Title: Predicting U.S. Onshore Wind Generation

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Author(s): Joshua Couch

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Abstract:

Wind turbine generation is an old technology but new for generating electricity in the U.S. In the last three decades wind energy has received much research and development in the U.S. and continues to grow. It's been enough of a focus that White House has set goals and the U.S. Department of Energy has accomplished advanced studies. For those interested in the wind industry it is worthwhile to forecast the generation coming from wind in the decades to come. This paper focuses on the wind generation in the U.S. that comes from onshore resources and what the future holds for total electrical generation.

Keywords: Wind Energy, Wind Turbines, Forecasting, U.S.

1. Introduction

The objective of this study is to forecast the future capacity of onshore wind generation within the United States. Wind turbines date centuries back and have only recently been implemented in the United States for the last couple of decades [1]. Wind turbines have had a long history in many places around the world, but have only recently been utilized in the states for electricity generation. Between 1850 and 1970 wind mills in the US were primarily used for pumping water. Generating electricity from the wind didn't take full effect until the oil crisis in the early 1970s. From 1973 until 1986 wind turbines (WTs) moved quickly from domestic & agriculture to utility wind farm applications. The first major penetration development occurred in California when 16,000 turbines were installed ranging from 20 to 350kW between 1981 and 1990. After 1990, most of the wind generation market shifted to Europe, with the US close behind [2]. The US wind turbine market is still young and has barely begun to tap the onshore resources. Considering the great potential, it is of interest to many people and companies what a forecast of wind turbine installation growth looks like in the U.S. for the years to come.

2. Methods:

Forecasting by means of growth curves is the methodology used in this paper to predict the future of wind turbine, WT, generation in the US. The most common equations used by forecasters are the Pearl and Gompertz curves [4]. These growth curves are based on historical data and project future development based on that data [3]. Both curves operate under the assumption that there is a technical performance limit [4]. These limits could be anything from physical, like absolute zero, speed of light, carnot efficiency, to ratio limits, like efficiency or percentage [4]. The Pearl curve equation is $y=L/(1+a\exp(-bt))$ with L acting as the upper limit of growth. The variables a and b change the shape of the curve. The curve is symmetrical and is used with technologies where imitation aids adoption. Basically, when one person buys a product the more he influences another to buy the same product. It can also be said that existing adoption aids further adoption. When given a set of historical data, like this study on gross WT generation, it becomes necessary to linearize the Pearl Curve and use regression techniques to find the necessary variables. The other popular growth curve, Gompertz, is different from the Pearl curve. The Gompertz curve is asymmetrical and follows the line of thinking that says existing adopters do not have any bearing on new adopters. The equation for the curve is $y=L/\exp(-b\exp(-kt))$. Again, like the Pearl Curve, L is the upper limit of growth while b and k dictate the shape of the curve toward the beginning and end. This particular curve is asymmetric but still has the ability to be linearized to find necessary variables. The steps and equations used to create the Gompertz forecast are listed below in Table 1.

For this paper a Gompertz curve was used to predict future U.S. wind generation. Reasons for choosing a Gompertz forecasting technique are explained in the discussion section toward the end of the paper.

3. Theory & Calculations:

First a theoretical limit was researched for total wind generation capacity within the U.S. for the variable "L" [5]. Then historic wind turbine generation data was collected from 1982 up to 2014, just for the U.S. These data points were used as x and y values and fitted to a Gompertz curve. The process of using historical data to calculate a fitted curve is listed in the table below.

Step	Description	Equations - Gompertz
1.	Start with the growth curve.	$y = Le^{-be^{-kt}}$
2.	Take the natural log of each side and simplify to linearize the graph.	$\ln\left(\ln\left(\frac{L}{y}\right)\right) = \ln(b) - kt$
3.	Separate components to match a linear equation	$Y = \ln\left(\ln\left(\frac{L}{y}\right)\right)$, $A = \ln(b)$, $B = -k$
4.	y = historical data. t = years 1983-2014 Use linear equation to back solve for variables *b, k*.	$Y = A + Bt$
5.	Plot new curves with calculated variables.	$y = Le^{-be^{-kt}}$

Table 1 *Process showing the integration of growth curves with known historical values [4].*

The Gompertz curve was plotted with the historical data and compared with the White House goals of doubling 2013 WT generation by 2025 and achieving 20% WT generation by 2030 wind study. First a forecast was created solely based on historic generation, then two more forecasts were created using the two government goals paired with the historic data. Each of the government goals were included separately while forecasting the other two curves. An example of this process is given in the 3 figures below. Each graph contains different linear trendlines & equations, which correspond to different b and k values calculated in steps 3 & 4 in Table 1.

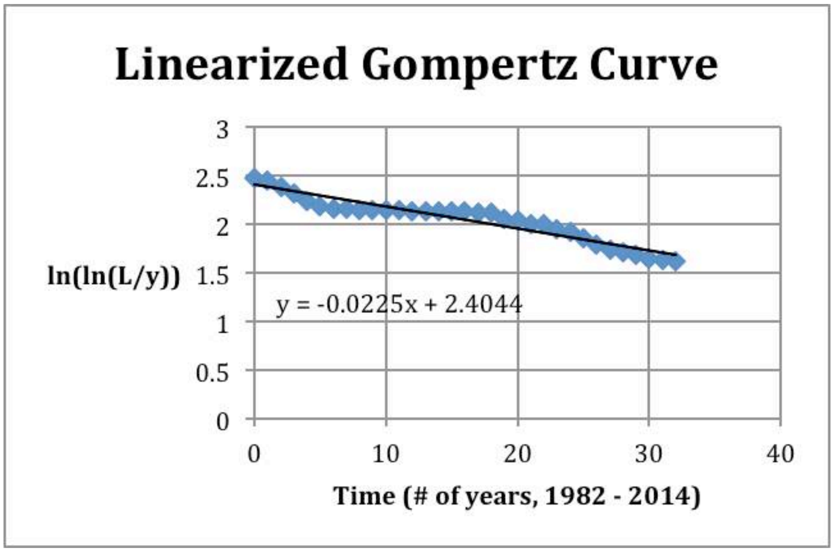

Fig. (1) *Linearized Gompertz curve purely based on historic wind generation data between 1982 – 2014*

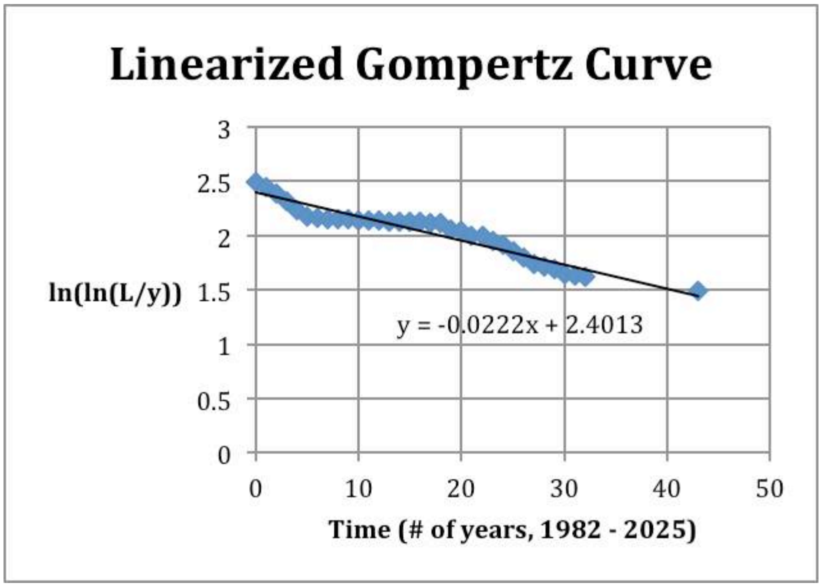

Fig. (2) *Linearized Gompertz curve including the 2025 White House goal.*

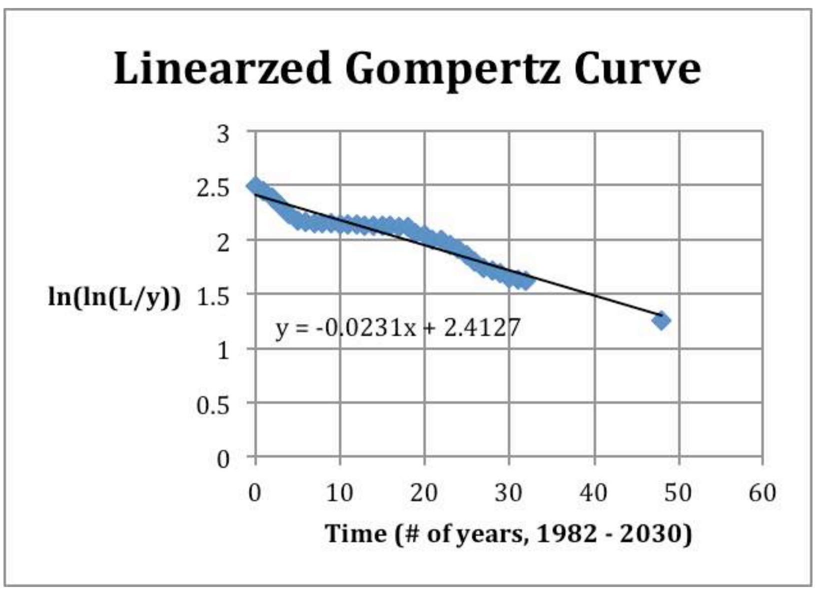

Fig. (3) *Linearized Gompertz curve including the 20% WT generation by 2030 goal.*

In Figure 2 it is assumed that the U.S. is able to achieve the goals set by the White House by 2025. It also makes this assumption without knowing what happens between 2015 and 2025, merely that the U.S. met a finite goal. Figure 3 assumes the U.S. meeting the goal of 20% by 2030 publicized by the U.S. Department of Energy. It also assumes the U.S. meeting a finite goal by 2030 without any idea what happens between 2015 and 2030. With all this in mind, it is necessary to show the Gompertz curve forecast results from the methods and theory listed above.

4. Results

The first figure shown, Figure 4, graphs the historical wind generation in all 50 U.S. states and represents all the data used to calculate relevant forecasts. The predicted Gompertz curves are also shown below in Figures 5, 6, and 7. Figure 5 is forecasting the future generation solely based on the historical data. Figure 6 includes the two extra forecasts. The orange curve includes the 20% wind turbine generation by 2030, and the yellow curve includes the White House goal of doubling 2013 generation by 2025. The forecasts extend a couple centuries and are hard to distinguish between the curves, so Figure 7 shows the same forecast, just up to the year 2050.

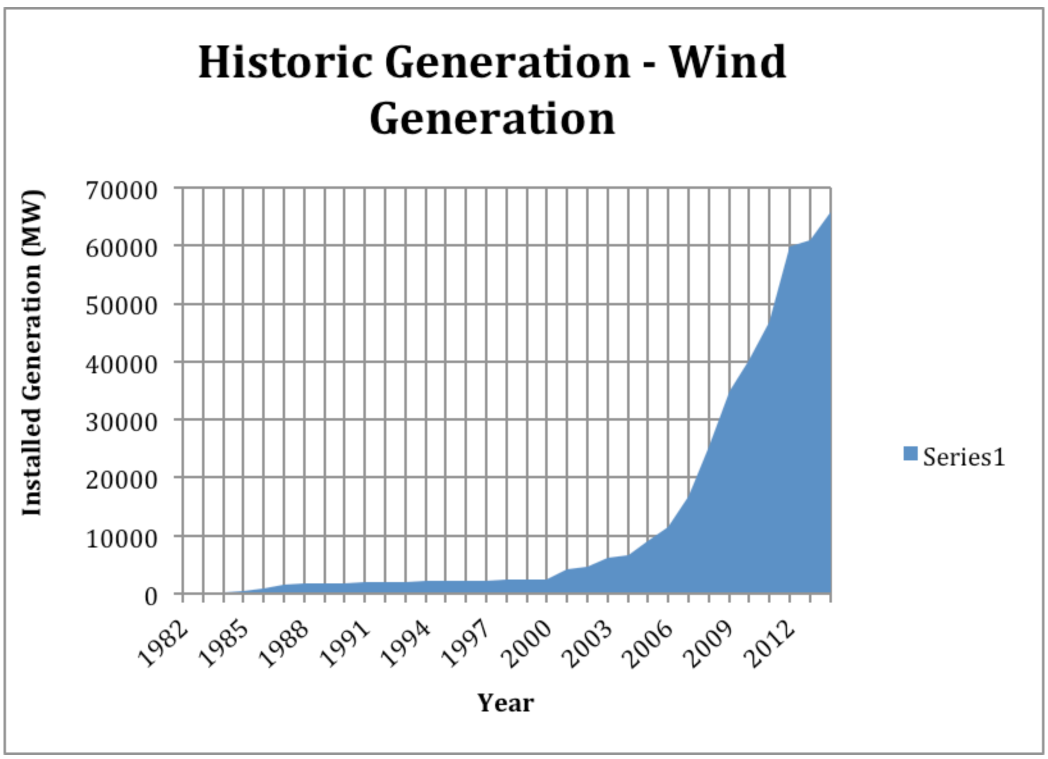

Fig. (4) Historic data of onshore U.S. wind turbine generation, used with growth curve.

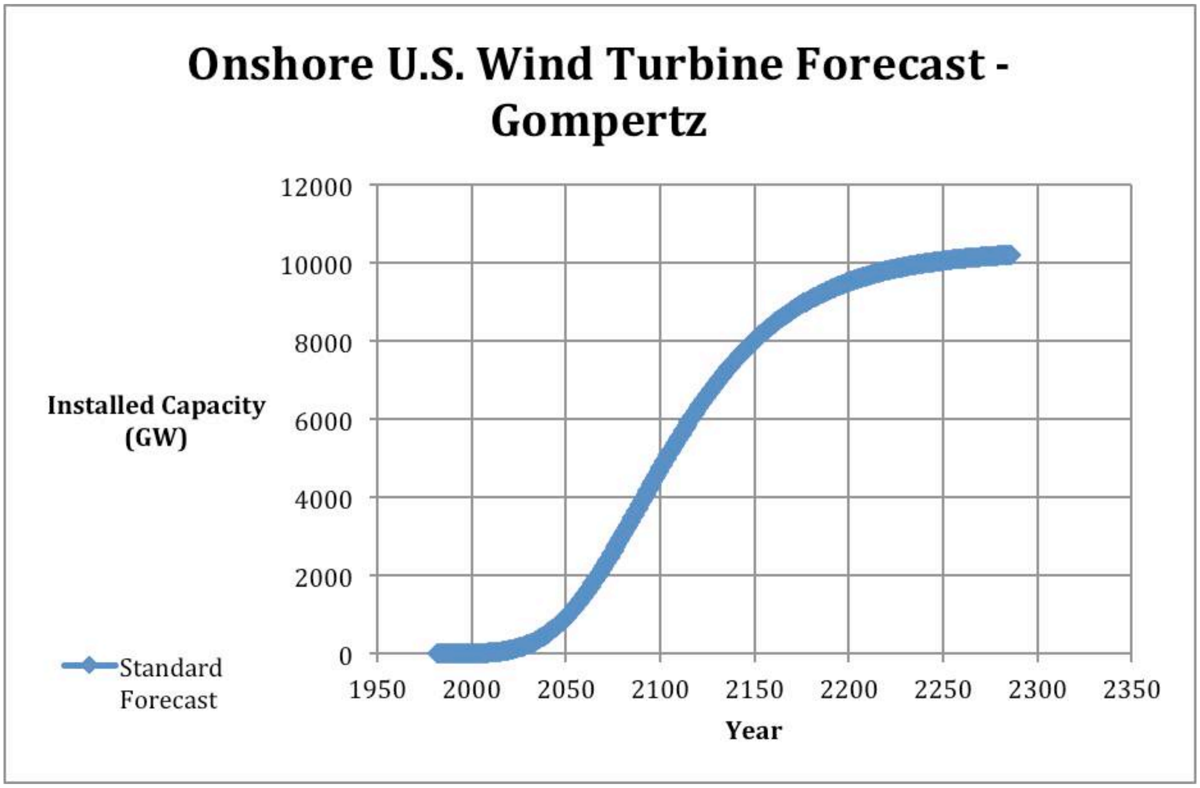

Fig. (5) Gompertz forecast results using only historical data

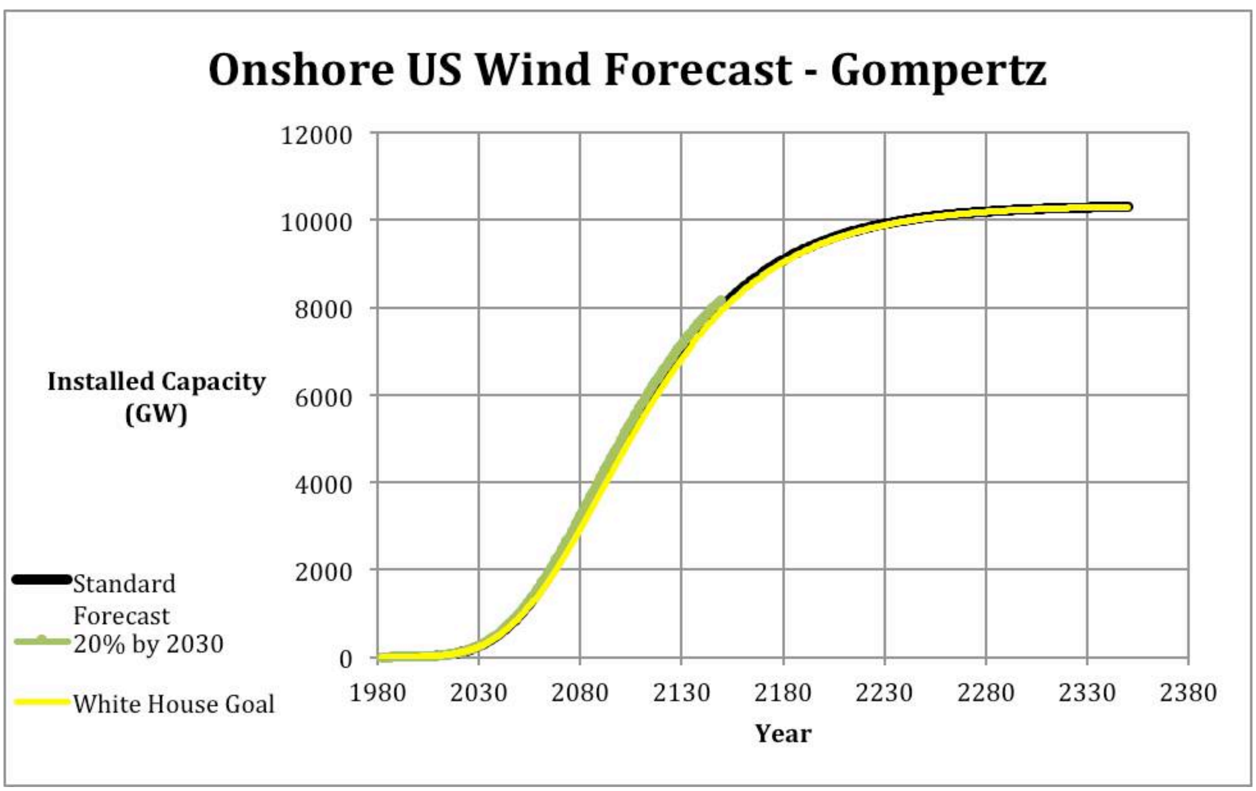

Fig. (6) Gompertz forecasting results with historical data and both government goals.

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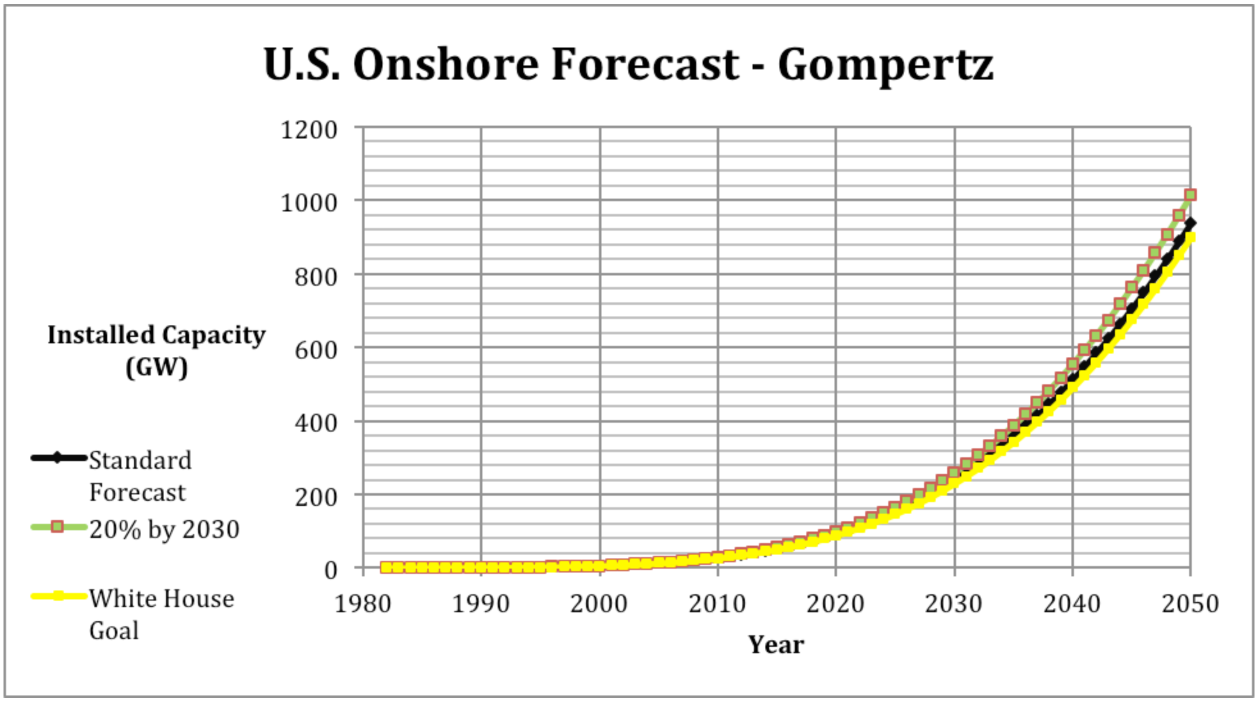

Fig. (7) Gompertz forecasting results with historical data and both government goals up to 2050.

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Figure 6 shows mainly two forecasts based on historical data and government goals. The orange and yellow curves demonstrate the predicted outcome decades down the line given we meet the White House goal and 20% by 2030 respectively. For the purpose of seeing all three curves the orange curve was not drawn any further than year 2150. Figure 6 has the complete predicted forecast drawn out to the year 2350, while Figure 7 has the model drawn out to the year 2050. Figure 7 basically zooms in on the first part of Figure 6. Though there are differences between each of the three curves, they all close in and intersect around 2350 in an extended forecast. These curves are not infallible and do come with their assumptions and potential pitfalls which are worth discussing in the next section.

5. Discussion:

Looking at these predictions, there is significant data to pull from for a future forecasting, see Figure 4. The numbers go back to the early 1980s; but 32 years of data allows room for error in a forecast looking out to the year 2350. For this reason it is likely that the Gompertz curve gives a better projection of what WT generation looks like in the U.S. in the next 45 years. This near future picture is shown in Figure 7. It is easier to see the difference between the three forecasts here; and the 20% by 2030 is the most liberal while the White House goal is the most conservative. The largest difference between the curves is about 100 GW with the standard forecast sitting right in the middle. This may seem like a huge gap; but considering the large scope of Figure 6, it's a good forecast.

It is necessary to talk about the legitimacy of the selected theoretical limit, which is the variable L. The researched limit of 10,300GW is found in [5] and is based on wind resource data at various hub heights above the ground in each state. In the study they disregard land that cannot be developed by wind turbines including urban areas, wilderness, parks, national parks, airports, wetland, water features, etc. The study considered three different technologies with capacity densities of 4.88MW/km^2, 2.53MW/km^2, and 1.83MW/km^2. For the sake of this paper the value of 2.53MW/km^2 was used because it is based on 2014 wind turbine technology [5]. The study also limited the U.S. onshore capacity to sites and locations where wind could be produced at a gross capacity factor, GCF, >=35%. This value is typical for wind developers and represents the ratio of actual power output to rated power output [7]. This provides a reasonable limit for the onshore max potential of wind turbines (WTs). Both Pearl and Gompertz curves use the same value for L, but calculate very different forecasts.

That being said it was also assumed the Gompertz curve provided a more reliable forecast than the Pearl curve. As mentioned previously, the Pearl curve is symmetrical and based on the idea that progress achieved enhances future growth [4]. This curve is more advantageous with consumer goods and less effective at predicting technology growth dependent on tax policy, market structure, and government set goals. The Gompertz curve is not symmetrical and is fundamentally based on absolute technical performance. Wind turbine advancement relies not so much on progress achieved but on scale economies, reduced maintenance and operation, gradual upscale and funding development programs [1]. For these reasons the Gompertz curve is accepted as being the more realistic forecast.

As for the government goals, the objective to reach 20% wind provision by 2030 originated with President Bush's administration in 2006 [6]. Talks of increasing efficiency and diversifying the U.S. energy portfolio led to a collaborative. What came out of the effort was a report on what would need to happen between 2008 and 2030 in order to reach 20% of electricity provided by wind turbines. In order to generate the report a list of common assumptions were made while holding realistic constraints in balance [5].

It is interesting to note that both forecasts including the government goals, the orange and yellow curves in Figure 6, and show close forecasts to the standard. This encourages the accuracy of the standard forecast. Even though there are many obstacles to overcome to reach this goal, it is a goal that lines up with the prediction from historical data. As seen in Figure 7, reaching 20% by 2030 is the most liberal of the three forecasts. This curve has the potential to be more conservative. In the report [5] they predicted some of the 20% generation to come from offshore wind. These reports only deal with onshore wind; but taking this into account, the 20% by 2030 curve might line up much more with the White House goal.

The forecasts are based on historic data and big goals. These two characteristics hold a lot of weight in the prediction, but can't account for everything. There are still problems of transmission line upgrades, raw material resource, market structure, infrastructure expansion, education and skills gap, and manufacturing [5]. There are also questions of how photovoltaic panels will be integrated and used in the same land space as WTs. Even with much of the uncertainty, the model assumes that these problems get solutions as the technology expands and develops further.

6. Conclusion

Wind turbine generation has been a part of U.S. history for the last four decades. It started with research being implemented because of an oil crisis; and now it's building on momentum created in the last 15 years. In this paper a forecast of onshore wind generation in the U.S. was conducted using a growth curve. The particular type of growth curve selected was a Gompertz curve. 32 years of historical data were fitted to a Gompertz curve and compared with similar predictions that included governmental goals. Considering the forecast predicts growth until year 2350, it was concluded the forecast is best utilized in the near future, no further out than year 2050. As shown in Figure 7, the standard forecast is sandwiched between the other two government goals, making it a reasonable forecast for future generation.

7. Acknowledgements

Firstly I would like to express my sincere gratitude to my professor Dr. Jisun Kim for his input, professional experience, and continuous support of my research. Besides my professor, I would like to thank my peers Nicholas Metzar and Bhaskar Uthanumalliah for their input and help with clarifying my research.

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