind/storage system allows improved performance with smaller battery storage than just solar with battery and also provides more effective utilization of interconnection capacity. A 2023 analysis considered a site in Texas that had a capacity limitation to the amount of power it could put on the grid at any time [46]. By combining wind and solar, they were able to use their allowed interconnection capacity more fully, and thus sell more power into the grid. They consider capacity credit of the system, which represents its "*ability to provide firm capacity or its contribution to maintaining adequate supply to meet demand throughout the year.*" For some cases they consider, adding wind to a solar plus storage system increases the capacity credit from 15% to nearly 80%.

For Kentucky, the complementarity of wind with solar is more cost effective towards decarbonization of the grid than solar power alone. The complementarity of wind with solar in Kentucky's energy mix has been analyzed in joint research done at the University of Kentucky in partnership with PPL [3]. Using state-wide analyses, wind and solar PV were found to be complementary, with high output from wind during winter months and high output from solar PV during summer months. Their analysis shows that Kentucky's grid could handle up to 25% of its energy generation from solar and wind without additional increases to LCOE. This is higher penetration of renewables than what would be possible for solar PV alone. The study also considers a more extreme case of high-renewables in a deep decarbonization scenario, reducing emissions by up to 80%. In that scenario, the grid is also supplemented by batteries and by natural gas facilities that can ramp more quickly than older, less-nimble coal plants. The need for batteries or for peaking and newer high-ramp natural gas combined cycle plants is reduced in these scenarios when wind is included in the renewables with solar. Consequently, the cost of converting the grid to reduce emissions by up to 80% is less when wind is used with solar than when solar is used alone.

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