Joint optimization of predetermined and condition-based maintenance for offshore wind farms

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[1] Sintef Energy Research AS

Maintenance planning

- Find the best times to execute a set of maintenance tasks.
  - Predetermined maintenance
  - Condition based maintenance
    - Avoid failure
    - Return de-rated turbine to full production
- Optimize Revenue-costs
- Formulated as a Mixed Integer Linear Program:

$$\max \sum_{t \in \mathcal{T}^{short}} \left[\sum_{i \in \mathcal{W}} \left[\lambda(P_{ti}^0 a_{ti} + (P_{ti} - P_{ti}^0) b_{ti}) - C^f \rho_{ti}(1 - \bar{y}_{ti}) \right] - C^{tr} v_t \right]$$
$$- \sum_{t \in \mathcal{T}^{long}} \left[C^f \sum_{i \in \mathcal{W}} \rho_{ti}(1 - 0.5 y_{ti} - \bar{y}_{ti}) + \sum_{k \in \mathcal{K}} h_{tk}(\lambda P_{tk}^{loss} + \frac{C^{tr}}{\tau^x + \tau^y + \tau^z}) \right]$$

Example of maintenance schedule

Short term daily schedule

Wind turbine	Day 1	Day 2	Day 3	…
PM	1,2	3,4,5	6,7,8,9	10,11,12
CBM type 1	1	4		10
CBM type 2		7		

Long term weekly schedule

Wind turbine	Week 2	Week 3	Week 4	…
PM	14,15		21,22	
CBM type 1				
CBM type 2	3			

Estimated loss based on production forecasts

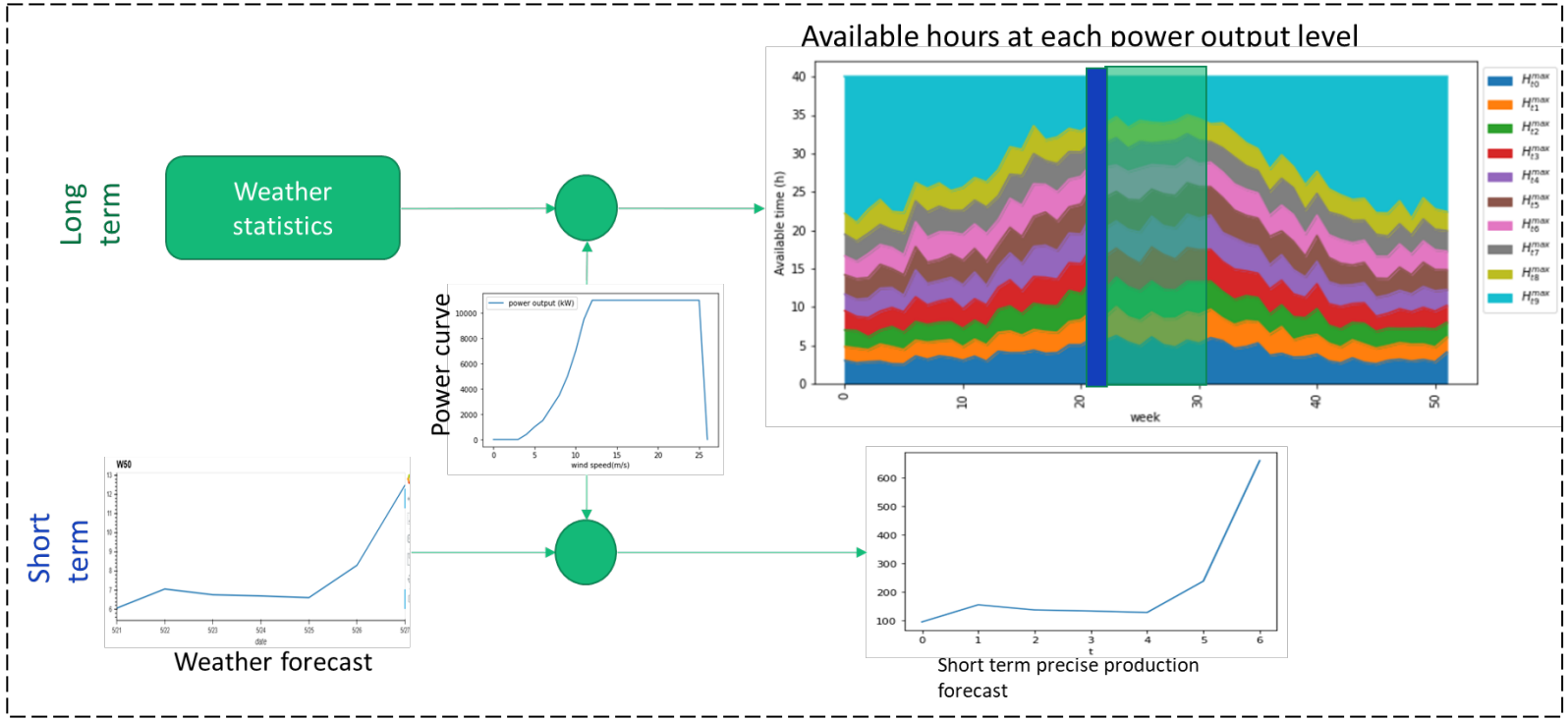
Two time horizons are considered[1]

- Short ~1 week
- Long ~ 1-6 months

Short term forecast based on precise wind forecast and power curve.

Long term forecast based on statistical weather data and power curve.

- Available hours at production level H_{tk}^{max}
- Treated by constraints



$$\sum_{i \in \mathcal{W}} (\tau^x x_{ti} + \tau^y y_{ti} + \tau^z z_{ti}) = \sum_{k \in \mathcal{K}} h_{tk}$$

$$h_{tk} \leq H_{tk}^{max}$$

1 Besnard et. al. 2010

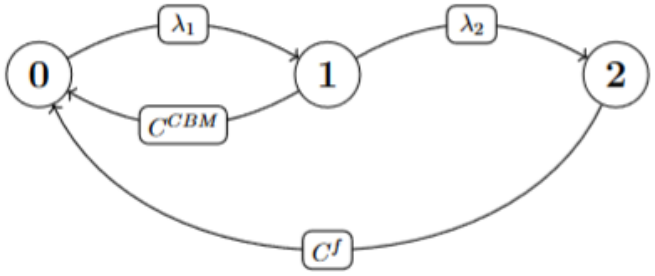
Condition based maintenance

Failure modelling

Condition is monitored and registered on a categorical scale

Condition state	Description
0	No indication of corrosion
1	Corrosion detected
2	Corrosion allowance depleted

Condition state follows a Markov model

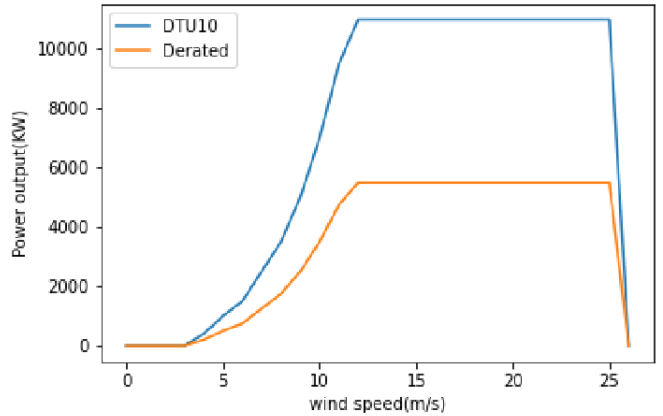


The state can be bought from state 1 to state 0 by sandblasting and recoating.
State 2 is considered a failure.
Requires a complete renewal at a cost C^f.
Calculated by net present value of accelerated renewal

$$C^f = \frac{C^{turb}(1-(1+r)^{T^{RUL}})}{1-(1+r)^{T^L}}$$

De-rating

- A degraded condition is detected on a turbine
- To avoid failure the turbine is run at a lower effect.
- Modelled by de-rated power curve

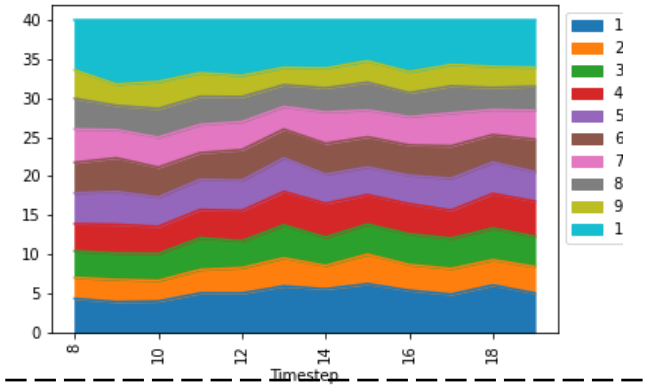


Example study

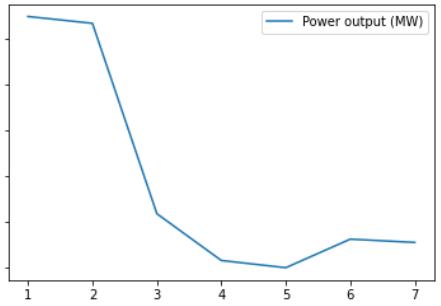
- Wind farm with 16 turbines
- Starting week 15 (~april)
  - Short term: 7 days
  - Long term: 12 weeks
- Corrosion indicated on wind turbines 1,2 and 3.
- Bearing problem and de-rating on wind turbine 4

Input

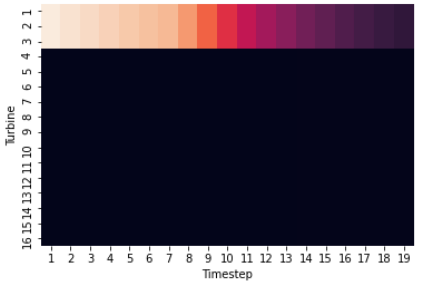
Available hours



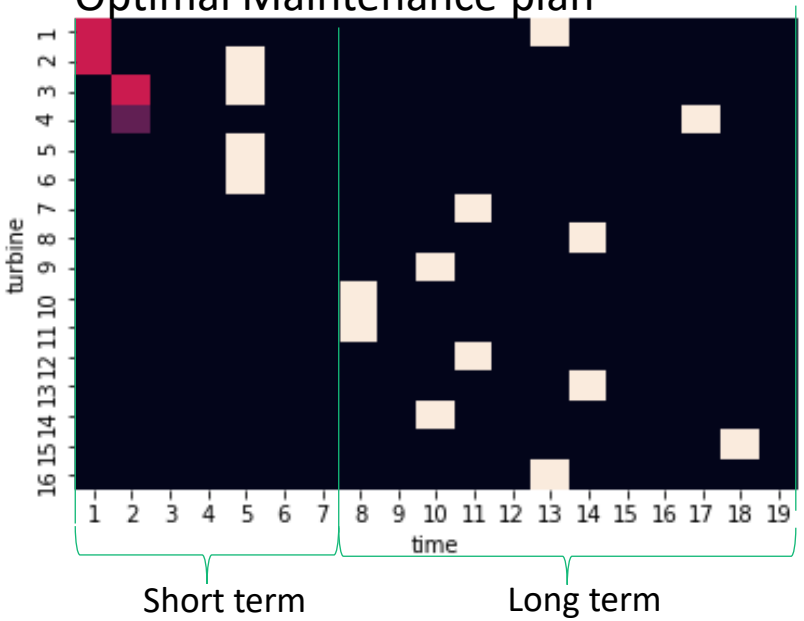
Production forecast



Failure probability



Optimal Maintenance plan



CBM: recoating

CBM: bearing repair

PM

Short term

- CBM tasks are prioritized
- Tasks are planned on days with low production forecast

Long term

- Available hours with low production are utilized