Determining the Upper Economic Limit of Wind Fleets

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Abstract: Wind fleets have become significant en-ergy sources within national grids. However, future expan-sion of wind fleet capacity may result in little incremental benefit due to the inability of present grid architectures to absorb high levels of excess generation. Determining the upper economic limit is a topical issue but its solution is complicated by variations in energy system architectures and local weather conditions, making energy models essential to system planning. This paper outlines a simplified methodology, referred to as the histogram model, to calculate the upper economic limit for wind fleets, based on annual data for energy generation, recorded at hourly intervals, and the system's headroom, defined as the difference between base load and demand. The amount of 'useful energy' is derived from the wind energy frequency table, the total installed wind fleet capacity, and the headroom. The calculations lead to values for the incremental decarbonisation cost, which can be directly compared to the cost of decarbonisation for gas-based energy generation. The results indicate that the upper economic limit is a wind fleet capacity of 3 times the headroom, where 78 % ***of the required energy is derived from wind and the wind fleet efficiency is*** 82 % ***(***18 %***of the available wind energy is shed). The development of the model has implications for energy planners, who can now more easily simulate the performance of energy systems as a function of various input parameters.***

Additional keywords: Economic Limit, Incremental Decarbonisation Cost, Wind, Histogram Model

1 Introduction

Higher levels of wind energy penetration, defined as the wind energy proportion within the total energy mix, are both economically and environmentally desirable, given that wind energy is the lowest-cost energy technology [1]. However, there is a trade-off between incremental benefit and incremental cost as the contribution of wind fleets to the total energy supply increases. It is, therefore, useful to consider the upper economic limit for wind fleets, beyond which further additions to wind capacity are no longer economically justifiable [2].

The trade-off property of wind fleets is a consequence of three aspects of system architecture, namely the inability of energy systems to store large amounts of electricity; energy demand, which itself fluctuates and must be instantaneously supplied; and wind, which is an intermittent resource, fluctuating over often quite short periods (such as 4 to 8 hours) from strong ($> 20\,\mathrm{m\,s^{-1}}$) to minimal ($< 2\,\mathrm{m\,s^{-1}}$). The intermittency of supply, the immediacy of demand and the absence of storage together result in a mismatch between demand and supply, with energy systems generally designed for excess generation capacity, leading to the phenomenon of wind shedding, whereby energy available in excess of demand must be curtailed.

Curtailment inevitably introduces economic inefficiency since existing assets cannot perform at their design output and the cost of energy generation per unit of electricity rises. This paper explores the curtailment issue within South Africa's national grid (Grid SA) using a model for wind fleet efficiency as a function of headroom (the difference between base load and demand) and installed wind fleet capacity. These values for efficiency are then translated into economic costs and, finally, the marginal cost of decarbonisation, expressed as unit cost per unit of electricity (electrical energy) generated. The latter is compared to the cost of carbon capture and storage (CCS), from which the upper economic limit is derived.

The example is a useful illustration of a spreadsheet model developed to investigate the question of energy system designs and how these designs can be optimised. There are probably endless possible architectures for national energy systems and models essential to evaluating their relevant merits. However, many existing models are proprietary and inaccessible to researchers and policy practitioners. This paper presents a simplified approach that can be easily copied and used by the broader public without losing the key insights that may be derived from more comprehensive approaches.

In Section 2, the model's assumptions and algorithms are explained. Section 3 presents the analysis of wind fleet efficiency as a function of capacity, followed by Section 4 discusses the results and suggestions for other applications.

2 Literature Review

Models for energy systems are widely used to simulate system performance under various input conditions, including different combinations of generation technologies, consumption patterns, storage capacity, and the design of energy distribution networks. The models are helpful to multiple stakeholders, including researchers, policymakers, and industry professionals, and are invaluable in the evaluation of complex systems for which single input/output assumptions are not valid.

A brief review of the literature on the "energy system model" listed more than 1850 documents over the period 2006 to 2023, covering topics from energy systems modelling for

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just transitions [3], transformation pathways to achieve net zero [4], the role of storage [5] and the impact of electric vehicles [6]. The models can be categorized according to their purpose (simulation, optimisation, economic/equilibrium), their spatial coverage (local, regional, national and global), their temporal resolution (millisecond to decades), and other parameters [7]. The wide variety of choices of the most suitable model is a little overwhelming, although some guides are available to understand the options and assist in the most appropriate choice [8].

In terms of wind energy modelling, accurate and reliable forecasting of energy supply is considered to be a major challenge, with only a small number of models able to simulate the stochastic nature of wind energy [9]. This article covers a simple approach to system-level modelling, incorporating wind energy models into broader energy system models to understand the overall impact of wind energy on the entire energy infrastructure. This type of model is useful in looking at scenario-based modelling to assess different future scenarios, considering factors like energy demand, technological advancements, and policy changes. The models are also useful in uncertainty and sensitivity analysis, such as probabilistic modelling (account for uncertainties in wind speed, turbine performance, and other parameters by using probabilistic models, such as Monte Carlo simulation), and sensitivity modelling, which identifies key parameters significantly influencing the performance of wind energy systems, and thereby helping to focus research and development efforts.

The abundance of existing models suggests little reason to develop yet another. However, the author's experience is that many simpler models are deterministic. Stochastic models are available, but these tend to be complex, proprietary and expensive to access, using large libraries of weather data, system demand and technology performance values to determine the levelised cost of electricity (LCOE) and other parameters. Although the predictions and outputs of these models may be accurate within the user's specifications, in most cases they are expensive to access, operate and maintain, making them impractical for routine applications by non-experts. The objective of this work was to develop a simple, stochastic model with sufficient versatility to allow the investigation of multiple system architectures and configurations.

3 Model Design and Assumptions

In this analysis, a spreadsheet model, previously described in the literature, is used to model energy demand and supply on the RSA Grid [10]. The inputs to the model are as follows:

- Hourly data for wind energy delivered to Grid SA, as reported on the Eskom data portal [11], covering one full year (2022) and separated into 12 comma-separated value (CSV) files, one file for each month of the year
- Total average power (or energy) demand, also extracted from the Eskom data portal (in this study, 26 GW was used)
- the total base load available within the system, as a proportion of the average demand or as an absolute value (20 GW was used, leaving a residual of 6 GW GW for the headroom)
- The levelised cost of electricity for wind and gas/diesel with and without CCS. The values were obtained from the literature and were set at $\$34\mathrm{MW}^{-1}\mathrm{h}$, $\$88\mathrm{MW}^{-1}\mathrm{h}$ and $\$38/\mathrm{MW}^{-1}\mathrm{h}$ respectively [1]
- The LCOE for gas/diesel is predominantly the cost of the fossil fuel (capacity utilisation has little impact on gas/diesel LCOE).

Full details on how these input values are processed to generate the histogram have previously been reported in the literature [10, 12, 13, 14]. In brief, the following steps were applied:

- Transfer of the values from the 12 CSV files into separate pages of a single spreadsheet, previously formatted to allow subsequent calculations, with one page for each month of the year
- analysis of the wind generation data to generate frequency tables for incidences of wind energy within the pre-determined generation bands (for example, the 2022 data used in this study was analysed using 15 generation bands, each of 200 MW, extending over the range zero to 3 GW
- calculation of the net energy delivered by the wind fleet from the product of the generation band and the measured frequency, and hence the efficiency of the wind fleet relative to its performance in the absence of curtailment [13]
- calculation of the marginal decarbonisation efficiency [13, 15] and the marginal decarbonisation cost from the gradient of the efficiency curve.

By way of example, RSA Grid data for the first week of August 2023 is shown in Figure 1.

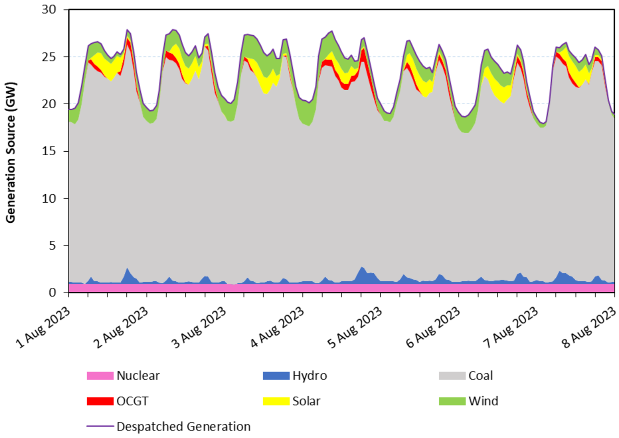

Figure 1 Electricity supply and demand on Grid SA (Week 1 of August 2023).

The profile of supply and demand is typical of the winter months in South Africa, with a characteristic morning and evening peak, reduced demand over the weekends and highly variable inputs from wind, solar and open cycle gas turbines (OCGT), the latter by design since diesel is used as a dispatchable resource.

The frequency data for wind generation on Grid SA for 2022, extracted as explained earlier and represented in a histogram format, is shown in Figure 2. The total installed capacity in 2022 was 3,433 MW, a figure which changed little during the year as a result of delays to further implementation of the Renewable Energy Independent Power Producers Procurement Programme (REI4P). Based on the values from the frequency table, it is calculated that the average wind power delivered to Grid SA for 2022 was 1,096 MW, giving an overall efficiency (actual power/wind fleet capacity) of 31.8 %.

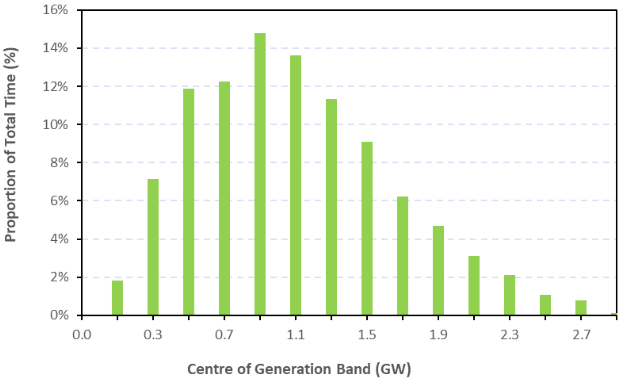

Figure 2 Wind histogram for 2022.

It is apparent from Figure 1 that demand on Grid SA is highly variable, fluctuating by as much as 6 GW over any 24 h period. The extent of this variability and wind intermittency, are even clearer in Figure 3, which shows the recorded data for GridSA's headroom in the first week of December 2022.

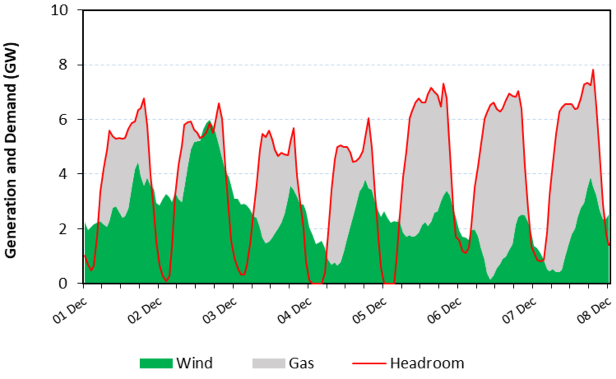

Figure 3 Variability in wind and energy demand (Week 1 of December 2022).

The figure also illustrates two important aspects of the model. Firstly, the objective of the model is to calculate an upper economic limit for the wind fleet, where the limit is determined by the relative costs of two net-zero carbon generation technologies, namely wind energy and gas/diesel turbines with CCS. This question is also important when considering options for grid expansion and replacement of coal-based generation.

Secondly, the figure raises the question of how a steady state assumption for headroom and a wind energy frequency table can deal with the variable nature of both wind and demand in calculating energy shedding as a function of wind fleet capacity. Previous studies have shown that assuming non-variable demand in conjunction with using wind frequency tables does not result in significant errors in calculating wind energy that can be accommodated by the headroom [15]. Therefore, this study assumes that the demand variability can be ignored.

Values for shed wind energy can now be calculated in the following steps:

- The total size of the wind fleet is scaled according to the desired energy output
- The quantity of wind energy within each generation band, similarly scaled, is estimated and then compared to the available headroom
- If the calculated power exceeds the available headroom, the total generation is capped within the headroom
- The net values for energy used by Grid SA are summed and compared to the predicted output in the absence of curtailment, leading to a value for the fleet efficiency (relative to the average value with zero curtailment)
- The latter is then used as the basis for calculating the total energy cost, and the incremental cost.

4 Modelling Results

The research question for the modelling work of this study has been to determine the upper economic limit for wind fleets as a function of the available headroom. As already noted, the model makes a zero-carbon assumption. In other words, the energy demand of the headroom must be met with either wind energy or gas/diesel with CCS. The optimum level of wind energy is calculated in the analysis as the optimum wind fleet capacity in proportion to the headroom. An increasing value of this ratio results in a decreasing levelised cost of electricity as the higher cost of gas/diesel with CCS ($\$88\mathrm{MW}^{-1}\mathrm{h}$) is replaced by wind ($\$32\mathrm{MW}^{-1}\mathrm{h}$). However, the benefit of lower-cost wind energy is lost once the total wind fleet capacity exceeds 3 times the headroom, at which point wind energy accounts for 78 % of the headroom, the wind fleet has an overall efficiency of 82 % of its available capacity, and carbon emissions are close to 6 million tonnes per year. This result is shown in Figure 4.

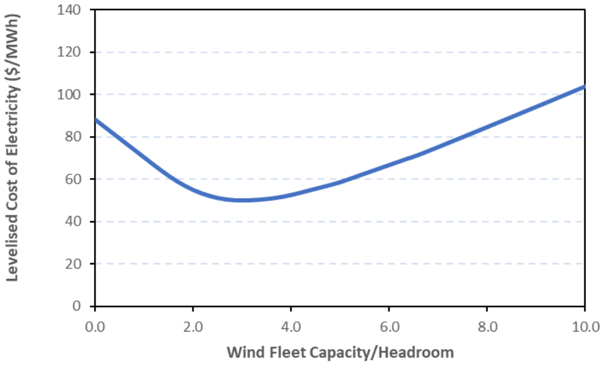

Figure 4 LCOE as a function of wind fleet capacity in proportion to headroom.

An alternative approach to calculating the upper economic limit is to consider the marginal decarbonisation efficiency [15], and hence the marginal decarbonisation cost, the latter expressed as cost per MWh of energy, rather than the conventional measure of the levelised cost of carbon removal. The use of marginal cost, rather than the system-level LCOE, is more informative in energy planning since the expansion of wind fleet capacity is typically incremental. In other words, planners and investors must consider the return on investment from new additions to the wind fleet, given that these investments need to deliver project-specific returns. The analysis using marginal cost suggests that a lower economic limit for wind fleets is more applicable, with the limit being reached at about 2.5 times the headroom, at which point the marginal cost exceeds the cost of CCS ($\$50\mathrm{MW}^{-1}\mathrm{h}$) when used with gas/diesel turbines (see Figure 5) and the wind fleet contributes only 71 % of the available headroom.

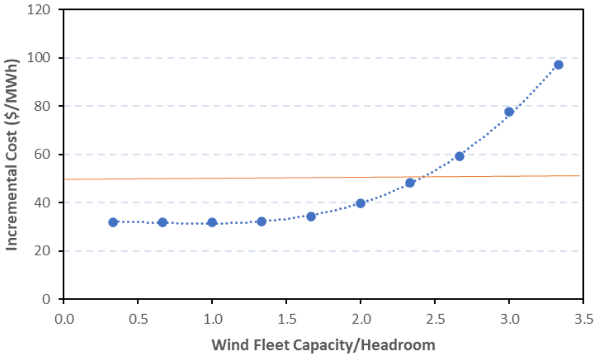

Figure 5 Marginal decarbonisation cost vs wind fleet capacity.

5 Discussion

The multiplicity of options for energy system architecture complicates the decisions of investors and energy planners in reaching an optimal configuration. The use of models as a means of evaluating these options, and hence identifying the preferred architecture, has become invaluable. It is simply too complicated to conduct such evaluations without tools to consider the impact of alternative designs.

However, many energy system models are not in the public domain and are inaccessible to energy planners within government departments and small companies. There is, therefore, a need for accessible and less specialised models that can be easily implemented and applied to various energy systems to provide the necessary insight into the planning process. In this article, such a model is presented.

The model draws from data for South Africa's wind fleet output throughout 2022. This data is analysed using frequency tables and then structured to allow the calculation of potential wind energy output over a range of generation bands for a pre-determined size of the wind fleet. The outputs are then compared to the available headroom and capped where necessary to ensure that the total wind energy remains within the system's headroom.

This paper has illustrated the methodology for the case of Grid SA, with a specific focus on the maximum economic limit for South Africa's wind fleet based on a headroom of 6 GW. The analysis concludes that the wind fleet capacity should not exceed 3 times the headroom. At this point, the fleet will be 82 % efficient (18 % of the available power will be shed), and wind energy will contribute 78 % of the headroom, with the remainder being derived from gas/diesel turbines with CCS.

The result reflects the decreasing efficiency, and hence increasing cost, of wind energy as the size of the fleet is increased and more wind must be shed since it cannot be accommodated by Grid SA. As calculated in this analysis, the specific values for the maximum economic limit will depend on the input assumptions and changing values for LCOE. Indeed, the power of modelling is that such changes in the input values can easily be investigated.

The model can be extended to consider other questions, such as the economic limit for wind fleets operating within systems supporting significantly higher headroom or lower base load. It is anticipated that national grids will need to increase as the use of electrical heating and battery electric vehicles expands [16]. For instance, it is not inconceivable that Grid SA will need to meet an energy demand of double its present size, with a base load of perhaps one-third of the present values, as coal-based electricity generation is retired per the energy policy [17]. In such circumstances, a wind fleet of 90 GW, operating at an efficiency of 80 %, may be optimal.

6 Conclusions

This paper describes a histogram model, built using spreadsheets and data from the Eskom data portal. The model has been developed to meet the needs of energy planners and investors who wish to investigate the implications of multiple options for designing energy systems but do not have access to large proprietary databases.

The histogram model is illustrated with a single example used to calculate the upper economic limit for the South African wind fleet. Surprisingly, the result indicates that this limit is at least 3 times the headroom, at which point the wind fleet is only 82 % efficiency (18 % of available energy is shed).

Wind fleet efficiency is an important indicator in this analysis and its demonstration of the histogram model. Based on the 2022 data, the South African wind fleet has a present efficiency of 32 %, under conditions where the fleet is still relatively small compared to the headroom, there is little shedding and the wind LCOE is at a base level of $\$32\mathrm{MW}^{-1}\mathrm{h}$. As the fleet increases, the extent of shedding will, by implication, increase, thereby reducing the efficiency and making wind less competitive as a means of decarbonising the electricity grid. The optimal size correlates with an overall efficiency of 26 % and an LCOE of $39MW h. Beyond this level, it makes more sense to consider the use of gas/diesel with CCS, although it is noted that this comparison is still entirely hypothetical given the untested status of large-scale CCS.

In summary, the study shows that simple spreadsheet models can solve important questions about energy systems. Further applications will be considered as energy systems evolve and new scenarios emerge.

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