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Lifetime Extension, Repowering or Decommissioning? Decision Support for Operators of Ageing Wind Turbines

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Abstract. In Germany, more than one third of the installed wind energy capacity will leave the feed-in tariff funding between 2021 and 2025. Operators of affected turbines are therefore increasingly concerned with the design of profitable end-of-funding strategies. This requires feasibility analyses of both lifetime extension and repowering options and entails the subsequent challenge to determine the optimal lifetime extension and corresponding repowering timing. To support operators and other stakeholders dealing with wind turbines' end-of-life issues, this study presents a geographic information system that permits evaluating optimal end-of-funding strategies at different spatial scales reaching down to detailed analyses on individual turbine level. The decision support system processes topographic, wind, turbine, and finance data in an integrated system of resource simulations, spatial planning analyses and economic viability assessments. Case-study results show that a uniform end-of-funding strategy cannot be applied to all ageing turbines. Conducted sensitivity analyses rather indicate that the best strategy highly depends on various turbine-specific aspects, especially the location, type and maintenance costs as well as exogenous factors, including the developments of electricity spot market prices and tendered feed-in premiums. In light of latest trends regarding the exogenous factors, lifetime extension and repowering potentials increase. However, the results also indicate that dismantling, disposal and recycling of numerous ageing turbines will become a major challenge for the wind energy sector in the next decade.

1. Introduction

At the end of 2020, more than 5,000 wind turbines (≈ 3.9 GW) will reach the end of the feed-in tariff funding period according to the German Renewable Energy Sources Act (EEG). More than 8,000 turbines (≈ 12.5 GW) will follow by the end of 2025. If a lifetime extension beyond the funding period is technically viable, operators of affected turbines need to find alternative sales models for the generated electricity once the feed-in tariff expires. The most popular sales model is trading the generated electricity directly or via contracts with trading companies on the



European Energy Exchange (EEX). An alternative is the signing of power purchase agreements (PPAs) with industrial partners, which is already a widespread sales model in many countries worldwide and is becoming increasingly established throughout Europe. In Germany, the first PPAs with the purpose of ensuring a lifetime extension of turbines beyond 2020 were concluded in 2018. Nevertheless, regardless of the sales model chosen, the future sales price per unit of electricity is likely to be significantly lower than the previous feed-in tariff, which raises the question in how far a lifetime extension beyond the EEG funding period is economically viable.

Consequently, an alternative to a lifetime extension could be a repowering of one or multiple old turbines by a modern turbine. In Germany, this would require a successful participation in the renewable energy auctions implemented with the 2017 EEG amendment to determine the level of a feed-in premium, which would then be guaranteed to the repowering project for another twenty years of operation. However, whether the repowering option can be exercised also depends on various spatial aspects in the immediate vicinity of the location of the old turbines. Increasing overall heights of modern turbines in combination with restrictive regulations regarding required minimum distances to settlements and other areas impede a repowering for many old turbines. If both lifetime extension and repowering are not viable, the only remaining option is a permanent shut-down of wind turbine operation at the affected location.

Since the viability of lifetime extension and repowering depends on various endogenous and exogenous factors, selecting and designing the optimal end-of-funding (i.e., expiry of feed-in tariff funding) strategy for a specific turbine are challenging tasks. To provide decision support to operators and other stakeholders, this study presents a geographic information system (GIS) that permits systematically evaluating the optimal choice between lifetime extension, repowering and decommissioning for operational wind turbines in Germany at different scales reaching down to detailed analyses on individual turbine level. Current research tends to investigate lifetime extension (e.g., [1–3]) and repowering (e.g., [4–6]) separately. Studies combining both options to decide on the optimal repowering timing are rare (e.g., [7–10]). Furthermore, to the knowledge of the authors, no study has so far been published combining resource, spatial and economic analyses to investigate both lifetime extension and repowering potentials on a macro scale. Consequently, the focus of this study is on a macro-scale analysis of end-of-funding strategies for ageing wind turbines located in the German federal state of Lower Saxony.

2. Methodology and Data

To permit the macro-scale analysis, the GIS handles extensive topographic, wind, turbine, and finance data in an integrated system of resource simulations, spatial planning analyses and economic viability assessments. Figure 1 shows the system architecture of the GIS. Firstly, the spatial analysis is applied to the coordinates of all operational turbines under investigation to determine whether the corresponding location allows a repowering with respect to the spatial planning regulations or whether a lifetime extension of the old turbine is the only remaining option. Secondly, based on the results of the spatial analysis, the economic analysis is applied to each turbine to determine the optimal end-of-funding strategy.

2.1. Spatial Analysis

When it comes to the repowering of a wind turbine in Germany, the same legal regulations apply as for the construction of a turbine at a greenfield site. Whether or not a construction permit is granted depends in particular on a wide variety of spatial aspects. In general, the protection of the habitats of man and nature is in the foreground of legislative measures. By preventing the construction of turbines, harmful impacts on the environment and life are to be limited. Correspondingly relevant guidelines are protection laws such as the Federal Nature Conservation Act, Landscape Protection Act and Immission Protection Act. These regulations result in legally conditioned exclusion areas for wind energy operation. Based on these exclusion areas, which also

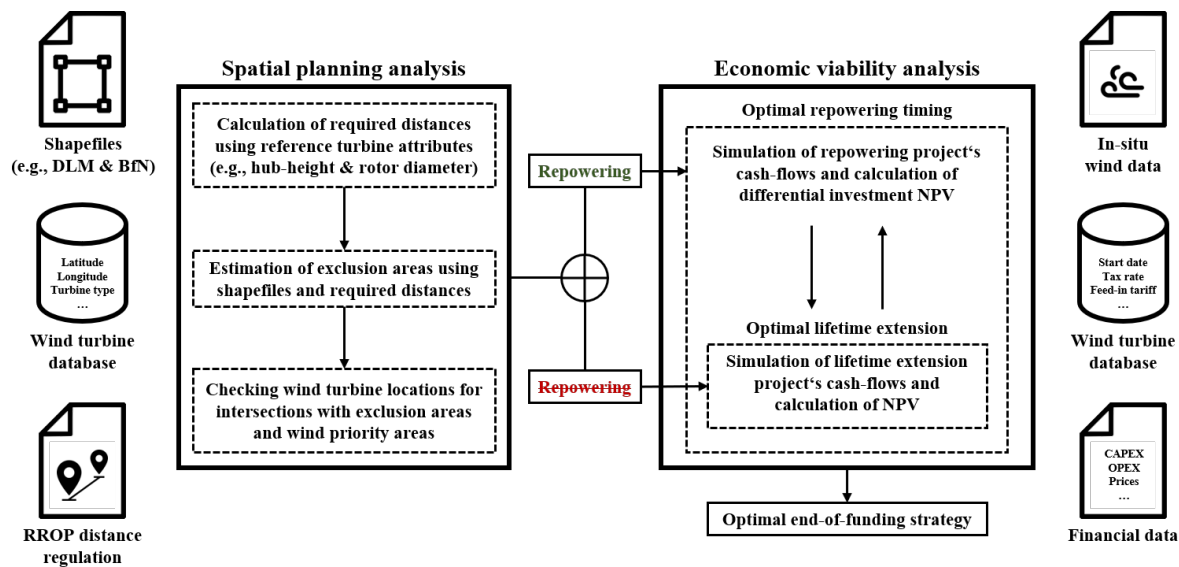


Figure 1. System architecture of the decision support system and required data inputs.

consider specific distance regulations, the spatial planning laws (RROP) resulting from federal law feature wind priority areas at municipal level, which eventually represent the areas legally intended for the construction of wind turbines. These priority areas are based on applicable law but offer municipal legislators the possibility of supplementary individual regulations to enable more granular political action. The approval of a repowering project within such designated areas is extremely probable, whereas outside it is rather unlikely, making priority areas well suited as indicators for a possible project approval. However, due to increasing turbine heights and more restrictive distance regulations, it is highly uncertain for many old turbines whether the repowering option can be exercised, since many old turbines were built very close to settlements or other protection areas. Consequently, the repowering option is especially dependent on the feasibility of an old turbine's location to be designated as a wind priority area.

To determine viable locations, various available datasets on protected areas, infrastructural exclusion areas and others were implemented in the GIS and applied to the locations of all turbines under investigation (see Figure 2). Necessary data was imported by vector-based shapefiles, converted into tabular form and imported or graphically created. The resulting geospatial datasets were stored in a local database. Based on the datasets relevant distance criteria is applied by generating buffer zones around each affected object. Turbine-specific distances are generated on the basis of the attributes of a preselected reference repowering turbine: a Vestas V150-4.0 with a rotor diameter of 150m, an assumed hub-height of 120m and a total turbine height of 195m. The choice of the reference turbine is based on the determined average wind speed in Lower-Saxony. The respective distance regulation relevant for Lower Saxony can be seen in Table 1. Further protected areas without distance regulation comprise industrial areas provided by DLM, nature reserves, national parks, nature parks, landscape reserves, protected forests, special protection areas, flora-fauna habitats, biosphere reserves and wetlands of international importance provided by BfN as well as military zones.

Based on the regulation, the exclusion areas are generated and matched with the old turbines' locations. By applying an intersect function, all locations are checked for an overlap with exclusion areas, deriving repowerable and non-repowerable turbines. In addition, a distinction is made between exclusion from currently designated priority areas. In this way a differentiated statement can be made as to how likely a repowering is at a certain location.

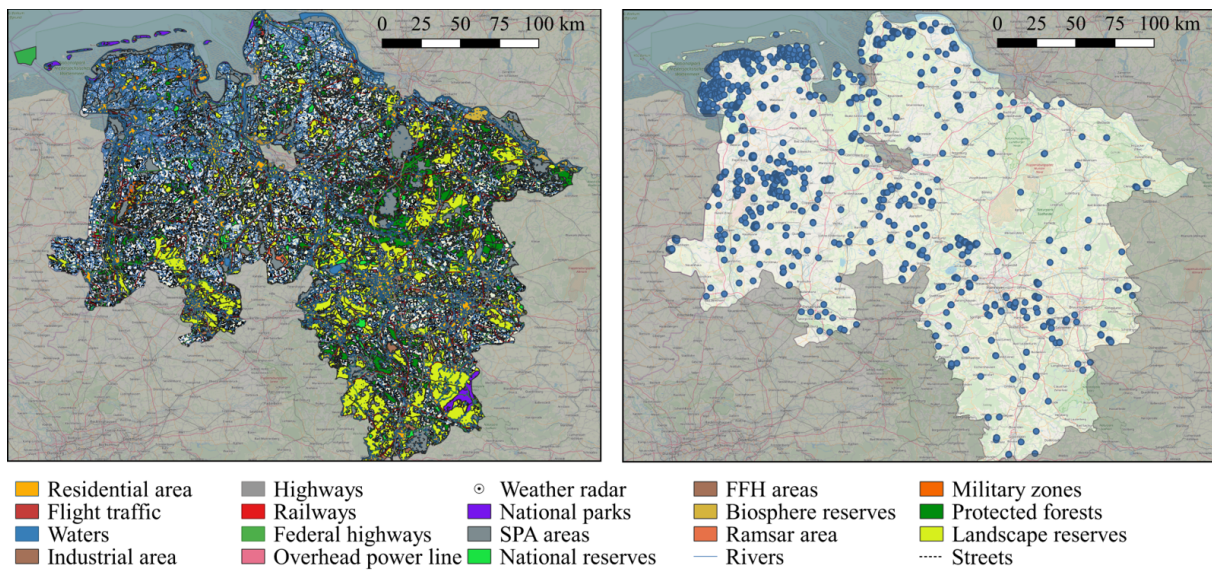


Figure 2. Relevant protection areas (left) and locations of investigated turbines (right).

Table 1. Relevant distance regulations in Lower Saxony and corresponding layer sources.

Protected areas	Distance regulation	Source of layer*
Residential areas	$2 \times$ turbine height	DLM
Waters	50 meters	DLM
Weather radar locations	5,000 meters	DWD
Overhead power lines	$3 \times$ rotor diameter (RD)	DLM
Railway	$1.5 \times$ (RD + hub-height)	DLM
Highway, federal highway, county roads	40, 20, 20 meters	DLM
Airports	5,000 meters	LuftVG

* Digitales Landschaftsmodell (DLM), Deutscher Wetterdienst (DWD), Luftverkehrsgesetz (LuftVG), Bundesamt für Naturschutz (BfN)

2.2. Economic Analysis

To determine the optimal end-of-funding strategy for a turbine, an economic analysis is applied based on the results of the spatial analysis. In the economic analysis, turbines not qualified for repowering according to the spatial analysis are examined for the economic viability of a lifetime extension, whereas all remaining turbines are also being investigated for the economic viability of a repowering. In both cases, a discounted cash-flow (DCF) model is applied to determine the economic viability. The net present value (NPV) is used as the decision criterion: a non-negative NPV indicates economic viability. Only if both options, lifetime extension and repowering, feature a negative NPV, the permanent shut-down of wind turbine operation at the respective site remains as the only viable option at the end of the funding period.

The general equation for determining the NPV is:

$$NPV = -I + \sum_{t=1}^T \frac{Z_t}{(1+r)^t}, \quad (1)$$

where I represents the investment and Z_t the net cash-flows. The latter are discounted using the discount rate r and summed over the lifetime T . To calculate the NPV of the lifetime extension option, expected net cash-flows generated over the expected lifetime extension period are compared with the mandatory investment in a technical lifetime extension assessment. Instead, the NPV for the repowering option is calculated on the basis of a standard project valuation in which the capital expenditures are compared with the expected net cash-flows over a project lifetime of 20 years. To determine the optimal lifetime extension period in addition to the economic viability of both options, a comparison between the options is necessary. For this purpose, a differential investment analysis following [10] is applied based on the cash-flow analysis of both options. A differential investment analysis allows to apply DCF models to compare investment alternatives with different characteristics, such as capital expenditures or horizons. In this study, the differential investment analysis permits evaluating the economic viability of the repowering option and the optimal lifetime extension period simultaneously. The end of the optimal lifetime extension period also represents the optimal repowering timing, which determines the commissioning of the repowering project. Since the resulting optimal lifetime extension period can feature negative values, it is also possible that the optimal repowering timing occurs already before the end of the regular 20-year lifetime of the old turbine.

The aim of the differential investment analysis is to constantly compare the profitability of the repowering and lifetime extension options in order to maximize the NPV of the combined project, which represents a hypothetical investment reflecting the difference between the cash-flow streams of the repowering and lifetime extension projects. The NPV of the differential investment also consists of an investment and net cash-flows and is calculated as follows:

$$NPV_{diff,t} = -C_t + R_t, \quad (2)$$

where C represents costs and R revenues arising from postponing the start of the repowering project to a later period t and continuing the operation of the old turbine. The costs mainly refer to the additional discounting effect that reduces the present value of the repowering project. The net cash-flows, which are compared to this hypothetical investment, mainly comprise the additional revenues arising from the lifetime extension of the old turbine. Nonetheless, both costs and revenues can also be influenced by other aspects, such as technological advances or the development of electricity spot market prices and feed-in premium levels in future auctions, which can increase or decrease the profitability of both lifetime extension and repowering over time. Consequently, it can be drawn from Eq. 2 that the optimal repowering timing is reached when the NPV of the differential investment is equal to or smaller than zero, as this implies that a further lifetime extension of the old turbine is no longer economically viable. The GIS determines the optimal repowering timing by solving an optimal stopping problem: Once the costs of the differential investment exceed the revenues, the old turbine should be dismantled and the repowering project implemented. Accordingly, the planning process for the repowering project must be initiated in advance of the optimal repowering timing.

The economic analysis is performed for any single turbine of the dataset and, hence, the in-situ wind resources are necessary for unbiased results. The wind speeds drive the electricity yield, which by means of the resulting revenues determine the net cash-flows. To estimate bias-corrected wind speeds for an arbitrary location, spatial statistical downscaling following [11] is applied to reanalysis wind data. The reanalysis data was obtained from NASA's Modern-Era Retrospective analysis for Research and Applications (MERRA-2) dataset following the virtual wind farm model [12], which is processed as follows: (1) acquisition of hourly wind speeds at 10m and 50m above ground at each of the twelve MERRA-2 grid points closest to the selected location; (2) utilization of LOESS regression [13] for the spatial interpolation of hourly wind speeds to the geographic coordinates of the selected location. Based on steps (1) and (2) the spatial statistical downscaling is applied as follows: (3) collection of wind speed distributions

for the same heights and the closest available grid point of the Global Wind Atlas (GWA), which features micro-scale information; (4) adjustment of the interpolated hourly wind speeds estimated from the MERRA-2 dataset to feature the local wind characteristics as captured by the GWA data using the in-situ roughness data from ESA's Global Land Cover Map. To calculate the expected electricity yield, the turbine-specific power curve is applied to the hourly wind speed time series. In addition, a turbine efficiency level is considered which covers wake effects, turbine availability and technical efficiency. The efficiency of a turbine in the first year of operation is set at 88.5% and an annual degradation of 0.5% is assumed.

Based on the expected electricity yield, the site quality according to the EEG is calculated for each location of the old turbines, which is then used to derive capital expenditures (CAPEX) and operating expenditures (OPEX) for both lifetime extension and repowering projects using the data shown in Table 2. The CAPEX of the lifetime extension project include the mandatory technical assessment at costs of 25,000 € [14], which are linearly depreciated over the maximum lifetime extension period of five years. The technical assessment includes the inspection and certification costs, but excludes costs for potential repairs needed to obtain permission. The site quality and the commissioning date of the old turbines are used to estimate the current feed-in tariff according to the corresponding EEG amendment. In addition, assumptions were made with regard to the development of the electricity spot market prices (3.86 ct/kWh in 2018 and 2.5% annual increase) and the CAPEX and OPEX (1.5% annual decrease) of a repowering project. The development of the tendered feed-in premiums (6.28 ct/kWh for a site quality of 100% in 2018) follows the same development as the cost parameters. The turbine-specific corporate tax rate was calculated according to the German tax legislation using a location-dependent municipalized tax multiplier. For the calculation of the discount rate r the weighted average cost of capital approach was used based on cost of equity of 5%, cost of debt of 3.5% and variable debt-to-equity ratios. Whereas the lifetime extension project was assumed to be entirely equity financed, the optimal debt-to-equity ratio was calculated individually for the repowering project based on turbine-specific cash-flows using a debt sculpting approach [15].

Table 2. CAPEX and OPEX data oriented towards recent cost studies [14, 16, 17].

Site quality	60%	70%	80%	90%	100%	110%	120%	130%	140%
CAPEX (€/kW)	1,355	1,355	1,308	1,308	1,308	1,216	1,216	1,216	1,216
Initial OPEX* (ct/kWh)	2.45	2.35	2.26	2.17	2.17	2.07	2.07	1.98	1.98
Basic OPEX (ct/kWh)	2.73	2.64	2.54	2.45	2.35	2.35	2.26	2.26	2.17

* OPEX in the first ten years of operation.

3. Results and Discussion

Due to the superior wind conditions, Lower Saxony is the federal state with the most and oldest wind turbines in Germany. More than 26.5% of the about 13,200 wind turbines that reach the end of the EEG funding period by the end of 2025 are operated in Lower Saxony. In this study, the GIS is used to investigate optimal end-of-funding strategies for the 1,645 turbines located in Lower Saxony reaching the end of their funding period at the end of 2020.

3.1. Spatial Planning Analysis

Initially, the spatial planning analysis is applied to the 1,645 locations using the attributes of the reference turbine. Afterwards, an additional sensitivity analysis is conducted based on changes

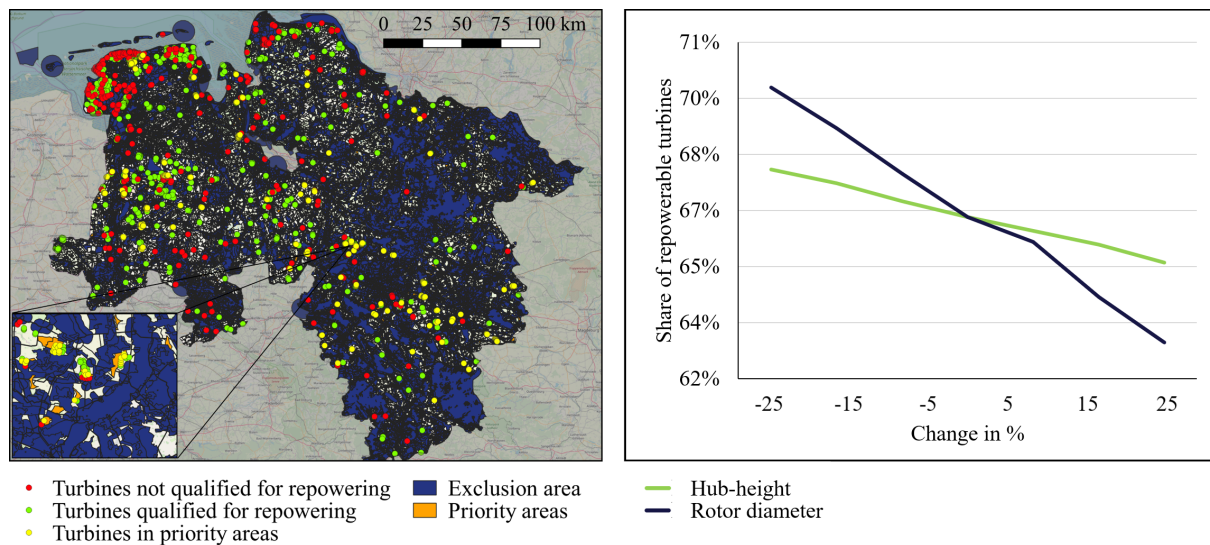


Figure 3. Results of spatial planning analysis and corresponding sensitivity analysis.

in the hub-height and rotor diameter of the reference turbine, since the criteria catalogue of Lower Saxony includes spatial restrictions that depend on the total turbine height. This enables an estimation of the extent to which the turbine attributes influence the spatial repowering potential. Figure 3 shows the estimated exclusion areas calculated based on the attributes of the reference turbine and the investigated locations. 547 locations (33.25%) intersect with the estimated exclusion areas and are thus not qualified for repowering. Accordingly, the remaining 1,098 locations (66.75%) do not violate the distance regulation and are thus qualified for a repowering by the reference turbine. As shown in Figure 3, the results of the sensitivity analysis indicate that the determined repowering potentials are robust against changes in the attributes of the reference turbine. Even a simultaneous increase in both hub-height and rotor diameter to 150 meters reduces the number of turbines qualified for a repowering by only 9.74%.

To estimate the current regulatory repowering potential in addition to the calculated repowering potential, Figure 3 also includes the current wind priority areas specified by the RROP of Lower-Saxony. The corresponding analysis indicates that only 317 locations (19.27%) intersect with current wind priority areas. For all remaining turbines the feasibility of a repowering is therefore highly uncertain, although 58.81% of the corresponding locations would allow a repowering given the current distance regulation as well as the attributes of the selected reference turbine. Consequently, the current RROP only partially exploits the calculated repowering potential given the estimated exclusion areas. A typical repowering ratio is to replace two to three old turbines by one modern turbine. Since the RROP only allows the replacement of one in five turbines, the results indicate a strong need for action on the part of the responsible authorities to increase the incentives for repowering projects in Lower Saxony.

3.2. Economic Viability Analysis

The results of the spatial analysis are explicitly considered in the economic analysis. For the 546 turbines that cannot be repowered due to distance regulation, only the economic viability of the lifetime extension option is assessed. All remaining turbines are also examined with regard to their economic repowering potential as well as their optimal lifetime extension and corresponding repowering timing by means of the differential investment analysis. Figure 4 shows the results of the economic viability analysis. The results indicate a high lifetime extension potential for the investigated wind fleet. 917 old turbines (55.75%) show a positive economic viability for a lifetime

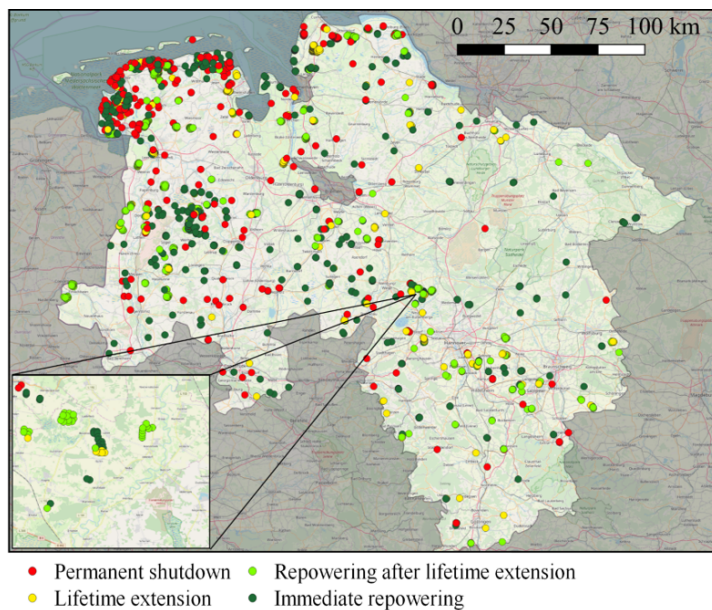


Figure 4. Optimal end-of-funding strategy for the 1,645 wind turbines under investigation.

extension beyond 2020, although this is not necessarily the optimal end-of-funding strategy for these turbines. An immediate repowering in 2021 without a preceding lifetime extension is the optimal strategy for 543 old turbines (33.01%), whereas further 469 turbines (28.51%) should be operated temporarily beyond 2020 before a repowering project is implemented in the following years. In contrast, a lifetime extension without a subsequent repowering is the optimal strategy for 281 (17.08%) turbines, while it must be taken into account that this figure increases significantly if the regulatory repowering potential based on the wind priority areas is considered. Consequently, 352 turbines (21.4%) and their corresponding locations are neither viable for a lifetime extension nor for repowering. At these locations the permanent shutdown of wind energy operation remains the only option, while the operators of affected turbines will then face further end-of-life challenges regarding the dismantling, disposal, recycling and/or resale of the old turbine. However, these challenges are also relevant in the case of a repowering project and are only postponed if a lifetime extension is carried out.

As the results of the economic viability analysis are based on assumptions for several inputs, a sensitivity analysis is conducted for a representative wind turbine with a site quality of 100% according to the reference yield model of the latest EEG amendment. On the one hand, these sensitivity analyses include calculations for the economic viability of a lifetime extension given changes in the electricity spot market price, the electricity yield (i.e., site quality), the OPEX as well as the lifetime extension investment and duration (see Figure 5). On the other hand, the sensitivity of the optimal repowering timing was evaluated by means of the estimated NPV of the differential investment at the end of funding period given changes in the costs (OPEX or CAPEX), feed-in premium and electricity yield of the repowering project (see Figure 5).

The results show that the economic viability of a lifetime extension highly depends on the OPEX and electricity yield of the old turbine as well as the development of the electricity spot market prices and/or related PPA prices. For the representative turbine, a drop of 23% in spot market prices would make a lifetime extension unprofitable. The same applies if the OPEX rises by 20%. With regard to the optimal repowering timing the results show that both OPEX and CAPEX of the repowering project as well as the level of the tendered feed-in premium have the highest impacts. The impact of the electricity yield is considerably lower due to the reference yield model implemented in the German auction mechanism. A change in the expected electricity yield also changes the site quality, which in turn adjusts the level of the

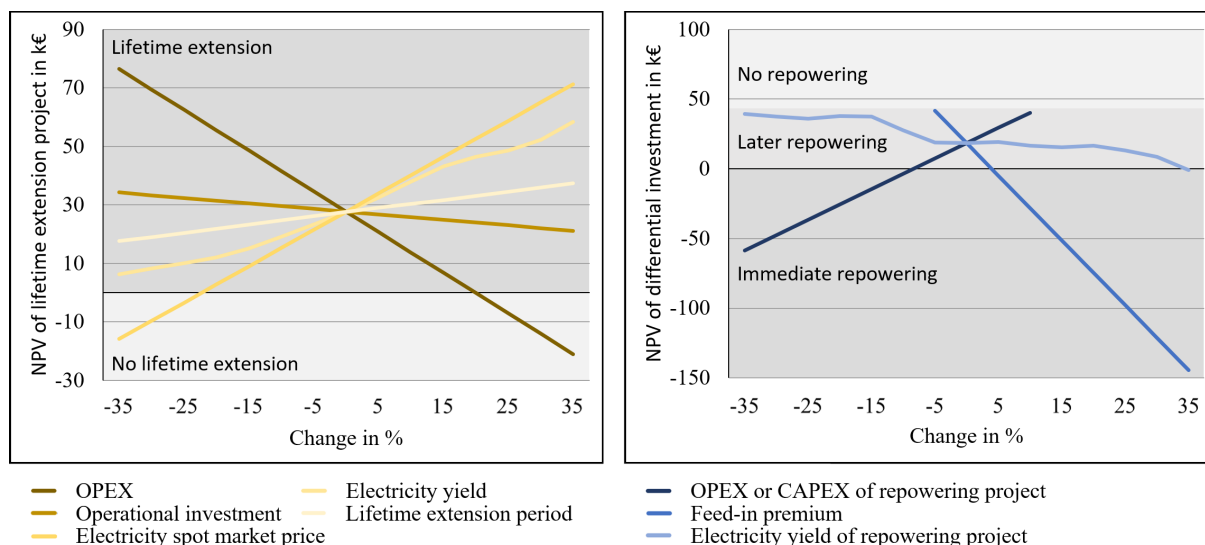


Figure 5. Sensitivity analyses of lifetime extension (left) and repowering (right) options.

feed-in premium, such that the opposite effects largely cancel each other out. The results further indicate that a repowering is no longer economically viable if the OPEX or CAPEX increase by 12% or the feed-in premium drops by 5%. Furthermore, they confirm the results of macro-scale analyses that an immediate repowering is the most likely optimal-end-of-funding strategy given that no spatial restrictions prevent a repowering at the corresponding location.

4. Conclusions and Outlook

In this study, the selection and design of optimal end-of-funding strategies for the ageing German wind fleet were under investigation. For this purpose, a GIS was developed integrating wind resource simulations with spatial planning and economic viability analyses. In a case study of the German federal state of Lower-Saxony, the GIS was applied to the 1,645 turbines reaching the post-EEG era at the end of 2020. Results show that increasing electricity spot market prices and tendered feed-in premiums in 2018, have a positive effect on the economic viability of both lifetime extension and repowering options. The highly limited availability of wind priority areas however prevents repowering projects in many locations, even though it would be an economically viable option. Nevertheless, a lifetime extension of the old turbine beyond 2020 will be an economically viable option at many of these locations. Consequently, in light of latest trends, the lifetime extension option is becoming more attractive, which could result in a smoothing effect on the entire German dismantling volume in the next decade.

In order to address related issues, future research will focus on analyzing the entire German wind fleet. First results indicate that the lifetime extension and repowering potentials are significantly lower in most of the remaining federal states. The relatively high lifetime extension potential in Lower-Saxony is due to the high average wind resources in this region that are well above the German average, whereas the relatively high repowering potential can be explained by spatial planning aspects, such as a moderate distance regulation and a relatively low population density. Consequently, despite the manifold results, the analyses indicate that the German wind energy sector is facing a large quantity of ageing turbines to be dismantled in the upcoming years. As other countries will also face this and other challenges related to the end-of-life of wind turbines in the next decade, future research will further focus on extending the scope of the GIS to other regions. In the course of the next decade, worldwide around 180 GW of installed wind energy capacity will reach the end of their originally planned operating lifetime of 20 years.

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