Irreversible investment in wind turbines: life-extension versus repowering

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1 Introduction

The member states of the European Union have agreed to reduce the emission of greenhouse gases substantially by 2050. Specific targets, like EU2020 and EU2030, have been set in order to reach this long-term goal. Therefore, there is a strong focus on generation of renewable energy, such as, for example, wind power. It is expected that wind, together with solar power, is the most important contributors to reaching this target. As Figure 1 shows[1], the wind power production is expected to increase drastically over the coming two decades.

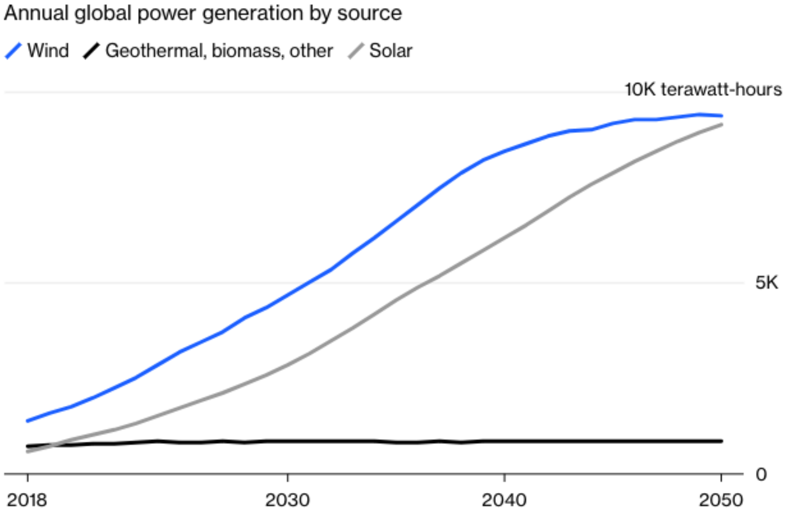

Figure 1: Expected annual global power generation by source (Source: Bloomberg NEF New Energy Outlook 2018)

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[1] Figure 1 excludes generation of hydroelectricity

Already by 2020, about 28% of the European wind power capacity will be older than 15 years ([Ziegler et al., 2018]). As wind turbines have an average life-time of about 20 to 25 years, it is important to analyze the decision what to do with the wind turbine after near the end of its life-time. Over time, the wind turbine becomes less efficient and produces less energy.

When a turbine is approaching the end of its technical or economical lifetime, there are primarily three options available: Decommissioning, life-extension and repowering, as schematically shown in Figure 2.

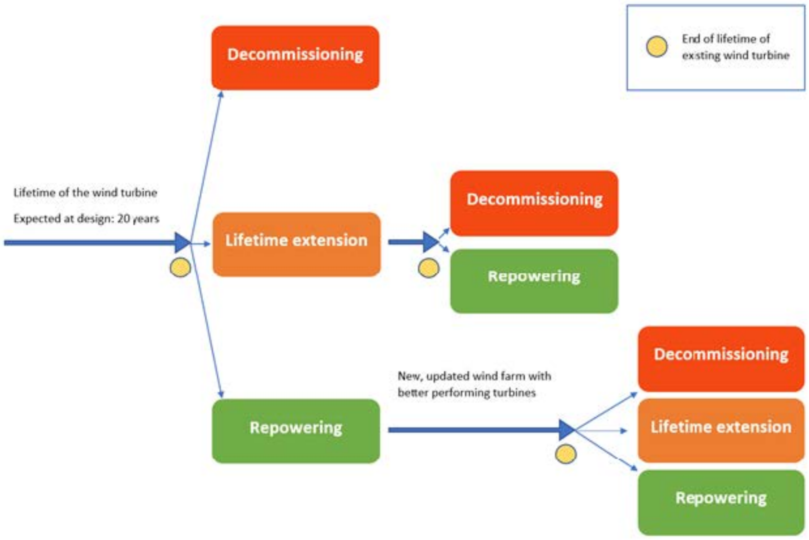

Figure 2: End-of-life options for wind turbines

Decommissioning is simply to dismantle a turbine and recycle the materials. Since the initial investment required to build and install a wind turbine is to a large extent a sunk cost, and the operations and management costs are low relative to the revenue generated, the operating profit of a wind turbine will almost always be positive. Therefore, wind turbines will generally not be decommissioned before the end of their technical lifetime unless they are to be repowered. There can however be reasons for why a wind farm has to be decommissioned instead of repowered at the end of its technical lifetime, e.g. lack of capital or that the government is unwilling to extend the concession.

Life-extension, also called lifetime-extension, is as the name implies to extend the technical lifetime of a turbine. This is done by renewing and/or upgrading components of the turbine. As the lifetime of different turbine components vary significantly, it is common to renew only one or a few components at a time. Life-extension can also have the added benefit of significantly improving the performance of the turbine and reducing the levelized cost of electricity, and is relatively inexpensive compared to repowering. Due to recent developments to monitoring systems it has made predicting the remaining lifetime of individual turbine components more accurate and less expensive, hence improving the viability of life-extension.

Repowering of a wind farm or a single turbine is to decommission the old turbines and build new, and usually better turbines in the same area. This is usually done at the end of the economic lifetime of the wind farm, when the opportunity cost of not repowering is estimated to be greater than the current operating profit. Because the operating profit of aging wind farms almost always is positive, scarcity of land is a necessary condition for repowering to be an economically viable option. If land is not a scarce resource, it would always be more beneficial to keep the old wind farm operating until the end of its technical lifetime and simply build the new wind farm elsewhere. Note that scarcity of land is not simply a matter of land being available for wind power production, the potential for wind power production is also very important.

2 Model

Consider a wind energy producer with a stochastic gross operating margin of one turbine that follows geometric Brownian motion:

$$g_t = \alpha g_t dt + \sigma g_t dZ_t \tag{1}$$

The wind turbines has an initial efficiency, Q, equal to Q_0. The efficiency of the turbines declines over time in the following way:

$$dQ_t = -\gamma Q_t dt \tag{2}$$

From $t = 0$, a firm has a possibility to repower, i.e. to install a new turbine with efficiency $Q_t^R = K_R e^{-\gamma t}$, with initial efficiency equal to $K_R > Q_0$. The costs of repowering are equal to I_R. Alternatively, the firm can extend the life-time of the existing turbine first by a fixed amount of years (and repower after the end of the extended lifetime). The turbine efficiency after the life-time extension is equal to $Q_t^L = K_L \mathrm{e}^{-\gamma t}$, with $K_R > K_L$ and costs $I_L < I_R$. Thus, repowering results in a more efficient turbine, but also costs more compared to the life-time extension.

Define the new variable G_t such that

$$G_t = g_t \mathrm{e}^{-\gamma t}. \tag{3}$$

Then G_t evolves according to the following GBM:

$$dG_t = (\alpha - \gamma) G_t dt + \sigma G_t dZ_t \tag{4}$$

Consider first the optimal repowering policy when life-time extension option is not available. Thus, the wind farm solves the following maximization problem:

$$V_R = \max_{\tau} \mathbb{E}_G \left[\int_0^{\tau} \mathrm{e}^{-rt} G_t Q_0 dt + \mathbb{E}_{G_\tau} \int_{\tau}^{\infty} \mathrm{e}^{-rt} G_t K_R dt - I_R \mathrm{e}^{-r\tau} \right], \tag{5}$$

where τ is the optimal repowering time.

Similarly, when only the life-time extension plus repowering option is available, then the firm solves the following:

$$\begin{aligned} V_L = \max_{\tau} \mathbb{E}_G \Bigg[\int_0^{\tau} \mathrm{e}^{-rt} G_t Q_0 dt + \mathbb{E}_{G_\tau} \int_{\tau}^{\tau+\Delta t} \mathrm{e}^{-rt} G_t K_R \mathrm{e}^{-\gamma t} dt \\ - I_L \mathrm{e}^{-r\tau} + \mathbb{E}_{G_{\tau+\Delta t}} \int_{\tau+\Delta t}^{\infty} \mathrm{e}^{-rt} G_t K_R dt - I_R \mathrm{e}^{-r(\tau+\Delta t)} \Bigg], \end{aligned} \tag{6}$$

where Δt is the fixed length of the life-time extension.

Proposition 1 *In the absence of the life-time extension option, it is optimal for the firm to repower as soon as its net operating profit margin, G_t, hits the optimal repowering threhold G_R, given by*

$$G_R = \frac{\beta}{\beta - 1} \frac{(r - (\alpha - \gamma)) I_R}{K_R - 1}, \tag{7}$$

where

$$\beta = \frac{1}{2} - \frac{\alpha - \gamma}{\sigma^2} + \sqrt{\left(\frac{\alpha - \gamma}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}. \tag{8}$$

The value of the wind power producer holding the option to repower is

$$V_R(G) = \begin{cases} \left(\frac{G}{G_R}\right)^{\beta} \left(\frac{G_R(K_R-1)}{r-(\alpha-\gamma)}\right) + \frac{G}{r-(\alpha-\gamma)} & \textit{if } G < G_R, \\ \frac{K_R G}{r-(\alpha-\gamma)} - I_R & \textit{if } G \geq G_R. \end{cases} \tag{9}$$

Similarly, when the firm only holds the option to implement the life-time extension followed by repowering (but cannot repower immediately without using the life-time extension), it uses the life-time when G_t hits the threhold G_L, given by

$$G_L = \frac{\beta}{\beta - 1} \frac{(r - (\alpha - \gamma))(I_L + I_R \mathrm{e}^{-r\Delta t})}{K_R \mathrm{e}^{\alpha \Delta t} + K_L(1 - \mathrm{e}^{-(r-(\alpha-\gamma))\Delta t}) - 1}. \tag{10}$$

The value of the wind power producer holding the option to life-time extension is

$$V_L(G) = \begin{cases} \left(\frac{G}{G_L}\right)^{\beta} \left(\frac{G_L(K_L(1-\mathrm{e}^{-(r-(\alpha-\gamma))\Delta t})+K_R \mathrm{e}^{\alpha t}-1)}{r-(\alpha-\gamma)}\right) + \frac{G}{r-(\alpha-\gamma)} & \textit{if } G < G_L, \\ \frac{G(K_L(1-\mathrm{e}^{-(r-(\alpha-\gamma))\Delta t})+K_R \mathrm{e}^{\alpha t})}{r-(\alpha-\gamma)} - (I_L + I_R \mathrm{e}^{-r\Delta t}) & \textit{if } G \geq G_L. \end{cases} \tag{11}$$

Looking at these two investment opportunities, it can be shown that

$$G_L \leq G_R \iff \frac{I_L + I_R \mathrm{e}^{-r\Delta t}}{I_R} \leq \frac{K_R \mathrm{e}^{\alpha \Delta t} + K_L(1 - \mathrm{e}^{-(r-(\alpha-\gamma))\Delta t}) - 1}{K_R - 1}. \quad (12)$$

This means that the life-time extension is performed earlier than the repowering if the life-time extension is much cheaper while the efficiency of the turbine after the life-extension is not much less than the one after repowering. If this condition does not hold, it means that the option to repower dominates the option to do the life-time extension. A similar situation in which two mutually exclusive projects are compared is analyzed in Décamps et al. [2006], but our case differs in the fact that both projects have a strong overlap, as both options include repowering. We find similar results as Décamps et al. [2006] if the length of the life-time extension, Δt, becomes infinite and the life-time extension does not include repowering after the end of the life-time extension.

3 Results

This paper analyzes the option to repower a wind turbine near the end of its life-time and compares it to the option to extend the life-time by a fixed amount of years and repower the wind turbine afterwards. We analytically derive the condition for which the wind turbine owner exercises the option for a life-time extension and repowering earlier than the option to repower.

Our results indicate that lifetime-extension is more valuable than repowering for practical input values. We also found that both end-of-life options will have lower investment thresholds for wind projects with lower interest rates, making them more attractive to wind projects with long-term power contracts relative to most other projects.

References

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