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Operation-Related Maintenance and Reinvestment Costs for Hydropower Scheduling

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Outline

- Introduction and history
- Equivalent operating time
- Average and marginal cost for one extra start/stop
- Adjustments for technical solution and length of standstill period
- Examples
- Cost of ramping, and cost of operating on (low) part load and overload
- Summary and final remarks

Introduction

- Experience has shown there is a connection between operating patterns, wear and tear, and failure development for hydropower equipment.
- Hence, in production planning, the revenues from power production and services should be balanced against the costs of operation and maintenance.

- Some challenges:
  - Start/stop costs are implemented in scheduling software, however, these costs may often be static or seldom updated.
  - Scheduling software usually have no similar penalty for running on (low) part load (or overload, or ramping …)
  - → To avoid the start/stop cost the software may suggest running on (low) part load during low price periods
  - → Possible cost of degradation not taken into account when bidding, e.g., in the reserve market

Model and tool for estimation of the cost of a start/stop cycle – brief history

- The first version was released in 2002
  - Based on a typical Norwegian hydropower unit, i.e., 150 MW with 100 – 200 start/stop cycles per year
  - Default values given for such a reference unit
  - Scaling functions to adjust to the capacity and technical solution of the unit to the analysed
  - Estimation of the average cost of a start/stop cycle
- The second version was released in 2011
  - Estimation of the marginal cost of a start/stop cycle
- The third version was released in 2022
  - Adjustment for actual technical condition
  - Adjustment for duration of standstill
  - A simplified estimation of cost of ramping, cost of running on (low) part load, and cost of running on overload

Estimation of operation-related costs

- The fundamental assumption is that operation deviating from the design specification leads to increased stress and increased degradation (e.g., increased wear) thus (potentially) reducing residual service life (e.g., accelerated rehabilitation).

$$C_{startstop} = \frac{(R_i + V_i + F_i) - (R_0 + V_0 + F_0)}{n_i - n_0} = \frac{\Delta R + \Delta V + \Delta F}{\Delta n}$$

R - Rehabilitation cost
V - Maintenance cost
F - Failure cost
n - Number of start/stop

- Some alternative approaches:
  1. **Maintain component lifetime**, resulting in increased maintenance → $\Delta R = 0$, $\Delta V > 0$
  2. **Maintain current maintenance practice**, resulting in reduced technical life → $\Delta V = 0$, $\Delta R > 0$
  3. **Probabilistic modelling** of the life, ageing or deterioration of components → Lots of data...

Cost elements

1. Work related to a normal start/stop
2. Water loss related to a normal start/stop
3. Failure related to start/stop
4. Preventive maintenance of main valve
5. Preventive maintenance of turbine
6. Preventive maintenance of the generator's smaller components

Cost elements incurring during, or close to, each start/stop cycle

7. Lifetime reduction for main valve
8. Rehabilitation of turbine
9. Lifetime reduction for turbine runner
10. Overhaul (preventive maintenance) of generator
11. Lifetime reduction for stator winding
12. Lifetime reduction for stator core
13. Lifetime reduction for rotor winding

Cost elements that accumulate and incur at the time of larger maintenance action or rehabilitation, calculated both as average and marginal cost

14. Waterway/tunnel/pressure shaft, Breakers, Power transformer
15. Other costs related to start/stop

Cost elements that, if relevant, must be given explicitly

Equivalent operating time vs. Equivalent lifetime reduction

- Total equivalent operating time *d* at calendar time *t* (for each relevant component)

$$d(t|\alpha, n, \Delta D) = \alpha \cdot t + n \cdot \Delta D \cdot t = (\alpha + n \cdot \Delta D) \cdot t$$

  – α - Share of calendar time the unit is in operation
  – n - Number of start/stop per unit of time (usually one year)
  – ΔD - Equivalent operating time per start/stop

- Assuming expected total operating time until rehabilitation is constant and determined by the unit's design:
  Equivalent lifetime reduction (reduced service time in calendar time) ΔL

$$\Delta L = \frac{\Delta D}{\alpha_0 \cdot 24 + n_0 \cdot \Delta D} \cdot 24 = \frac{\Delta D}{\frac{t_{operation}}{8760} \cdot 24 + \frac{n}{365} \cdot \Delta D} \cdot 24 \quad [\text{hours}]$$

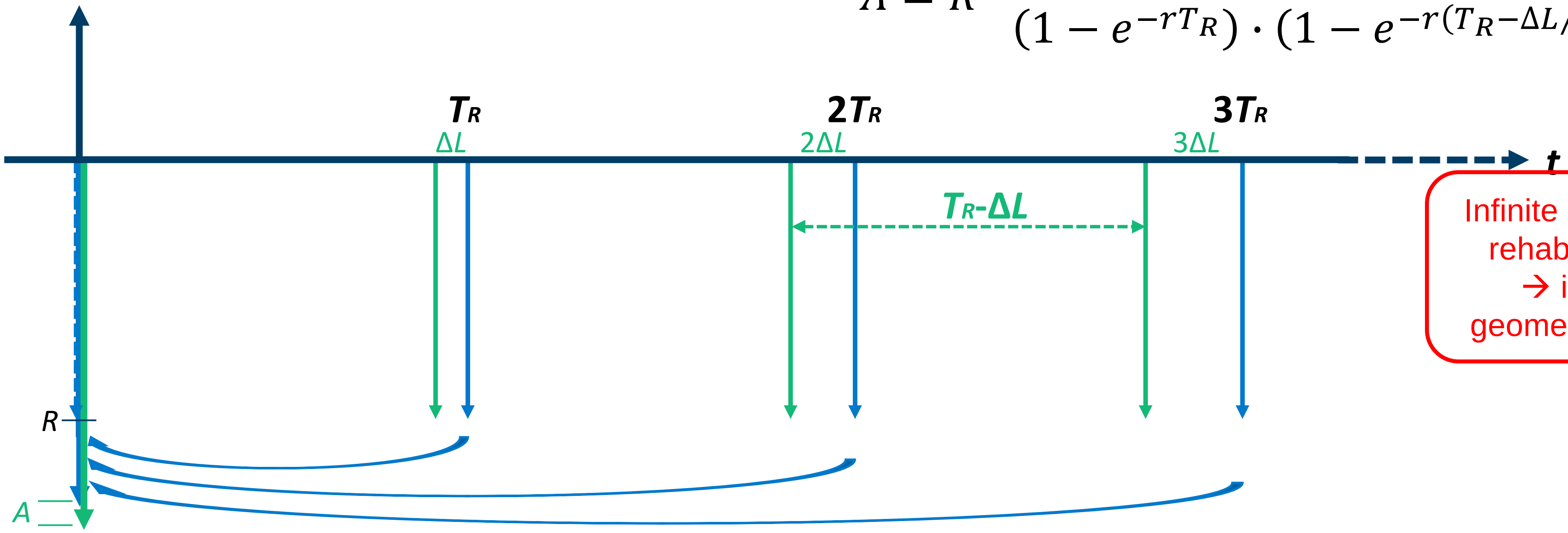
Challenge: estimate equivalent number of "normal" operating hours for the "deviating" operation

Transforming equivalent operating time to calendar time

Average cost for one extra start/stop

- The extra start/stop cycle is permanent (change in strategy), i.e., expected to change all future rehabilitation intervals.
- Useful for investment analysis and long term analysis.

$$A = R \cdot \frac{e^{-r(T_R - \Delta L/8760)} - e^{-rT_R}}{(1 - e^{-rT_R}) \cdot (1 - e^{-r(T_R - \Delta L/8760)})}$$

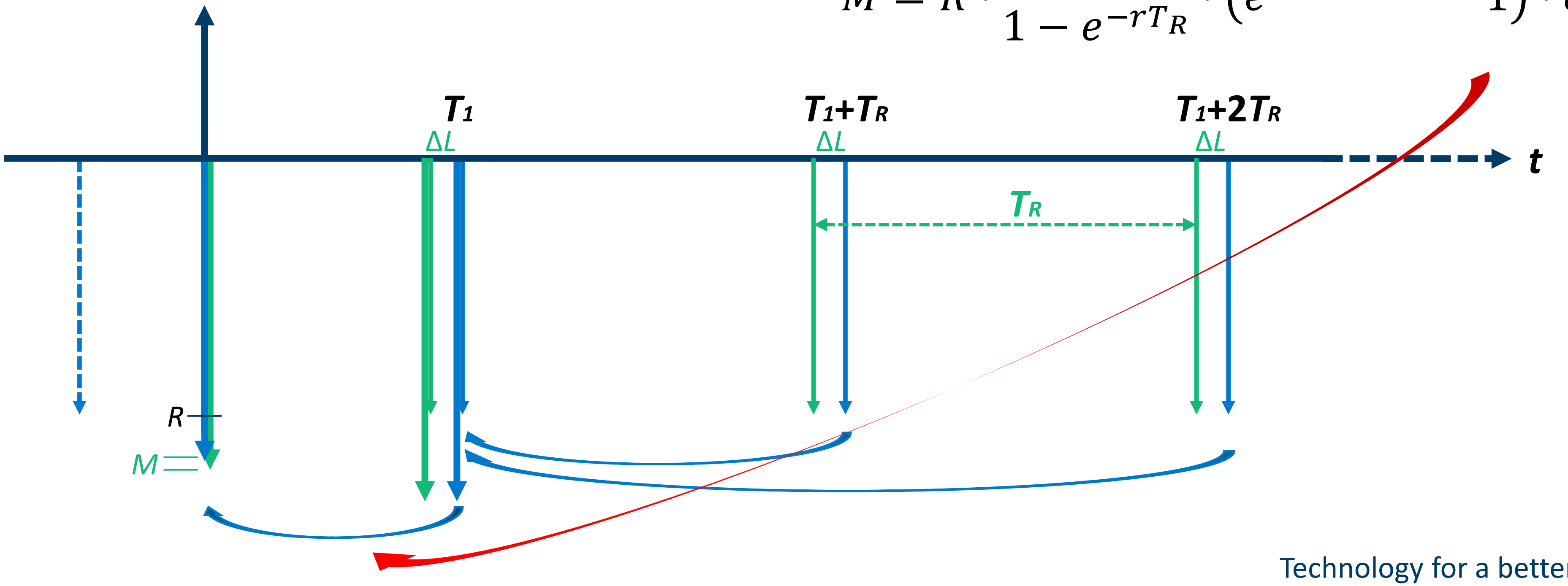


Infinite number of rehabilitations → infinite geometric series

Marginal cost for one extra start/stop

- The extra start/stop cycle is temporary (not permanent), i.e., not expected to change future rehabilitation intervals.
- Useful for short term scheduling.

$$M = R \cdot \frac{1}{1 - e^{-rT_R}} \cdot \left(e^{r\Delta L/8760} - 1\right) \cdot e^{-rT_1}$$



Equivalent operating time as function of technical condition

Marginal cost

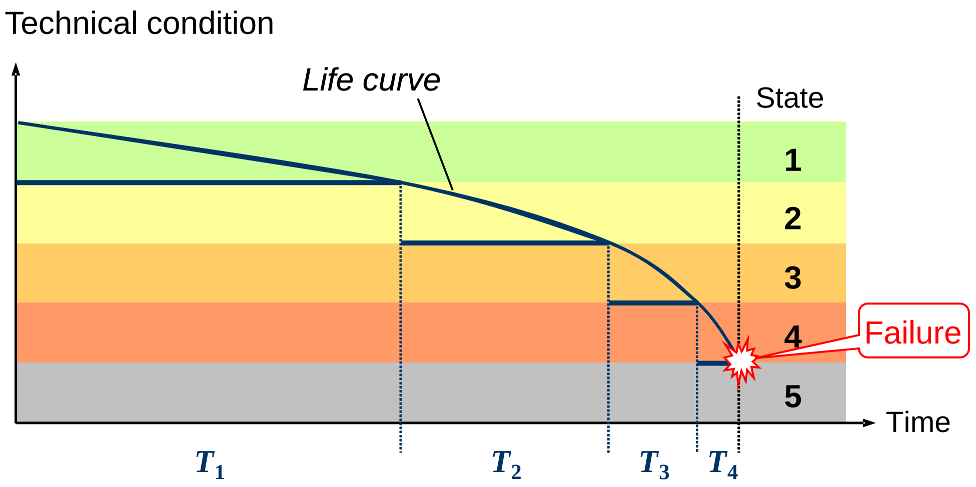
- Reference to condition monitoring handbooks, failure models and life curves
- Hypothesis: increasing tear and wear during start/stop with increasing age (reduced technical condition)

→ Δd as function of technical condition

$$\Delta d = \Delta D \cdot f_{technicalcondition}$$

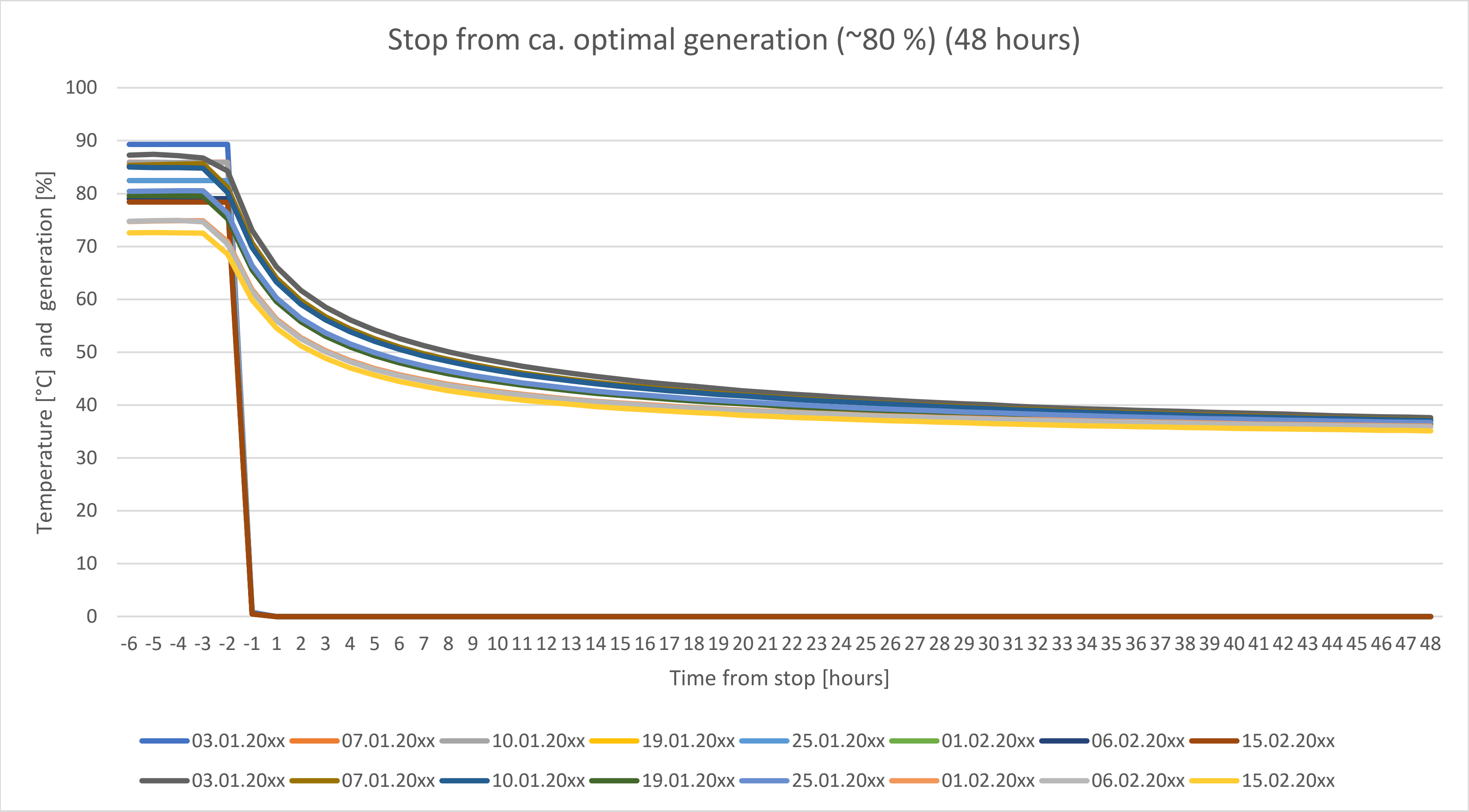
- $f_{technicalcondition=1}$ < 1
- $f_{technicalcondition=2}$ = 1
- $f_{technicalcondition=3}$ > 1
- $f_{technicalcondition=4}$ >> 1

State	Description
1	No indication of deterioration ('as good as new').
2	Some indication of deterioration. The condition is noticeably worse than 'as good as new'.
3	Serious deterioration. The condition is considerably worse than 'as good as new'.
4	The condition is critical.
5	Fault state.

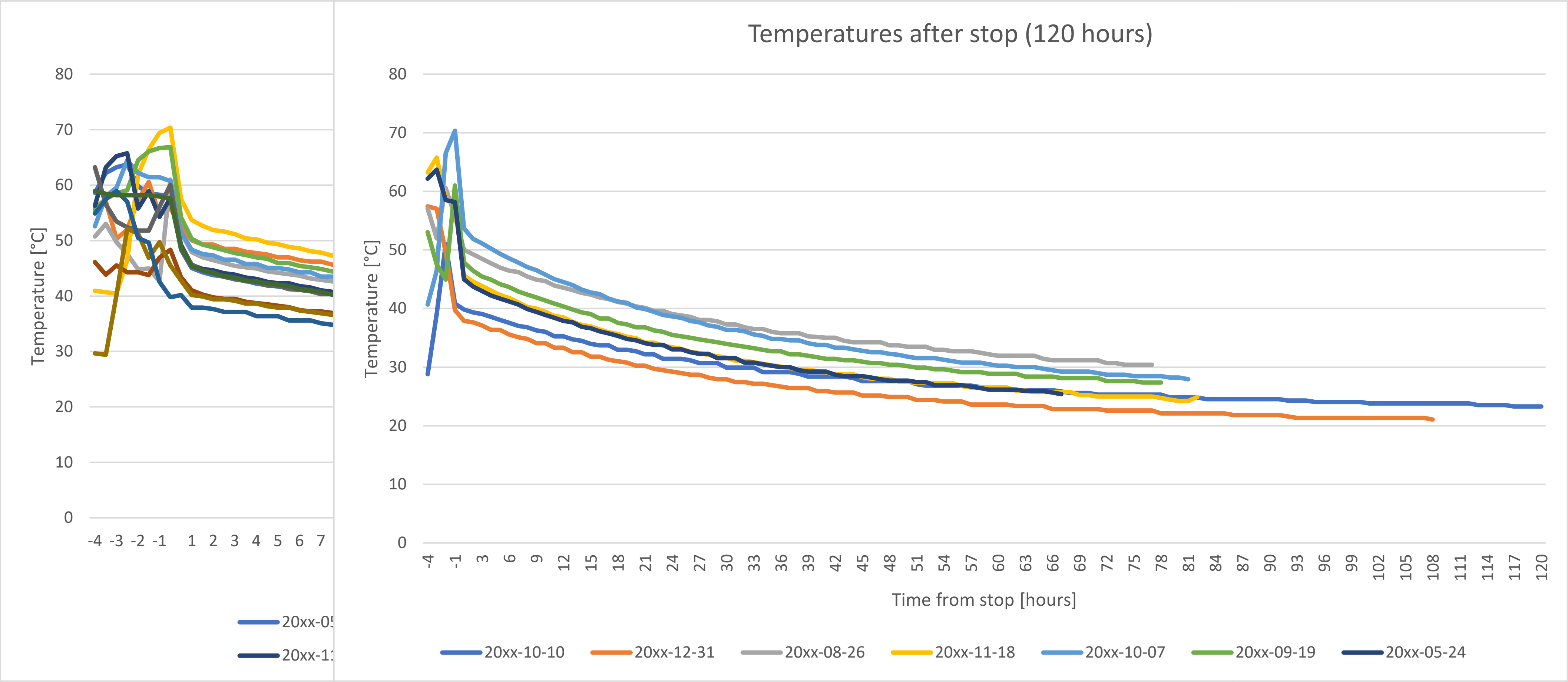


Welte, Eggen "Estimation of Sojourn Time Distribution Parameters Based on Expert Opinion and Condition Monitoring Data"

Stator winding temperatures – examples



Stator winding temperatures – examples



Equivalent operating time as function of length of standstill period

Marginal cost

- Original model/tool assumes a “cold start”
  → thermal cycling and delamination of winding insulation
- Examples based on few samples.
  - Stop from rated power:
    Rapid decrease in winding temperature the first ~30 minutes, followed by a much slower decrease.
  - Stop from part load:
    Much smaller decrease in temperature the first ~30 minutes, followed by a similar decrease.
- Hypothesis: Shorter standstill durations implies reduced thermal cycling, and hence reduced stress (delamination) and start/stop cost for generator.
- Δd as function of standstill duration (linear relationship between duration of standstill and equivalent operating time)

$$T_{standstill} < T_{limit}:\ \Delta d = \Delta D \frac{T_{standstill}}{T_{limit}}, \qquad T_{standstill} \geq T_{limit}:\ \Delta d = \Delta D$$

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Tool – 12 mandatory input parameters

- Valve
  - Yes/No — Yes
  - Type — Spherical
  - Control (water/oil) — Water
  - Dimension [mm] — 2000
  - Installation / last rehabilitation — 1990
- Turbine
  - Type (pelton/francis) — Francis
  - Head [m] — 300
  - Rpm [o/min] — 375
  - Number of needles (pelton) — -
  - Runner diameter (francis) [m] — 1.911
- Generator
  - Rated power [MVA] — 110
  - Next planned rehabilitation — 2030

- These mandatory input parameters describe the main characteristics of the unit.

- Based on these mandatory input parameters, and scaling of predefined default values for a 150 MW reference unit, a number of proposed values for the unit at hand are calculated.

Tool – Some recommended input parameters

Time of analysis	2021
Interest rate [%]	6.0
Energy price [€/MWh]	50
Labour cost, hourly rate [€/hour]	100
Cost of unavailability [€/hour/MW]	3
Failure probability at start-up	0.01

Annual operation [hours]	5000
Part load operation [hours]	0
Overload operation [hours]	0
Number of start/stop (current)	150
Number of start/stop (future)	150

- By changing the default values for these recommended input parameters, the accuracy of the proposed values for the unit at hand are improved.

Tool – Example

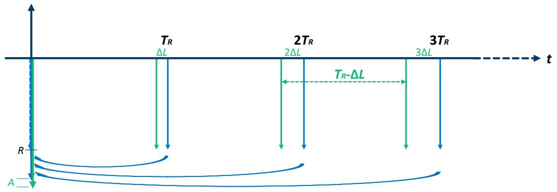
$\Delta D_{turbine}$ = 15 hours
$\Delta D_{statorwinding}$ = 10 hours
$\Delta D_{statorcore}$ = 5 hours
$\Delta D_{rotorwinding}$ = 10 hours

Costs closely related to each start/stop (average and marginal)

- Work related to a normal start/stop 100
- Water loss related to a start/stop 20
- Failure related to start/stop 107
- Maintenance of main valve 19
- Maintenance of turbine 8
- Maintenance of generator 22
- Waterway/tunnel/pressure shaft 0
- Power transformer 0
- Breakers 0
- Misc. 0
- Sum 277

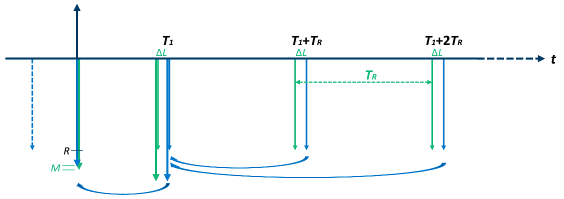
Costs related to future rehabilitations (average)

- Lifetime reduction for main valve 54
- Rehabilitation of turbine 39
- Lifetime reduction for turbine runner 122
- Overhaul of generator 44
- Lifetime reduction for stator winding 88
- Lifetime reduction for stator core 21
- Lifetime reduction for rotor winding 11
- Misc. 0
- Average cost of start/stop 656
- Specific cost of start/stop [€/MW] 6,62

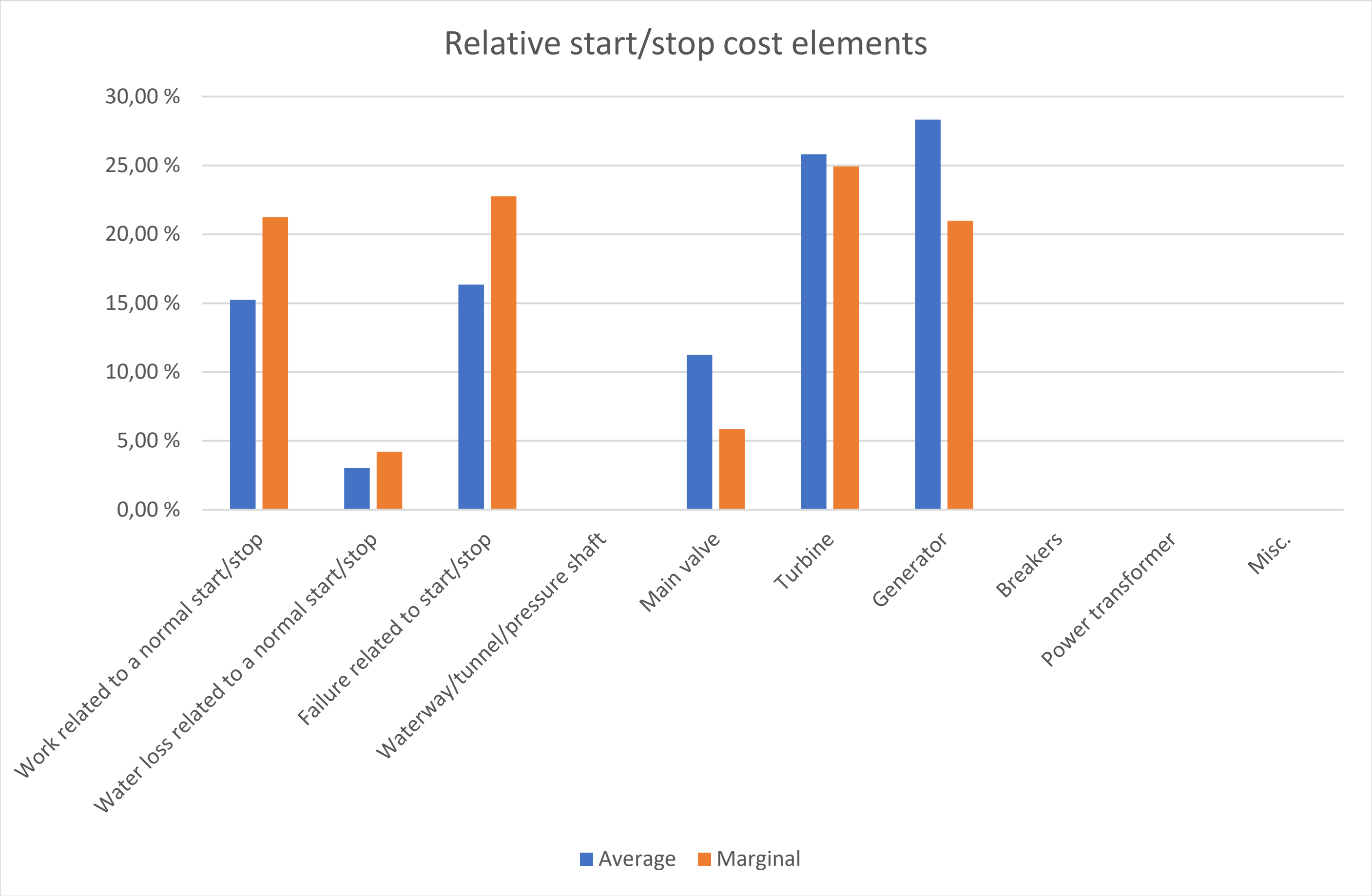


Costs related to future rehabilitations (marginal)

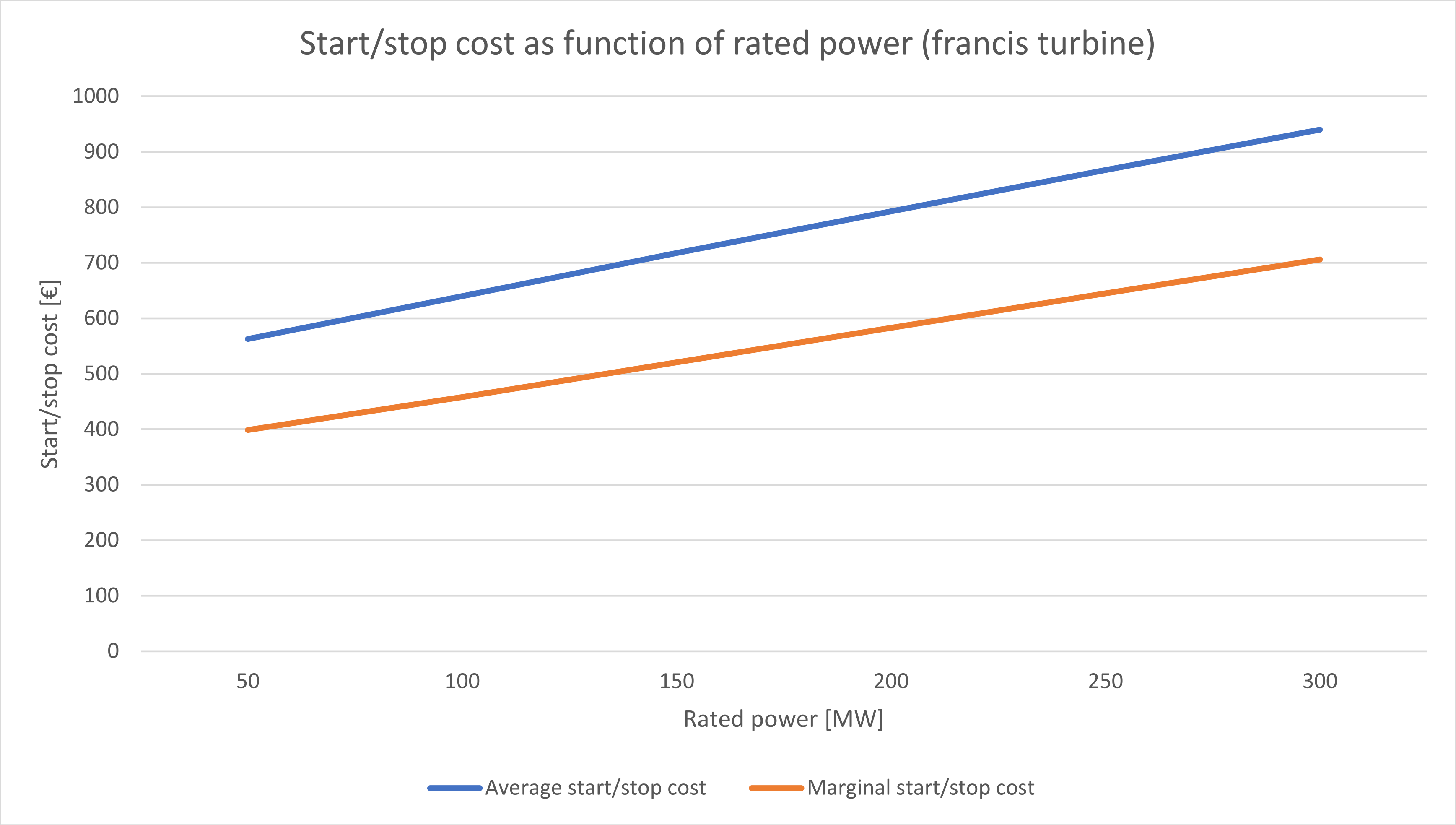
- Lifetime reduction for main valve 8
- Rehabilitation of turbine 39
- Lifetime reduction for turbine runner 70
- Overhaul of generator 8
- Lifetime reduction for stator winding 50
- Lifetime reduction for stator core 12
- Lifetime reduction for rotor winding 6
- Misc. 0
- Marginal cost of start/stop 471
- Specific cost of start/stop [€/MW] 4,76



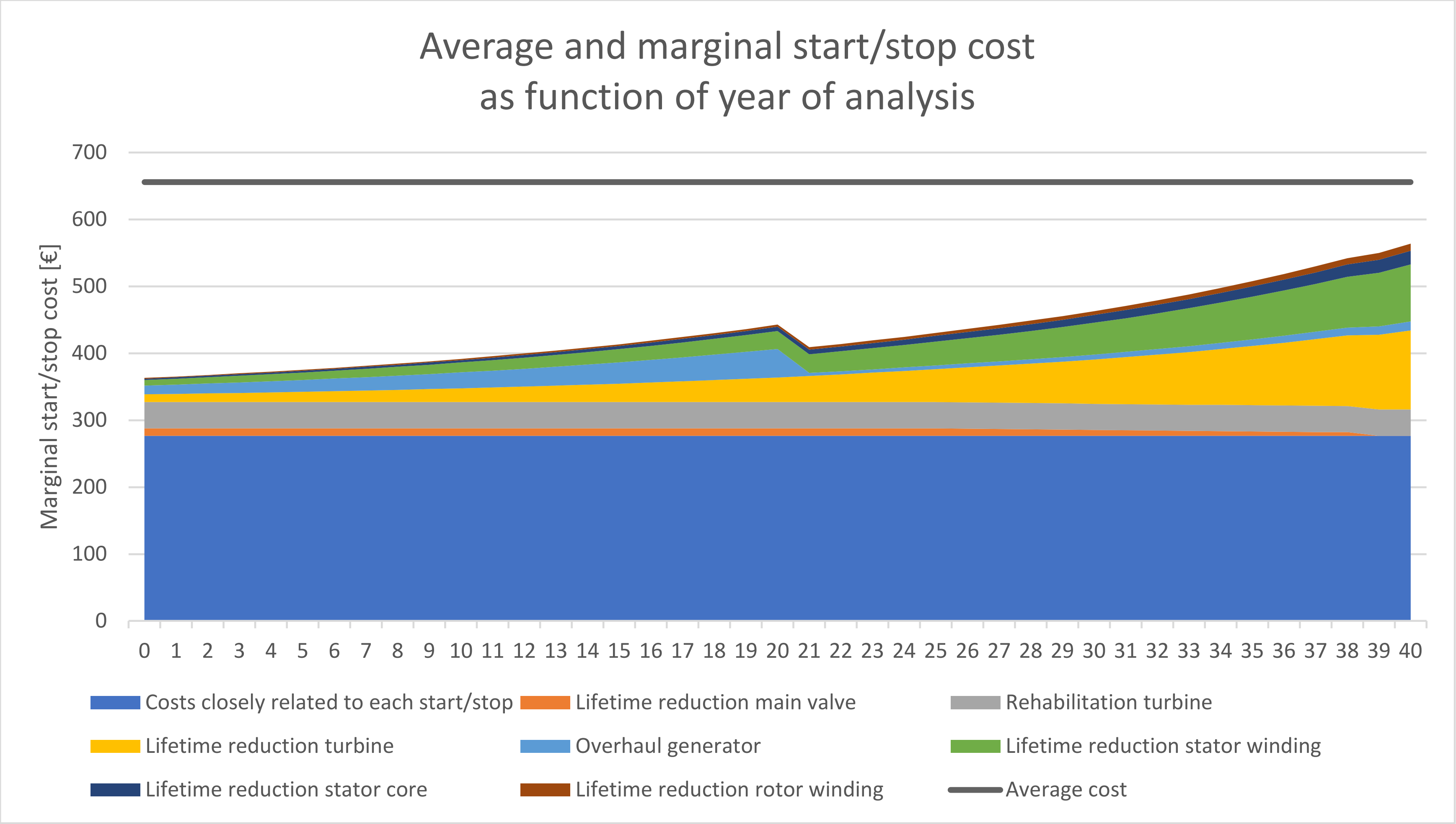
Tool – Example (relative cost elements)



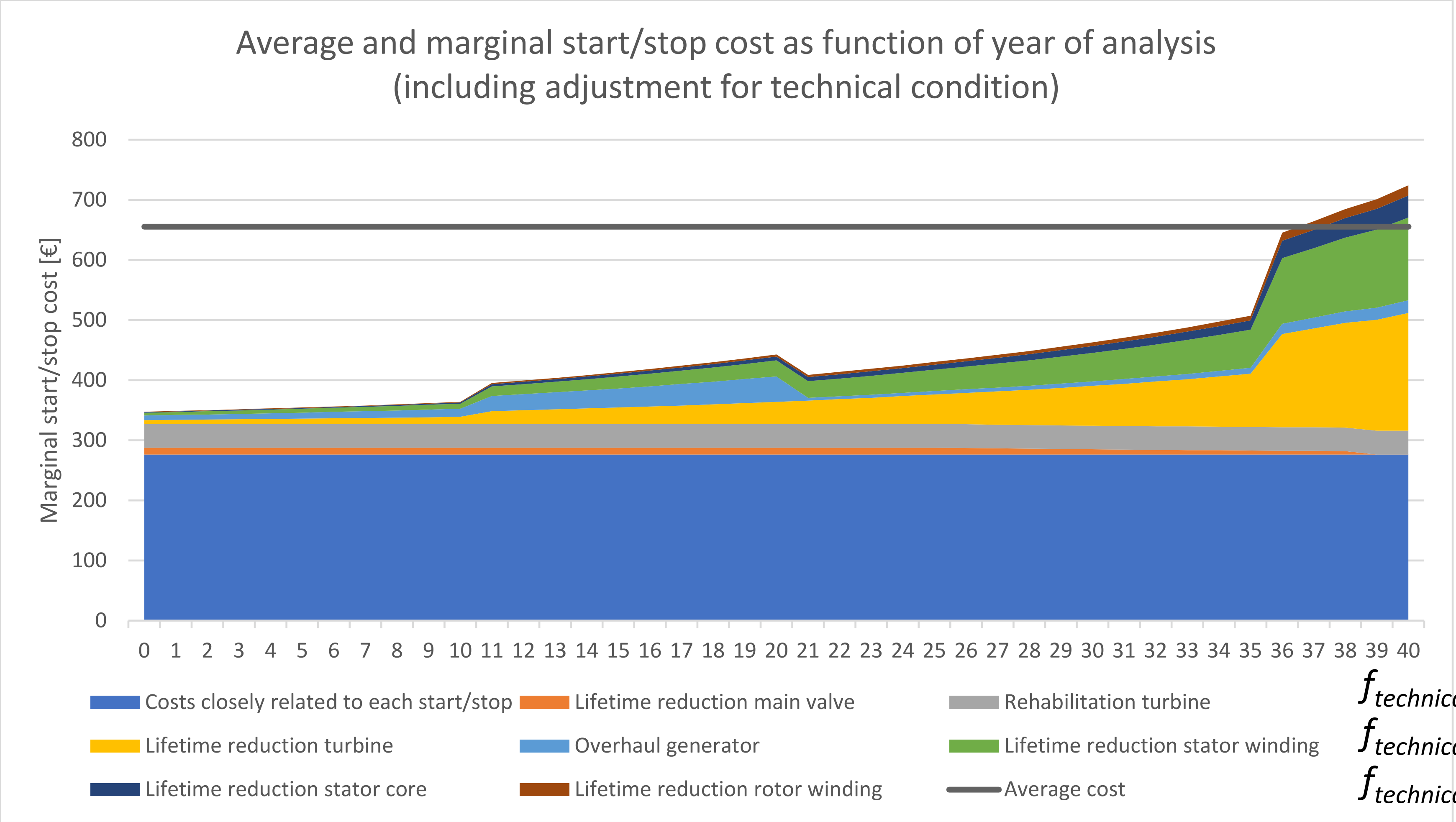
Start/stop cost as function of rated power



Start/stop cost as function of year of analysis



Start/stop cost as function of year of analysis (including adjustment for technical condition)



$f_{technicalcondition=1} = 0,5$

$f_{technicalcondition=2} = 1,0$

$f_{technicalcondition=3} = 2,0$

Cost of ramping

- Ramping is an “event”, and hence is modelled following the same principles as the cost of a start/stop cycle.
- However, since there is no actual start/stop, start/stop failures, loss of water, cost of degradation of valve and electrical components are not included.

- Hence, ramping is modelled as an equivalent operating time for the turbine only.
- This can be thought of as a factor *k* multiplied by the equivalent operating time of a start/stop cycle for the turbine:

$$\Delta D_{ramping} = k \cdot \Delta D_{turbine}$$

Cost of operation outside the normal operating range (part load and overload)

- To handle stress and degradation for unfavourable operation, the model (and tool) is extended by dividing operation into a share for each relevant operating range

$$d\left(t \middle| \alpha_{normalload}, \alpha_{partload}, \beta_{partload}, \alpha_{overload}, \beta_{overload}, n, \Delta D,\right)$$
$$= \left(\alpha_{normalload} + \alpha_{partload} \cdot \beta_{partload} + \alpha_{overload} \cdot \beta_{overload} + n \cdot \Delta D\right) \cdot t$$

  - α_i - Share of calendar time for operating in range *i*
  - β_i - Factor for “equivalent operating time” in operating range *i*

- Since the designed total operating time is assumed to be constant, it can be shown that the lifetime reduction for one hour operating on (low) part load is

$$\Delta L_{partload} = \frac{\beta_{partload}}{\left(\alpha_{normalload} + \alpha_{partload} \cdot \beta_{partload} + \alpha_{overload} \cdot \beta_{overload}\right) \cdot 24 \cdot 365 + n \cdot \Delta D} \cdot 24 \cdot 365 \ [\text{hours}]$$

Ramping, partload and overload

- Ramping ($\Delta D_{ramping}$ = 2 hours)
  - Average cost: 22 €
  - Marginal cost: 13 €
- Part load operation ($\beta_{partload}$ = 3 hours/hour)
  - Average cost: 24 € per hour
  - Marginal cost: 14 € per hour
- Overload operation ($\beta_{overload}$ = 3 hours/hour)
  - Average cost: 24 € per hour
  - Marginal cost: 14 € per hour

Cost of different types of operation for the same hydropower unit as in the start/stop example

Estimation of lifetime reduction and cost related to operating conditions

- The model/tool estimates both average and marginal cost of start/stop based on the assumption that start/stop leads to reduction of the component's lifetime.
  - Adjustment for actual technical condition
  - Adjustment for duration of standstill
- The model also has a simplified estimation of cost of ramping, cost of running on (low) part load, and cost of running on overload.

1. Work related to a normal start/stop
2. Water loss related to a normal start/stop
3. Failure related to start/stop
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Final remarks

- The main challenge is to find good estimates for the lifetime reduction for the involved components, i.e., to find with how many hours will the additional stress of one start/stop cycle, one ramping event, one hour of operation on low part load or overload reduce the lifetime of the components.
- Despite some uncertainties (in absolute cost), the model will give consistent estimation of the cost of start/stop, ramping, part load and overload for all units → reasonable relative values between the units for hydropower scheduling.
- The model and tool is tested by Norwegian hydropower companies giving positive feedback on both the tool interface and the reasonability of the results.

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