ESTIMATION OF WEAR AND LIFETIME FOR IMPROVED TURBINE OPERATION

EERA DeepWind'2021, Trondheim, 15 January 2021

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Stand: 07.12.2017

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CONTENTS

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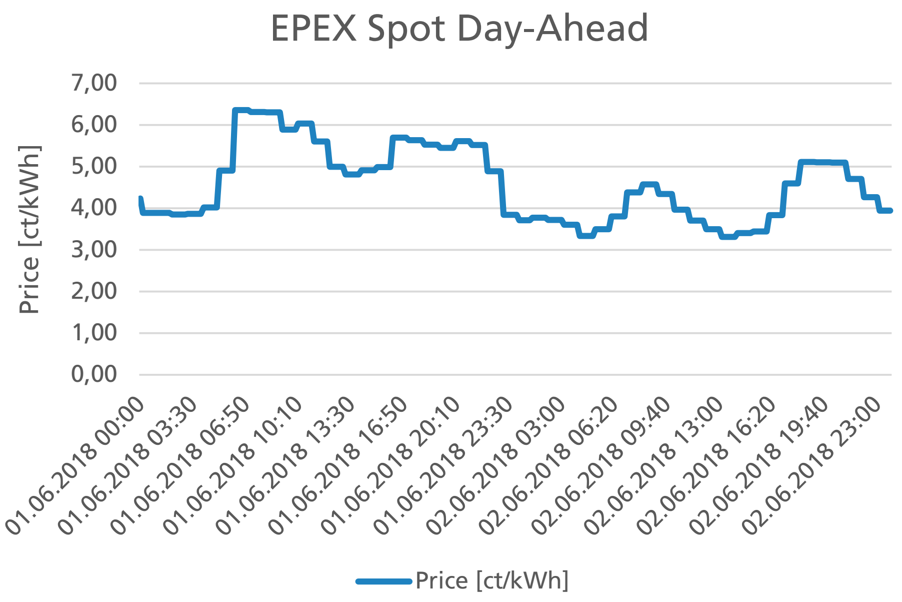
Motivation

- Present situation: an increasing number of WT have to compete on the wholesale energy market --> fluctuating prices!
- WT operation ignoring electricity prices does not make sense
- A paradigm shift to cost- and yield-optimized operation & control is urgently necessary.



Source: *European Energy Exchange AG. Epex spot auction: DE/AT (phelix); 2018*

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CONTENTS

- Motivation
- **Wear models**
- Economic issues
- Conclusion and outlook

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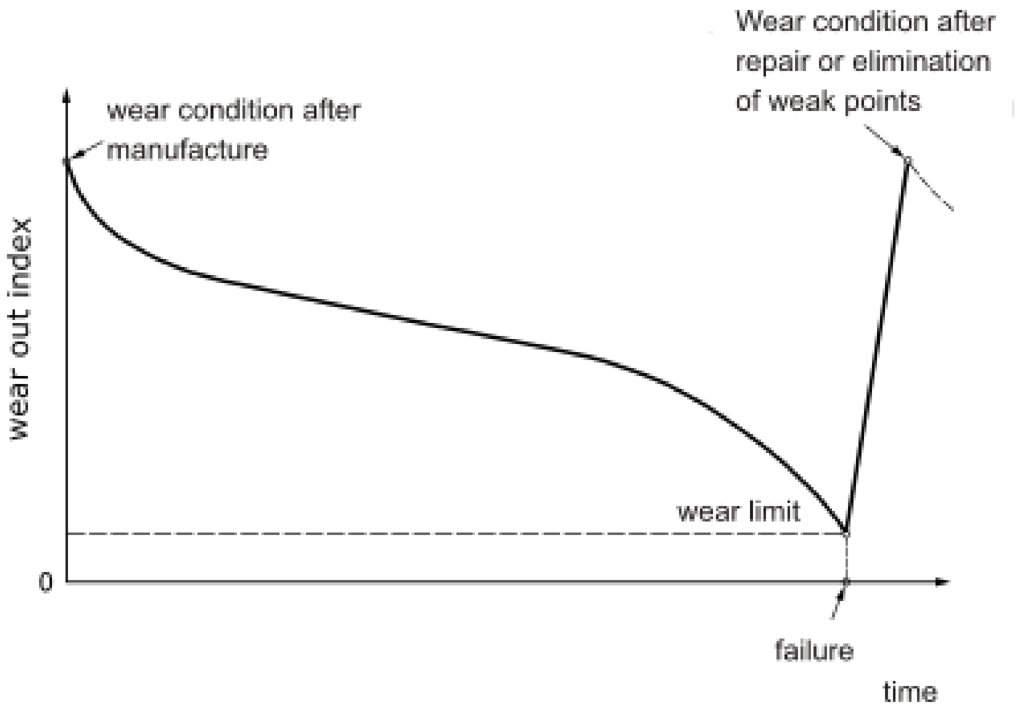
Wear models – What is wear/degradation?

- In accordance with DIN EN 13306:2010-12 "Maintenance – Maintenance terminology":
  - "Detrimental change in physical condition, with time, use or external cause"
  - "Degradation may lead to a failure"
- The wear limit defines the end of recommended lifetime (examples: tires, brake pads)
- Wear out index (woi) = normalized wear reserve



Source: In accordance with: DIN 31051:2012-09 „Fundamentals of maintenance“

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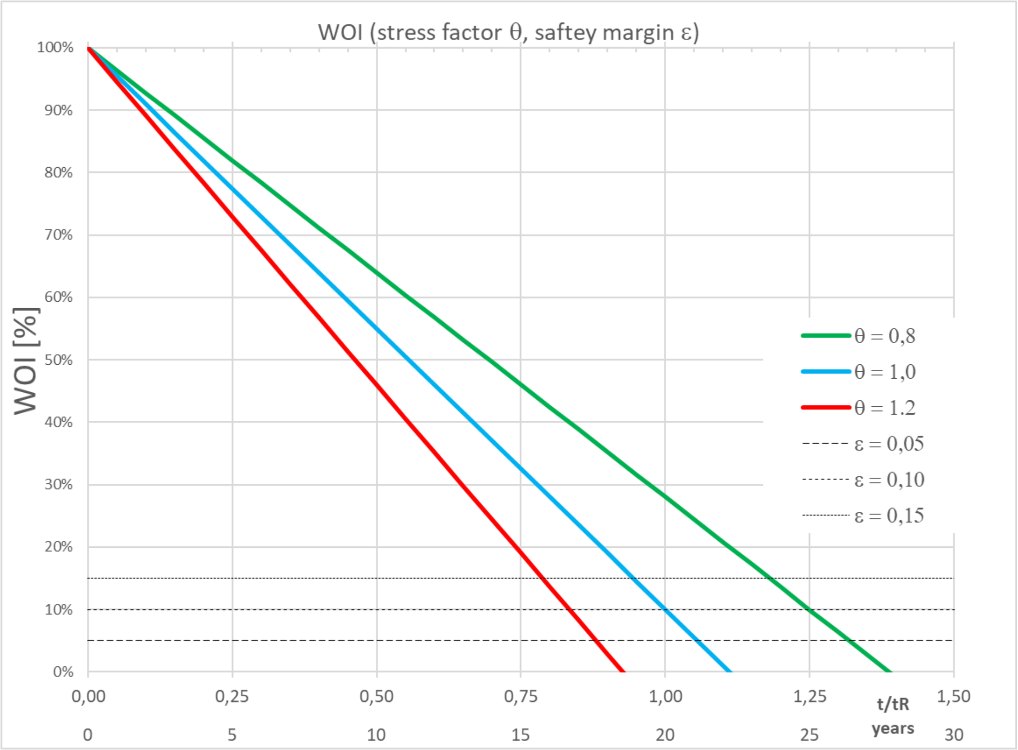
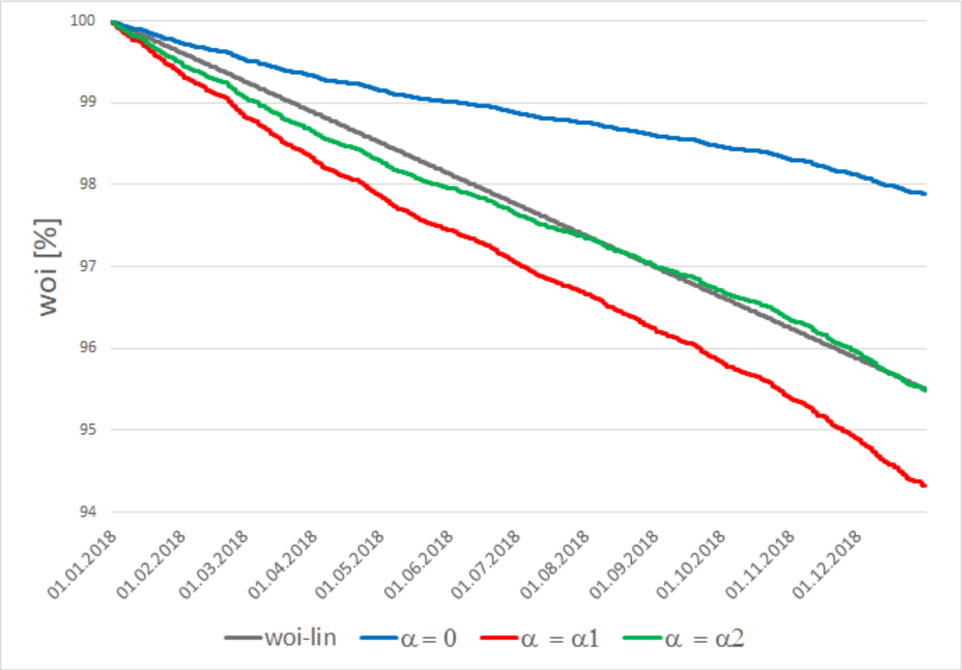
Wear models

- Simplified constant linear model:
  - $woi(t) = woi_N + \beta \cdot t$
  - $\beta = \frac{woi_{crit} - woi_N}{T_{LT}}$



- Power depending wear model:
  - $woi(t) = woi_N + \beta \cdot t \cdot p(t) + \omega(p(t)) \cdot \alpha$
  - $\alpha = \text{correction value}$
  - $\omega(p(t)) = 1 + 2 \cdot p(t)$



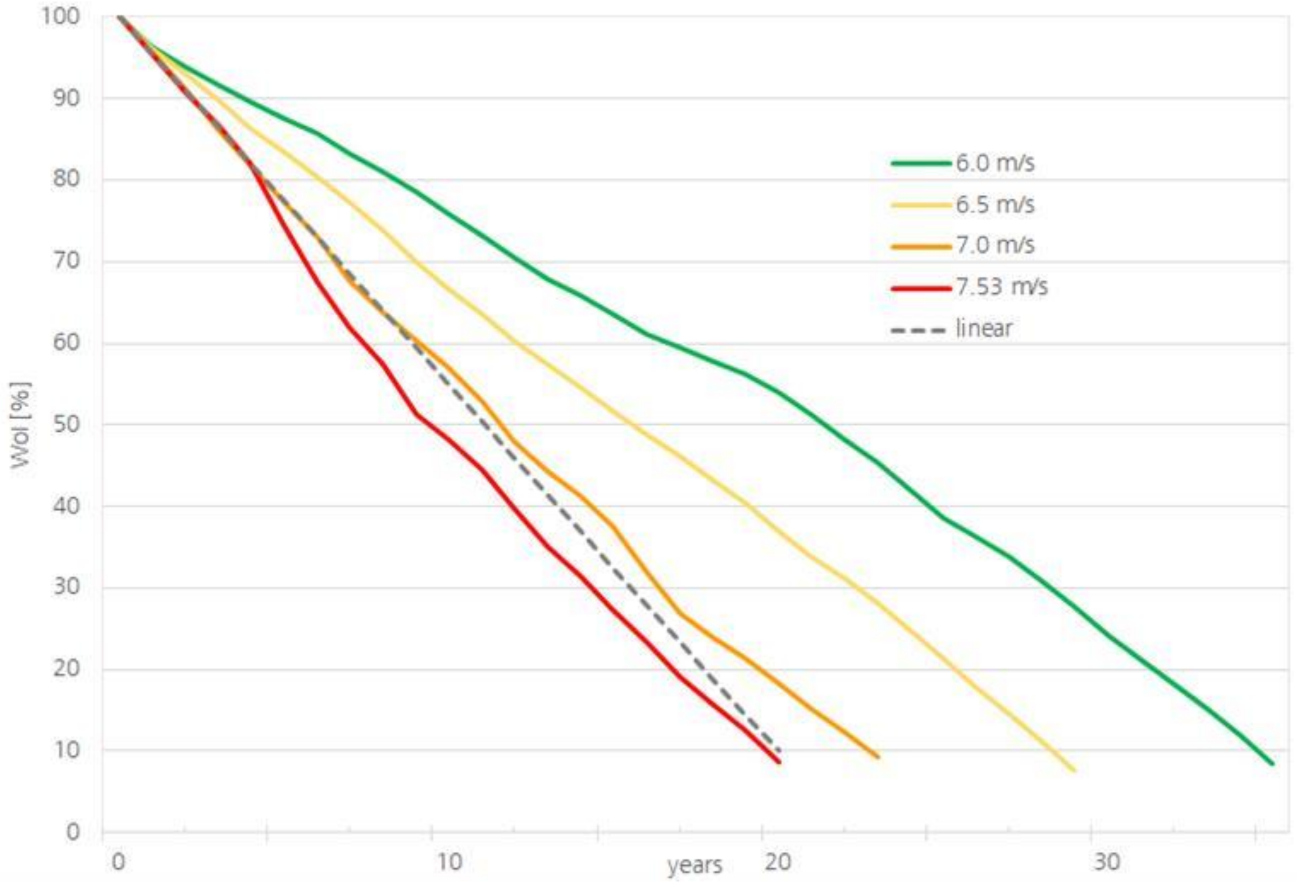
Model adaption and long term development

- Often the site conditions do not correspond exactly to the design conditions

- Lower wind conditions thus result in lower wear and tear

- Remaining life time T^*_{LT}

$$T^*_{LT}(t) = \frac{woi_{crit} - woi_i(t)}{\beta_i^*(t)}$$



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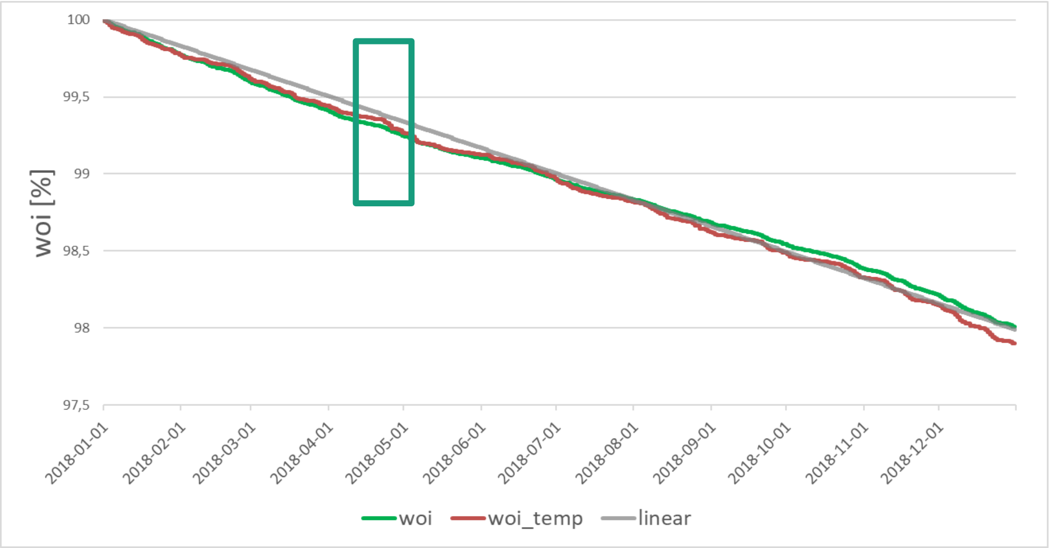
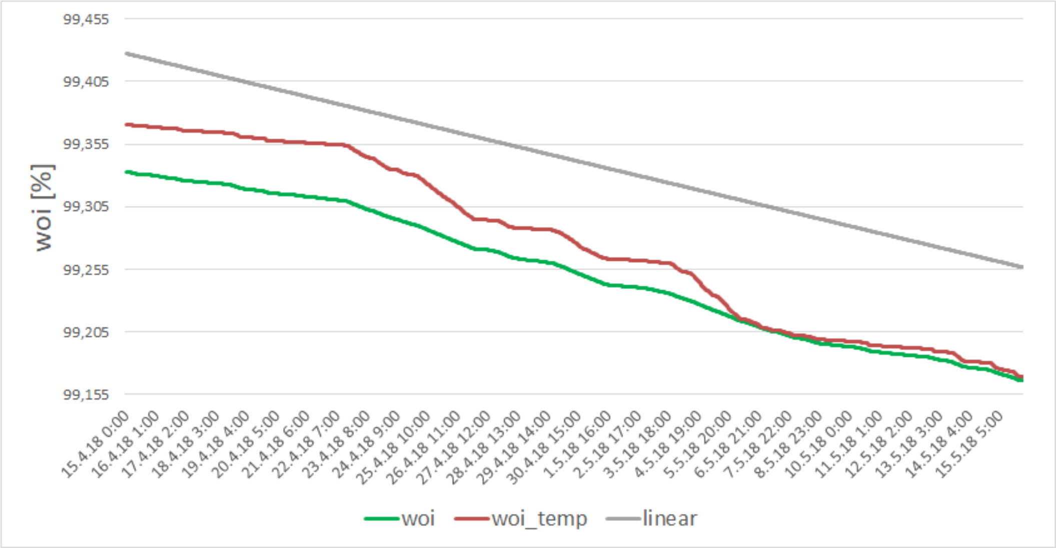
Wear models

- For an accurate condition monitoring of the entire WT a model for each component is needed
  - There are different wear mechanisms for the different components like
    - Fatigue loads resulting of the share forces, etc. For structural elements
    - Temperature as dominating wear mechanism for the isolation in the generator or transformer
    - ...
- Based on an empiric experimental formula the lifetime T for isolation can be calculated with:
  - $T_G = T_{G_0} \cdot 2^{\frac{\vartheta_0 - \vartheta}{k}}$
- For a 10-minute time interval:
  - $B_i = \frac{1}{T_{G_0} \cdot 6} \cdot 2^{\frac{\vartheta_i - \vartheta_0}{k}}$

Wear models

- Approximate the generator wear with the simplified model
  - The cumulative wear can approximated over one year
  - For shorter time periods the models differ
  - The generator load is delayed in time, but correlates with the power
  - For other components e.g. gearbox, blades, etc. the correlation between power, wind speed and the dominating wear mechanisms differs
  - → for an appropriate wear state monitoring individual wear models for each (main) component are essential





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Economic Issue – Assumptions KORVA

- The total lifetime is limited
- The correlation between load and wear is positive.
- There are no full maintenance contracts for the operators
- The energy is sold directly via the electricity exchange market and negative revenues are possible.
- The operational fix costs are nearly constant for every year.
- Goal → Develop an economic competitive strategy for WT

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Economic Issue – cost structure

- General rule: $Profit = Income – Costs$
- Income: $I(T) = \int_0^T r(t) \cdot p(t) dt$
- Costs: $C(T) = CW(T) + T \cdot C_{fix}$
- Marginal costs are neglected.

$I(t)$:= Income,

$C(t)$:= Costs,

$r(t)$:= Remuneration price per kilowatt-hour (kWh),

$CW(t)$:= Costs of wear and tear,

C_{fix} := Fix operational expense, installation costs.

Monetization of wear

- Consideration of individual components $CW_X(t) = C_X \cdot (1 - woi_X(t))$

$$\Rightarrow CW(t) = \sum_{X=1}^{n} CW_X(t) = \sum_{X=1}^{n} C_X \cdot (1 - woi_X(t))$$

- Total profit up to time T $G(T) = \int_0^T r(t) \cdot p(t)\ dt - \left(CW(T) + T \cdot C_{fix}\right)$

- In accounting: CW(T) are accruals for repair costs

C_X := Repair costs of a component X,

woi_X := Specific wear model

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Optimization

- Targets/ objectives
  - Maximize the total Profit $G(T)$
- Assumptions
  - All components have the same linear wear model
  - In graphic we set $\sum_{X=1}^{n} C_X := C_{WT}$

$C_{WT} :=$ Price for a new WT with

- Analytically you get a shutdown strategy

$$\max_{p_i \in [0,\ p(t_i)]} \frac{1}{6} \cdot p_i \cdot r(t_i) - \sum_{X=1}^{n} C_X \cdot (1 - woi(\frac{1}{6}))$$

$$= \max_{p_i \in [0,\ p(t_i)]} \frac{1}{6} \cdot p_i \cdot r(t_i)$$

$$- \sum_{X=1}^{n} C_X \cdot (\frac{1}{6} \cdot \beta_i \cdot p_i + ((1 + 2 \cdot p_i) \cdot \alpha)$$

- Condition to shutdown

$$\Rightarrow r(t_i) \ < \ -C_{WT} \cdot (\beta_i + 12\alpha)$$

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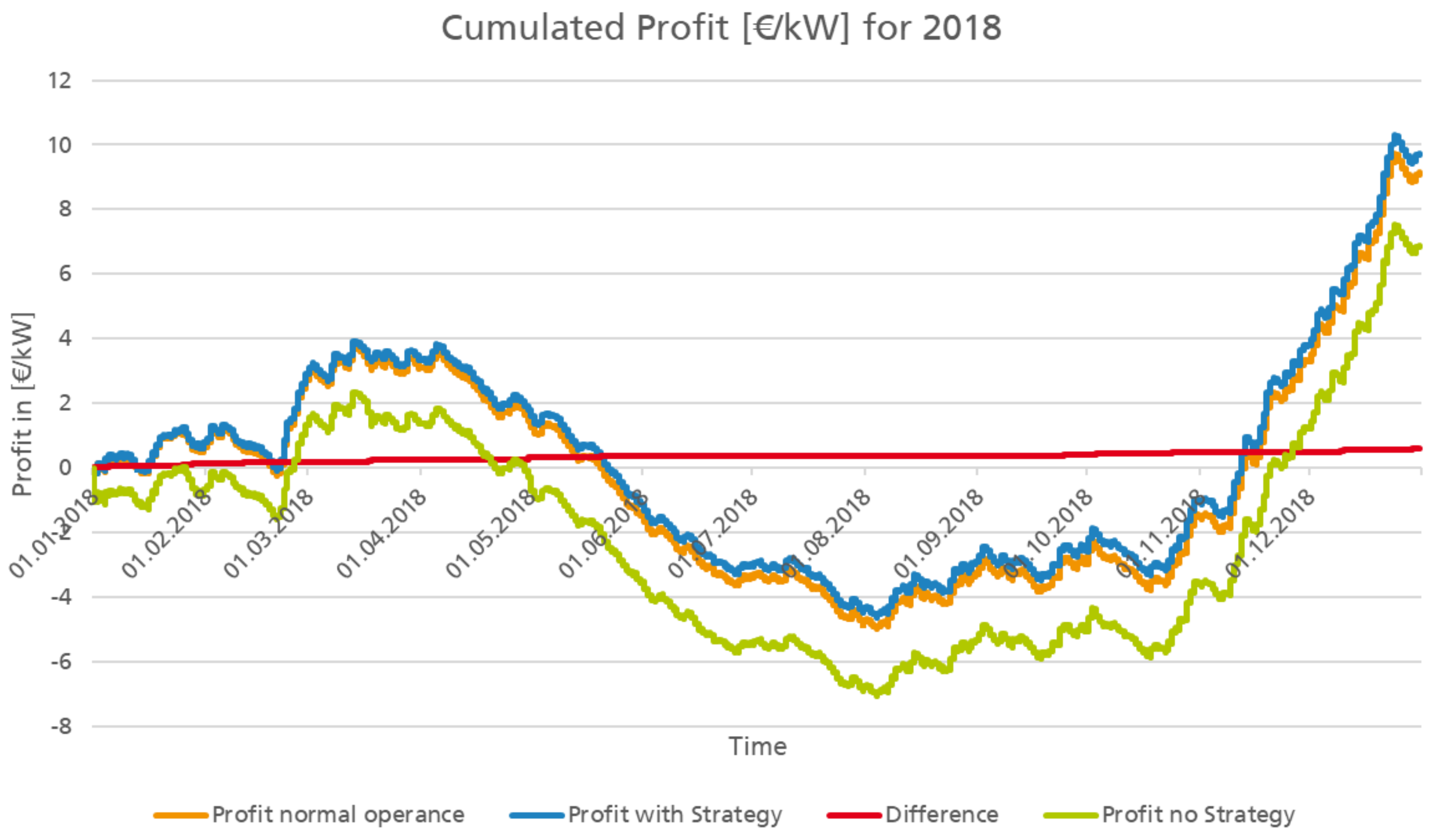
Comparison of the strategies

- Conditions of shutdown strategies
  - Normal: r < 0,00 ct/kWh
  - Maximum: r < 1,006 ct/kWh
  - No condition.
- The Difference is between the normal operance and with strategy.
- With the condition

$$\Rightarrow r(t_i) \ < \ -C_{WT} \cdot (\beta_i + 12\alpha)$$

We have 0,598 €/kW more profit.

→ 11,96 €/kW after 20 years



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CONTENTS

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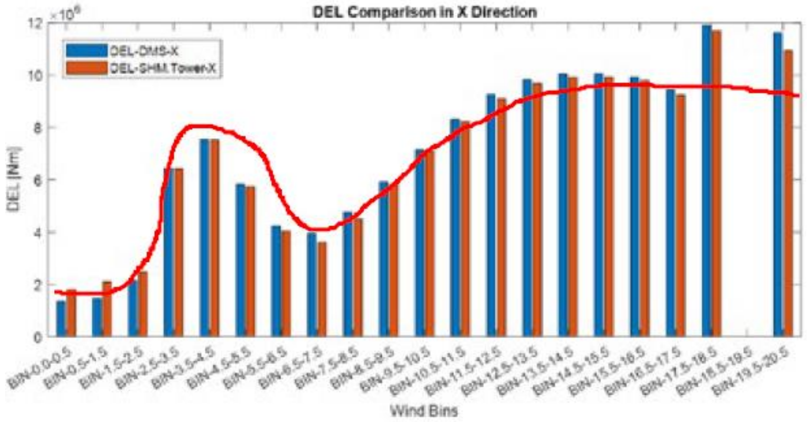
Conclusions and outlook

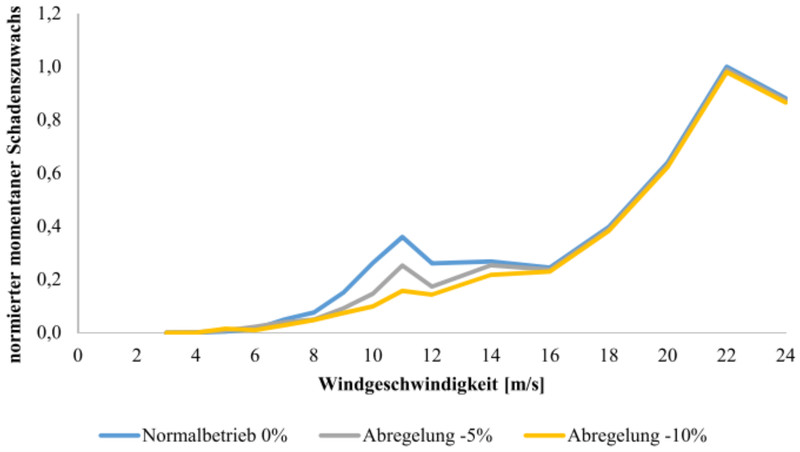
- Conclusions
  - A method for estimation of actual component wear was introduced.
  - The feasibility of the concept/method of estimating wear and lifetime was proven by dynamic simulations.
  - A rough estimation of the wear out index based on the power is possible.
  - The shown optimized control strategy demonstrates the possibility of increasing profit through wear-based control.

Conclusion and outlook

- Outlook
  - For a full optimized control strategy a component distinctive wear model for each component and **each power level** is needed
  - Wear models will be more complex and need more than power as input (e.g. wind speed, turbulence, thrust, bending moments, etc.…)
  - The integration of further information e.g. wind and electricity prices forecasts, current project costs etc. will be necessary for comprehensive, resilient WT operation application.
  - With complex wear models other optimization-methods can be tested
  - On site verification: partners for further development, testing and implementation wanted



Source: Jiri Vrbata, SHM.Tower®: Methodik zur Maximierung der Weiterbetriebszeit von Windenergieanlagen erfolgreich begutachtet (2020)



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Questions?

Thanks for your attention!

Sources

- DIN 31051:2012-09 "Fundamentals of maintenance“; 2012
- DIN EN 13306:2010-12 "Maintenance – Maintenance terminology"; 2010
- *European Energy Exchange AG. Epex spot auction: DE/AT (phelix); 2018*
- Jiri Vrbata, SHM.Tower®: Methodik zur Maximierung der Weiterbetriebszeit von Windenergieanlagen erfolgreich begutachtet; 2020.
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