Optimal repowering of wind energy converters: energy demand and CO_2 intensity as indicators

Till Zimmermann[1],* and Dr. Stefan Gößling-Reisemann[1]

[1]Universität Bremen, Faculty of Production Engineering & artec |Research Center for Sustainability Studies

*tillz@uni-bremen.de

Abstract Repowering of existing wind energy converters is an issue of upcoming importance. In many areas in Germany (and probably elsewhere) the best onshore sites for wind energy converters (WEC) are already taken. In order to still increase the electricity generation from wind in these regions repowering of these sites is the most promising option. By repowering, a better utilization of existing sites can be achieved. At the same time a reduction of environmental impacts is possible. Finding the right moment in time for replacing old WECs with new ones depends on a lot of factors. Here, we present a methodology to find the optimal repowering point with regard to the energy demand and the CO_2-emissions.

1 Introduction

As the rapid expansion of renewable energies and especially the wind energy in Germany continues we are coming to a point (if not already there) where most of the suitable onshore sites for wind energy are already in use. Here, repowering plays a key role.

Repowering means the replacement of older wind energy converters (WEC) by new state-of-the-art WEC, thereby improving the utilization of existing sites. Hence, repowering is the most promising option to further increase the electricity generation from wind in these regions. For this decade a boom of repowering is forecasted [1]. The potential for repowering in Germany is estimated at 25,000 MW, which equals approximately the rated power of WEC already installed in 2010 [2]. A glance at the worldwide development of wind energy indicates that also in many regions outside of Germany repowering is going to be an issue.

When talking about repowering the question about the right moment in time for replacing old WEC with new ones arises. This optimal repowering point depends on various factors and can differ depending on how it is assessed.

For investors the repowering point will basically be an economical issue and finding it is pretty straight forward. It depends on subsidies and feed-in tariffs or on the general development of electricity prices. However, finding the optimal repowering point from an environmental perspective is more complex and so far not integrated into the decision process by default. Theoretically numerous environmental aspects or impact categories could be taken into account here. But since the main reason for promoting wind energy is saving CO_2, the CO_2 intensity of the repowering process and its impact on the overall CO_2 intensity of the generated electricity is a key figure to be taken into account. In addition to this, the energy demand is another figure of great importance to be assessed here.

Based on a work performed in cooperation with Enercon GmbH (see [3]) we developed a tool that allows simulating different repowering options in order to find the optimal replacement strategy for WEC sites regarding cumulative energy demand (CED) per generated kWh and the respective specific CO_2-emissions. In this context it is demonstrated that there is an optimal point in time for repowering and it is shown how this point is identified with regard to the respective framework conditions.

2 Repowering in Germany: background, necessities and potentials

As mentioned before the term repowering describes the replacement of old WEC by new ones allowing a better utilization of sites that are already in use for the generation of power from wind. In Germany, a more detailed and precise definition can be found in the renewable energies act (Erneuerbare Energien Gesetz, EEG; [4]). In the EEG it says that WEC are to be considered as repowering WEC if they definitely replace a converter that has been operating for at least ten years in the same or a neighboring district and that has a rated power that amounts to between two and five-times the rated power of the old WEC [4].

Repowering is a key element in the further expansion of renewable energies. To support it, the EEG also grants additional 0.5 Cents for kWh on top of the regular feed-in tariffs [4].

The usual life span of a WEC is between 15 and 20 years. A converter that has undergone regular maintenance might have a few more years, but sooner or later it will reach a point where its age becomes noticeable. And even if it still operates trouble-free, its rated power will be quite low compared to state-of-the-art converters. As an example, in the early nineties the standard was some hundred kW while today WEC can have a rated power of over 7 MW.

Therefore, it is clear that the economic reasons for repowering go hand in hand with a technological necessity. Furthermore, at the same time as repowering increases the electricity generation at existing sites, it reduces various environmental impacts arising from the use phase like shadow casting, noise pollution, and interference with the natural scenery, especially when more than one WEC is replaced. Additionally, when already existing elements like access roads or foundation can be reused, the construction of the repowering WEC will cause less environmental impacts, too.

So, it is evident that there are quite a few reasons for repowering and its potential is huge. For Germany this repowering potential amounts to 25,000 MW [2] and a growing market share for repowering WEC is forecasted [5].

3 Methodological approach for the assessment of the optimal repowering point

As repowering plays an important role in the future energy sector, it is of great importance to find the optimal point in time for repowering to ensure to use its full potential. As mentioned before, this point can be assessed under economical as well as under environmental aspects. We focused on ways to perform an assessment under environmental aspects while the economical assessment is a question of investment appraisal and does not differ significantly from the assessment of any other investment decision.

As said above we decided to use the global warming potential (GWP) and the energy yield as the most relevant and most discussed impact categories in the field of energy production. However, if required, the methodology can be used for other impact categories like acidification, nutrification etc., or some aggregate measure, too.

For both figures, GWP and energy yield, the absolute numbers for the whole life cycle do not allow any conclusion about the efficiency of the converter and thus cannot be used to find the optimal repowering point. Here, we need the specific figures, i.e. the CO_{2e} emission per kWh and the consumed (fossil) primary energy per kWh that is fed into the grid. These figures must be identified for the old as well as for the new converter. Of course, these figures strongly depend on the converters' life span and the associated net energy production. However, a simple comparison of these specific figures still does not allow a statement about which repowering point is preferable.

Here, a set of crucial points needs to be explained first, in order to proceed. The first point is that we do not actually assess different repowering points for one available repowering WEC. We compare different repowering scenarios. A graphical example for this is given in Fig. 1.

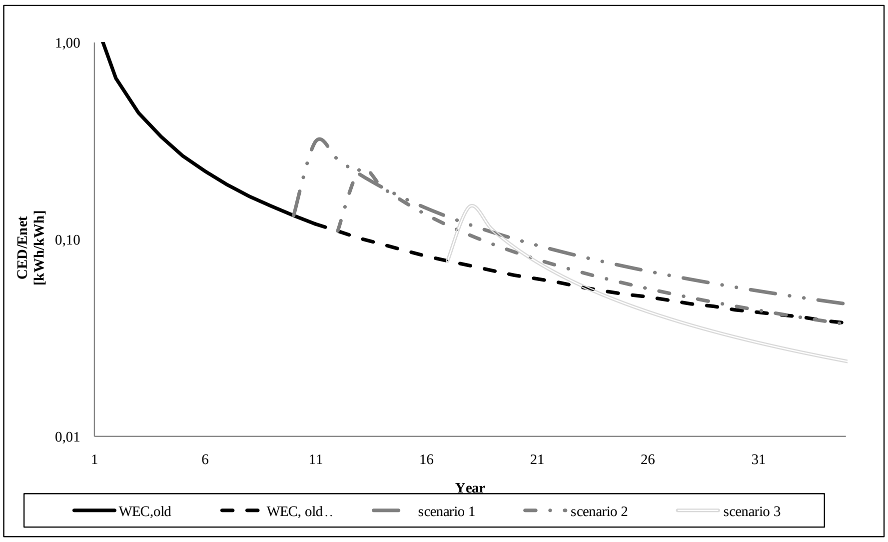

Fig. 1: Comparison of repowering scenarios

A repowering scenario is the combination of the performance of the old and the new converter, the repowering point and the life span of the new WEC. As an example, if we want to repower an old WEC (let' s call it WEC_{old}) and three repowering WEC become available at different points in time (WEC_1, WEC_2 and WEC_3) we analyze the environmental performance of each possible combination of WEC_{old} and repowering WEC_x by calculating the combined specific energy demand and CO2 footprint under the assumption that the new WEC_X replaces WEC_{old} as soon as it becomes available.

The second point is that repowering only makes sense if the repowering WEC has higher energy efficiency and a lower specific carbon footprint. Here, the energetic payback time can be used as an indicator for the energy efficiency. It is better suited than the harvest factor because it is independent from the life span of the WEC. If, for example, WEC_1 has an energetic payback time of 12 months, while WEC_{old} only needs 7 months to amortize energetically, we will not achieve a better utilization of this site by repowering with WEC_1. This point is also demonstrated graphically in section 4.3.

The third point is that for every converter that fulfils the above criteria the earliest possible repowering point is always the best. This point is given by the earliest time of production of the respective WEC. This does not mean that a particular repowering scenario generally makes sense, but that this combination of repowering point and WEC is preferable to any later repowering point for this WEC.

This being said, the first point becomes more obvious: The theoretically available repowering WEC result from the point in time we are starting our assessment from (of course, there are additional constraints like the financial scope). From the available WEC, in turn, the different possible repowering points result, also defining the life span of the old WEC that shall be replaced. These combinations of WEC (respectively their performance), life spans and repowering point are regarded as repowering scenarios.

In our example, this means that for the given WEC_{old}, there are three possible repowering WEC available (WEC_1, WEC_2 and WEC_3). Each repowering WEC has its own theoretical repowering point that is its earliest date of availability (t_1, t_2, t_3). The possible repowering scenarios result from this: repowering WEC_{old} with WEC_1 at $t_{1,}$ repowering WEC_{old} with WEC_2 at $t_{2,}$ and repowering WEC_{old} with WEC_3 at t_3.

Tab. 1 gives an overview of the relevant variables in this context.

Tab. 1: Overview of variables

Variable	Explanation
t_r	repowering point
$CED_{old}(t_r)$	Cumulative energy demand (CED) of the old WEC up to the repowering point t_r
$GWP_{old}(t_r)$	GWP (full lifecycle) of the old WEC subject to the repowering point t_r
$E_{net,old}(t_r)$	net energy production of old WEC up to repowering point t_r
X	index of potential repowering WEC, or of the potential repowering scenario, respectively
t_x	expected life span of repowering WEC X
$CED_x(t_x)$	CED of repowering WEC X subject to its life span
$GWP_x(t_x)$	GWP of repowering WEC X (full lifecycle)
$E_{net,x}(t_x)$	net energy production of repowering WEC X (full lifecycle)

$e_x(t)$	specific energy yield in repowering scenario X at point t
$cf_x(t)$	specific GWP/carbon footprint in repowering scenario X at point t

With the definition of different possible repowering scenarios, the analysis can be performed mathematically or graphically.

3.1 Energy demand as indicator

If we want to use the energy demand as the indicator on which we want to base our decision, we assess and compare the specific energy demand of each repowering scenario. It is calculated with the following equation:

$$e_x(t) = \frac{CED_{old}(t_r) + CED_x(t_x)}{E_{net,old}(t_r) + E_{net,x}(t_x)} \tag{1}$$

In the comparison of the specific energy demand, the scenario with the lowest values seems preferable. However, the life span needs to be taken into account here, too. If a scenario achieves a lower specific energy demand only when its life span exceeds the other scenarios' life spans, it is not the preferable option.

Even more straightforward is the graphical assessment. This is also demonstrated in section 4. Every repowering scenario has its own curve, the lowest curve within the time scope is the preferable option.

The optimal repowering point is determined accordingly.

3.2 Carbon footprint as indicator

The specific carbon footprint that is used here is calculated with the following equation:

$$cf_x(t) = \frac{GWP_{old}(t_r) + GWP_x(t_x)}{E_{net,old}(t_r) + E_{net,x}(t_x)} \tag{2}$$

The further assessment of the specific carbon footprint as an indicator for the optimal repowering point is analogous to the above discussion of specific energy demand. An exemplary graphical assessment of the specific carbon footprint as an indicator is made in section 4, too.

4 Exemplary assessments

In the following, the use of the described methodology in a graphical assessment is demonstrated. Different exemplary repowering scenarios are compared in terms of their specific energy demand and their specific carbon footprint. The first two assessments demonstrate the comparison of different repowering scenarios in terms of energy demand and carbon footprint. The third assessment illustrates the third point being made in section 3: If we look at one particular WEC, the earliest repowering point possible is always the best.

Besides different repowering scenarios the graphs shown in the following sections include a theoretical no-repowering scenario that is represented by a dashed black line. Although, due to the constraints mentioned before, this scenario is not very likely to be a real option; it can be used as a reference for the evaluation of the other scenarios.

4.1 Comparison of different scenarios based on energy demand

In the following example different repowering scenarios are going to be compared in terms of their energy demand. In this example a 0.5 MW WEC that was built in 1993 shall be replaced. There are three repowering scenarios in question. The first repowering scenario includes a 1.5 MW WEC that is available in 2002.The second repowering scenario includes a 2 MW WEC that is firstly available in 2005 and the third scenario includes a 2.3 MW WEC that is available from 2010. An overview of the different repowering scenarios is shown in the following table.

Tab. 2: Different repowering scenarios, example 1

Index of repowering scenario: x	Rated power [MW]	Year of availability / repowering point
1	1.5	2002
2	2	2005
3	2.3	2010

Fig. 2 shows the different repowering scenarios in comparison. The origin of the x-axis marks the installation of the original WEC. Its installation (including production, transportation etc.) is associated with energy consumption, while the energy production starts right after the installation. So, the graph showing the specific energy demand falls with increasing time. The installation of the repowering WEC is associated with additional energy consumption and thus there is a peak in specific energy demand at the point of repowering. Then, as the new WECs produce energy the curves fall again.

The values for the different repowering scenarios are calculated according to equation (1).

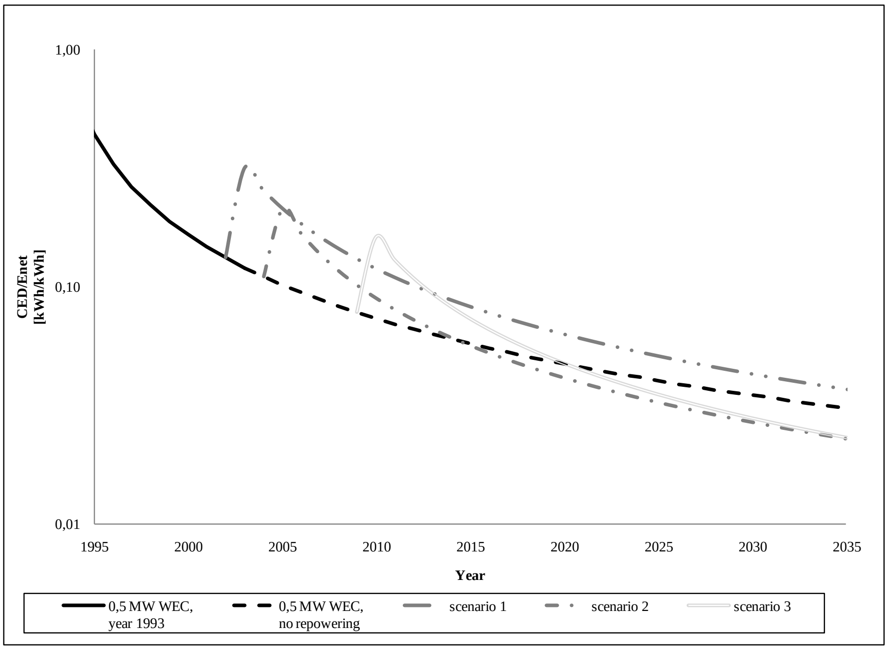

Fig. 2: Specific energy demand of different repowering scenarios depending on the years of operation. Peaks mark potential repowering points. The dashed black line marks the no-repowering option as a reference. Here, the early repowering scenario does not lead to lower specific energy demand within the expected lifetime of the WEC (around 20 years), while the two other scenarios do.

As is clearly visible from the graphs, the first repowering scenario (repowering through the 1.5MW WEC in 2002) never falls below the graph of the original WEC. This is in accordance with the condition described in section 3: Repowering only makes sense if the repowering WEC has higher energy efficiency, which is not the case for repowering scenario 1.

Repowering scenario 2 and 3 both appear to be favorable options. Their graphs fall below the curve of the (theoretical) no-repowering scenario after a few years and it appears that scenario 3 falls even faster than scenario 1. Here we need to take a closer look: Repowering in scenario 2 takes place in 2005. 20 years can be regarded as a likely life span for this converter. So it will probably be in operation until the year 2035. Scenario 3 does not become more efficient than scenario 2 until the year 2038, which is outside of the timeframe we are looking at. So in this example, scenario 2 is favorable and 2005 is the respective optimal repowering point.

4.2 Comparison of different scenarios based on carbon footprint

After demonstrating a comparison of different repowering scenarios in terms of their energy demand, a comparison of the specific carbon footprint of different repowering scenarios is presented here.

Again, a 0.5MW WEC that was built in 1993 shall be replaced. The first repowering scenario includes a 2 MW WEC that is available in 2002, the second scenario includes a 2 MW converter that is available in the year 2000 and the third scenario includes a 3 MW converter that is available in 2005. The different repowering scenarios are also shown in Tab. 3.

Tab. 3: Different repowering scenarios, example 2

Index of repowering scenario: x	Rated power [MW]	Year of availability / repowering point
1	1.5	2002
2	2	2000
3	3	2005

The graphical comparison of the repowering scenarios is shown in Fig. 3. The values for the different repowering scenarios are calculated according to equation (2). The general course of the graphs is the same as in the analysis of the specific energy demand. The explanation given in section 4.1 applies here, too.

The first repowering scenario never falls below the reference graph and does not qualify as a preferable repowering scenario. Scenario 2 shows a better performance and with the repowering point in 2000 it falls below the reference no-repowering scenario in 2009. Scenario 3 however, shows a lower specific carbon footprint than scenario 1 from year 2015 onwards. So scenario 3 is preferable to scenario 2 and the optimal repowering point is 2005.

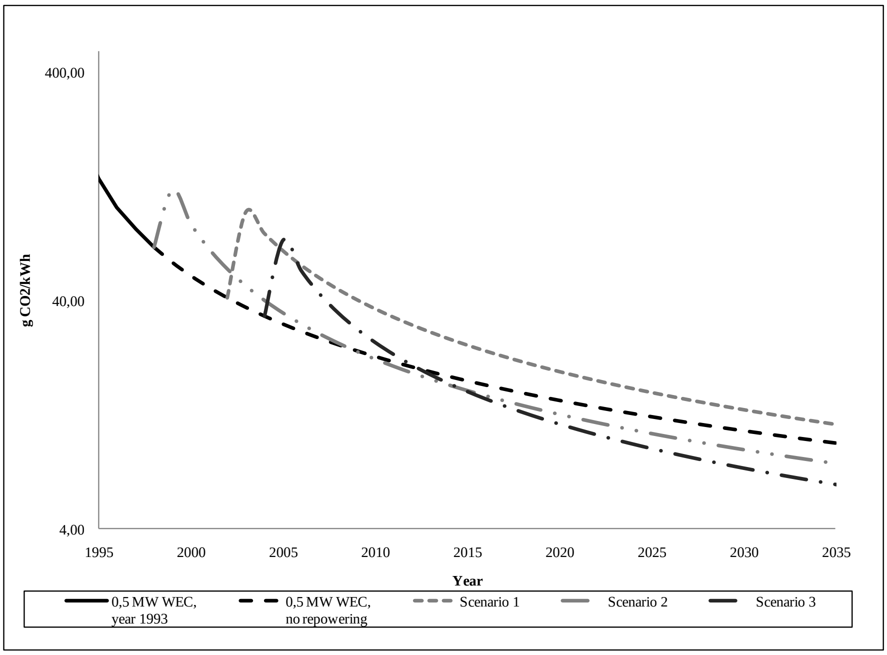

Fig. 3: **Specific carbon footprint of different repowering scenarios depending on the years of operation. The dashed black line marks the no-repowering option as a reference. Here, the early repowering scenario (in the year 2000) leads to a lower specific carbon footprint within only 9 years of operation, and thus well within the expected lifetime of the WEC (around 20 years). The late repowering scenario yields an even better specific carbon footprint after 2015.**

4.3 Comparison of different scenarios for one WEC

Fig. 4 shows the course of the graphs of the specific energy demand for the same repowering WEC with different repowering points. It can be seen clearly that the earliest repowering point is superior to the others. This is in accordance with the explanations made in section 3, where we stated said that for a particular WEC the earliest possible repowering point is always the best.

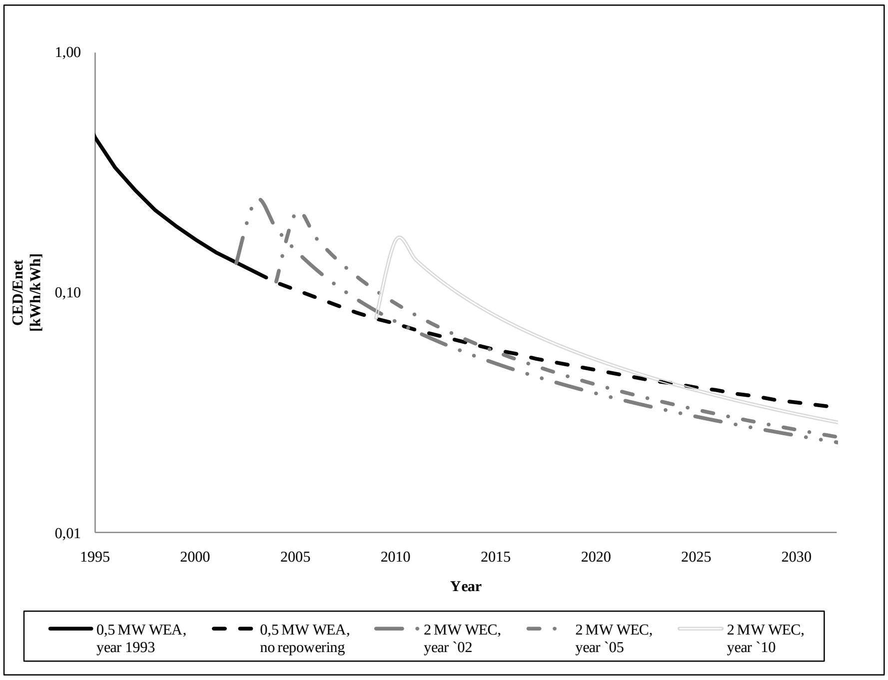

Fig. 4: Different repowering points for one WEC

5 Conclusion

The above described and applied methodology shows that with regard to case-specific constraints there always is an optimal repowering point in terms of the specific energy demand and the specific carbon footprint. With this methodology different repowering scenarios under varying boundary conditions can be compared. The optimal repowering point in turn results from the optimal repowering scenario.

Of course, the method can be applied to other impact categories, too. Assessing different impact categories though may result in different optimal repowering points, depending on the impact category. A more balanced and robust result might be achieved by using an aggregate measure of several impact categories.

6 References

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