Design and operation of Hybrid power plants with HyDesign

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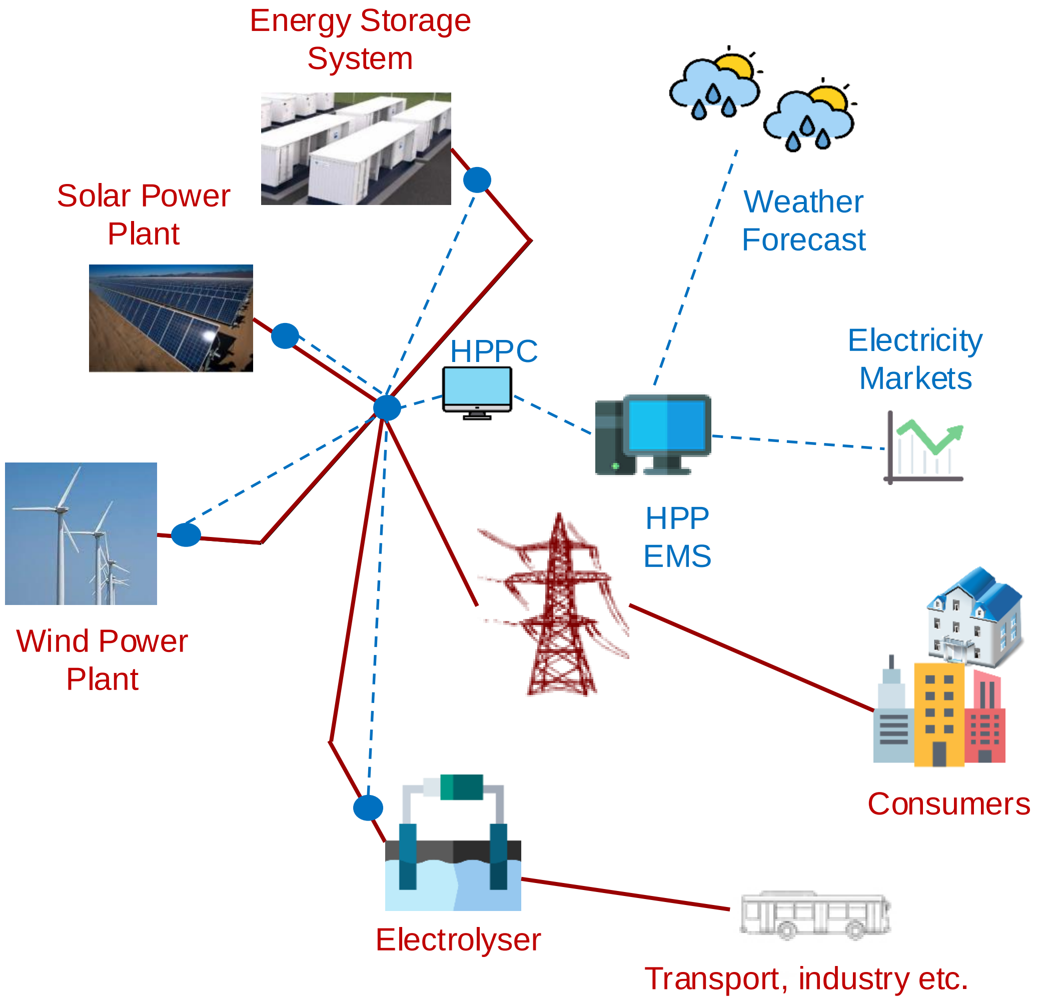
Design of Hybrid renewable power plants



General Features	More than one generation sources involved
	All assets are owned by same company so higher controllability
	More renewable energy integration with same grid connection
Motivation	To increase the **value of renewable energy**
	To reduce cost & **maximize revenues from different energy markets**
	One common energy management system
	Optimal utilization of land
	More flexibility allows for decommissioning of fossil fuel-based generators
	Integration of power to X

What is HyDesign?

https://topfarm.pages.windenergy.dtu.dk/hydesign/

- **Open source** tool for **non-linear** analysis and sizing optimization of Hybrid renewable power plants (HPP)

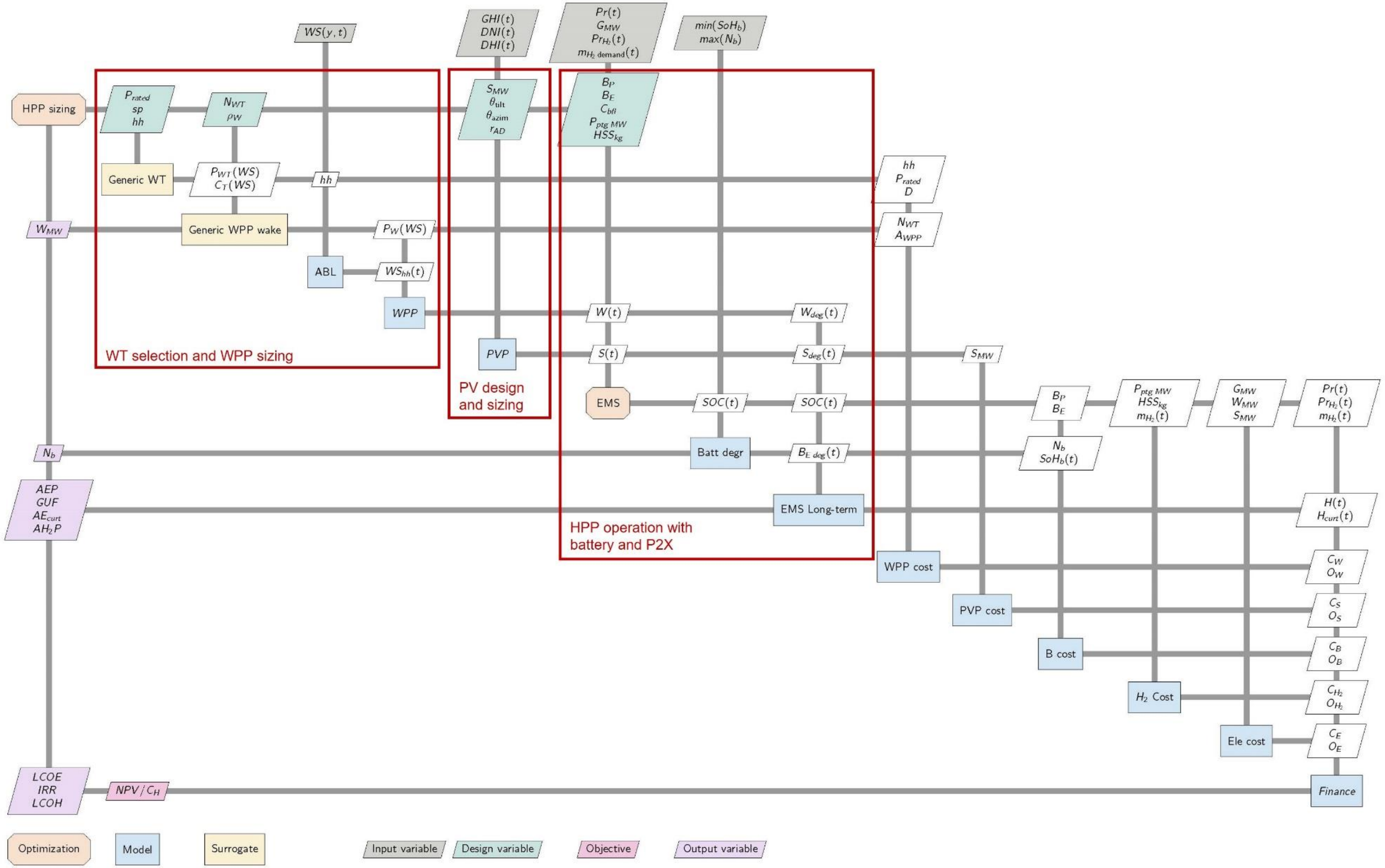
- Multi-disciplinary analysis and optimization.
  Built on top of **Open-MDAO** [1].

- **Main features:**
  – Wind plant design includes wind turbine selection, wind farm design and degradation
  – PV design includes panel orientation, tracking and degradation
  – Battery operation and degradation
  – MILP-based HPP operation optimization for battery and or P2X operation
  – Detailed cost and financial models
  – Forecast errors and participation in spot and balancing markets
  – Hybridization, Detailed inverter and PV modelling, Offshore topologies, SolarX, etc.

[1] J. S. Gray, J. T. Hwang, J. R. R. A. Martins, K. T. Moore, and B. A. Naylor, “OpenMDAO: An Open-Source Framework for Multidisciplinary Design, Analysis, and Optimization,” Structural and Multidisciplinary Optimization, 2019.

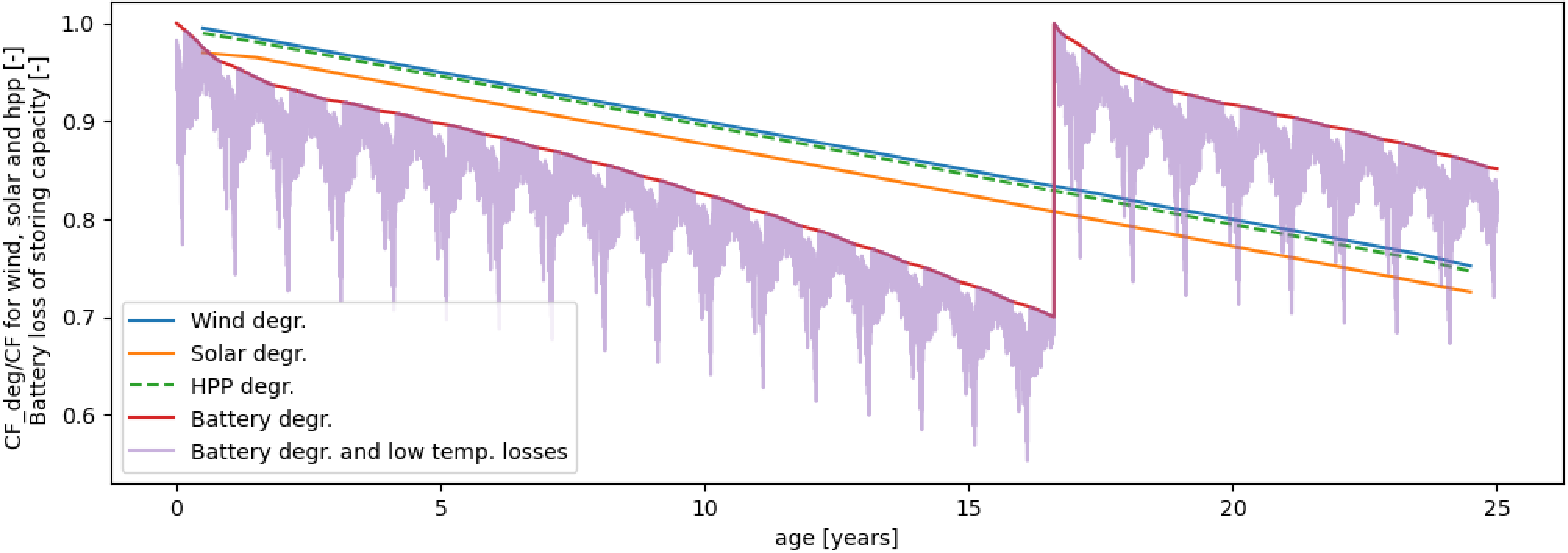
Workflow of HyDesign's HPP Sizing optimization

HPP sizing as a nested optimization
Non-linear external sizing optimization
Internal MILP operation optimization



Murcia Leon, Juan Pablo, et al. "HyDesign: a tool for sizing optimization for grid-connected hybrid power plants including wind, solar photovoltaic, and Li-ion batteries." *Wind Energy Science Discussions* 2023: 1-22.

Degradation plays a crucial role in the business case for HPP



Simplified Operation Optimization with battery and PtH2

$$\max_{B(t),P_{H2}(t)} \quad \boxed{\begin{array}{l}\sum_t \lambda_{spot}(t)\, H(t) \\ +\sum_t \lambda_{H2}(t)\, m_{H2}(t)\end{array}}$$
$$-l_b$$
$$-l$$

Revenue

Battery fluctuation penalty

Meet demand H2 penalty

$$\text{s.t.} \,\forall t \quad H(t) = W(t) + S(t) - P_{curt}(t) + B(t) - P_{H2}(t)$$
$$m_{H2}(t) = f_{H2prod}(P_{H2}/P_{H2\,max})$$

$$H(t) \leq G$$

$$E_{SoC}(t+1) = \begin{cases} E_{SoC}(t) - \eta_{\text{charge}} B(t)\,\Delta t & \text{if} \quad B(t) \leq 0 \\ E_{SoC}(t) - B(t)\,\Delta t/\eta_{\text{discharge}} & \text{if} \quad B(t) > 0 \end{cases}$$
$$E_{SoC}(t) \geq B_E \times (1 - B_{E\,\text{depth}})$$
$$E_{SoC}(t) \leq B_E$$
$$B(t) \leq B_P$$
$$B(t) \geq -B_P$$

Simplified Operation Optimization with battery and PtH2

$$
\max_{B(t),P_{H2}(t)} \quad \sum_t \lambda_{spot}(t)\, H(t) + \sum_t \lambda_{H2}(t)\, m_{H2}(t) - l_b - l
$$

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$$+ \sum_t \lambda_{H2}(t)\, m_{H2}(t)$$

$$-l_b$$

$$-l$$

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Meet demand H2 penalty

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Battery power

> 0 discharge, <0 charge

$$H(t) \leq G$$

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Effect of battery fluctuation penalty on degradation

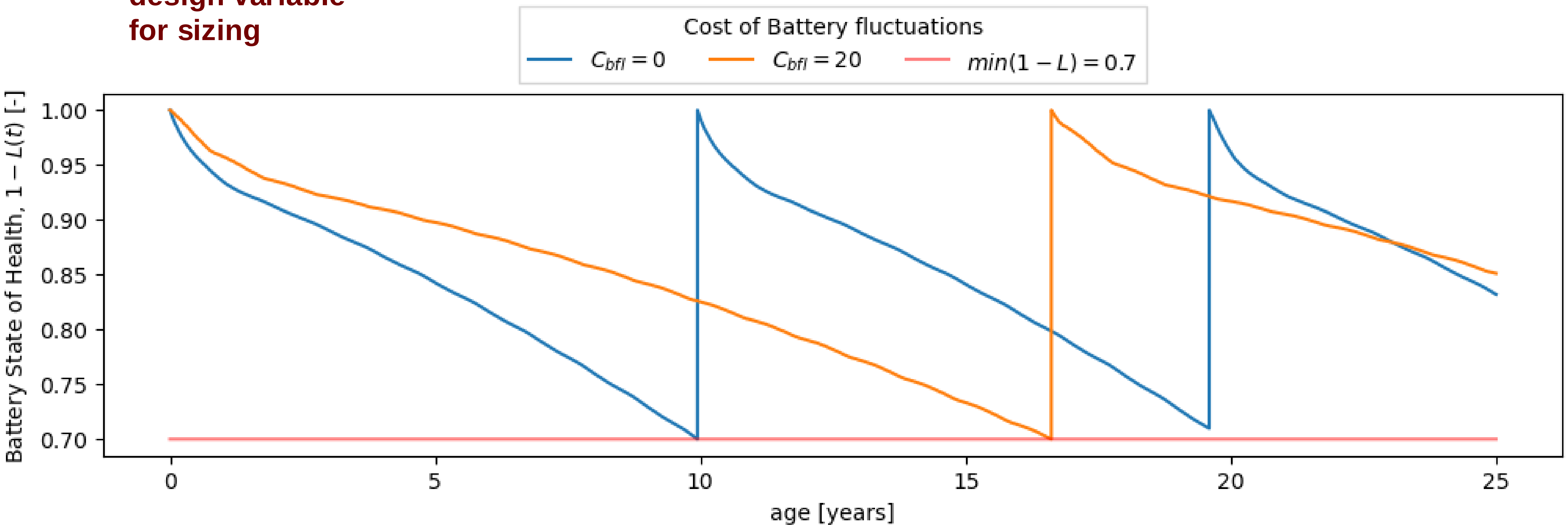
$$l_b = C_{bfl} \times \sum_t \left(|\Delta B(t)| \times \left(Pr_{\text{peak}} - Pr(t) \right) \right)$$

Battery fluctuation factor, a design variable for sizing

Battery fluctuations

Battery fluctuations are valued using the distance from peak elect. price

→ **If the price of electricity is high, the battery fluctuation penalty contribution is low**



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Piecewise linear approx.

$$H(t) \leq G$$

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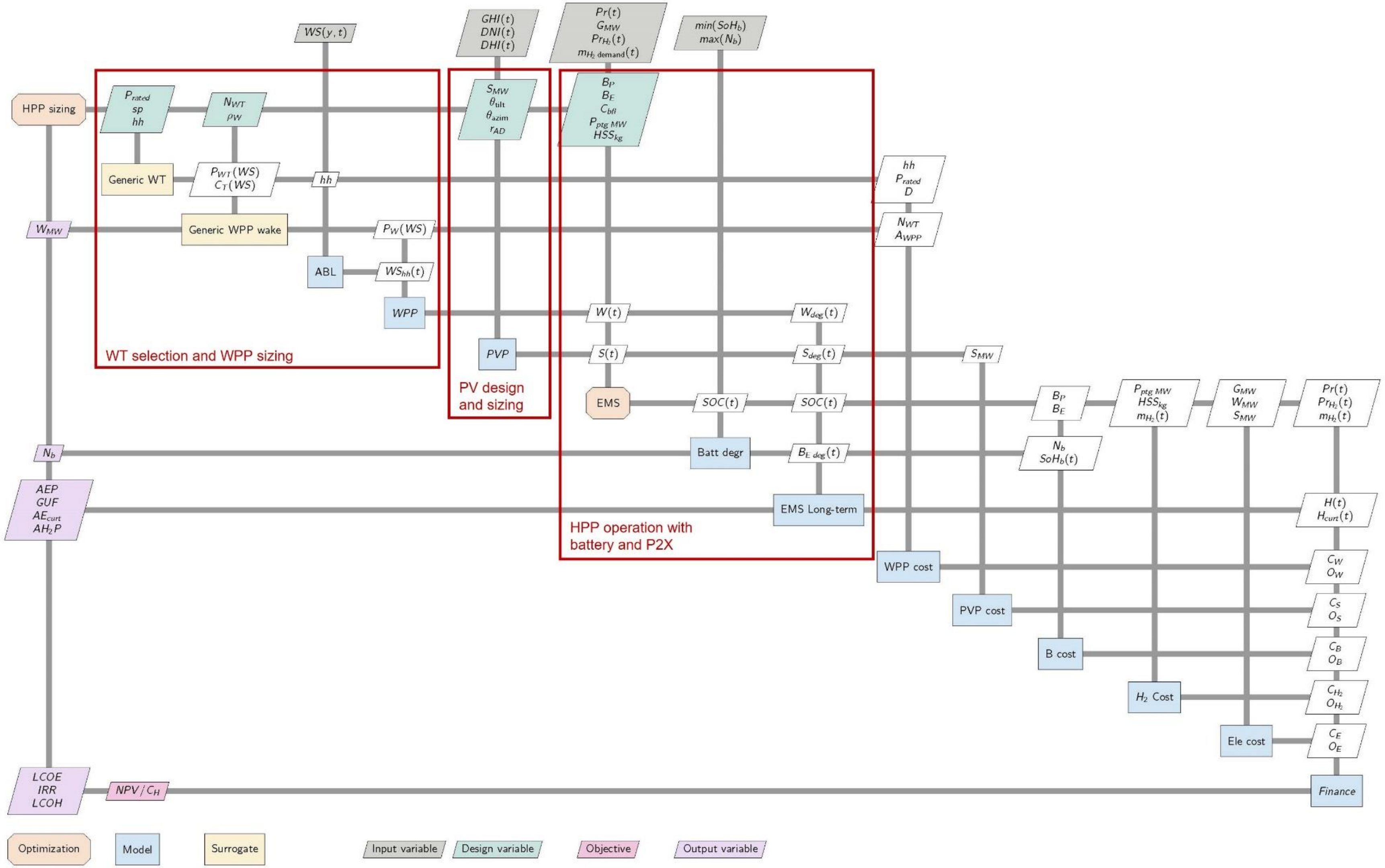
Workflow of HyDesign's HPP Sizing optimization



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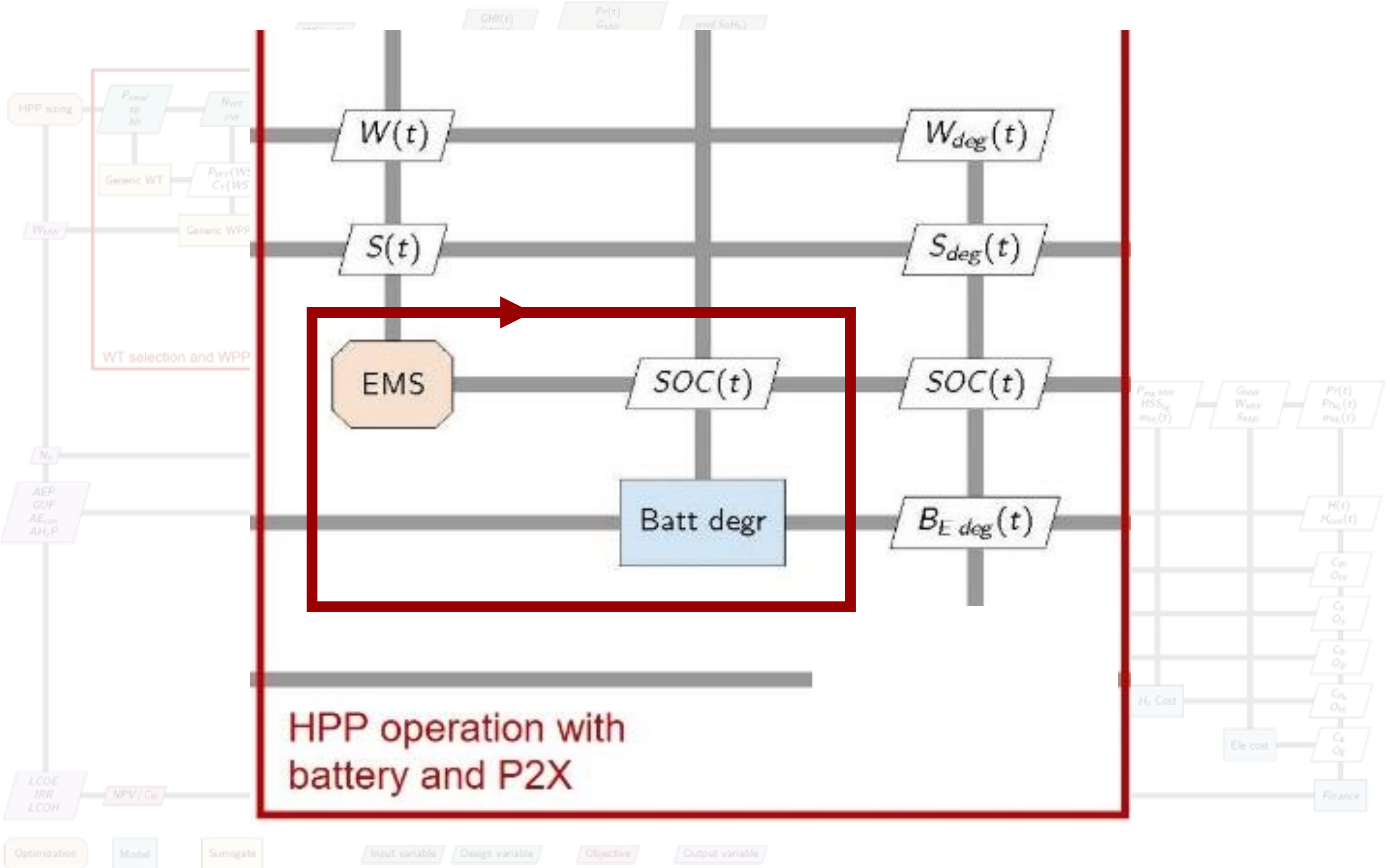

Evaluate the lifetime operation and its revenues in an iterative approach.

EMS solves the lifetime operation by splitting the lifetime in operation periods and using the resulting battery degradation of the previous period as initial condition for the next operation batch.

Very demanding:

- EMS operation optimization needs to be solved for the full lifetime

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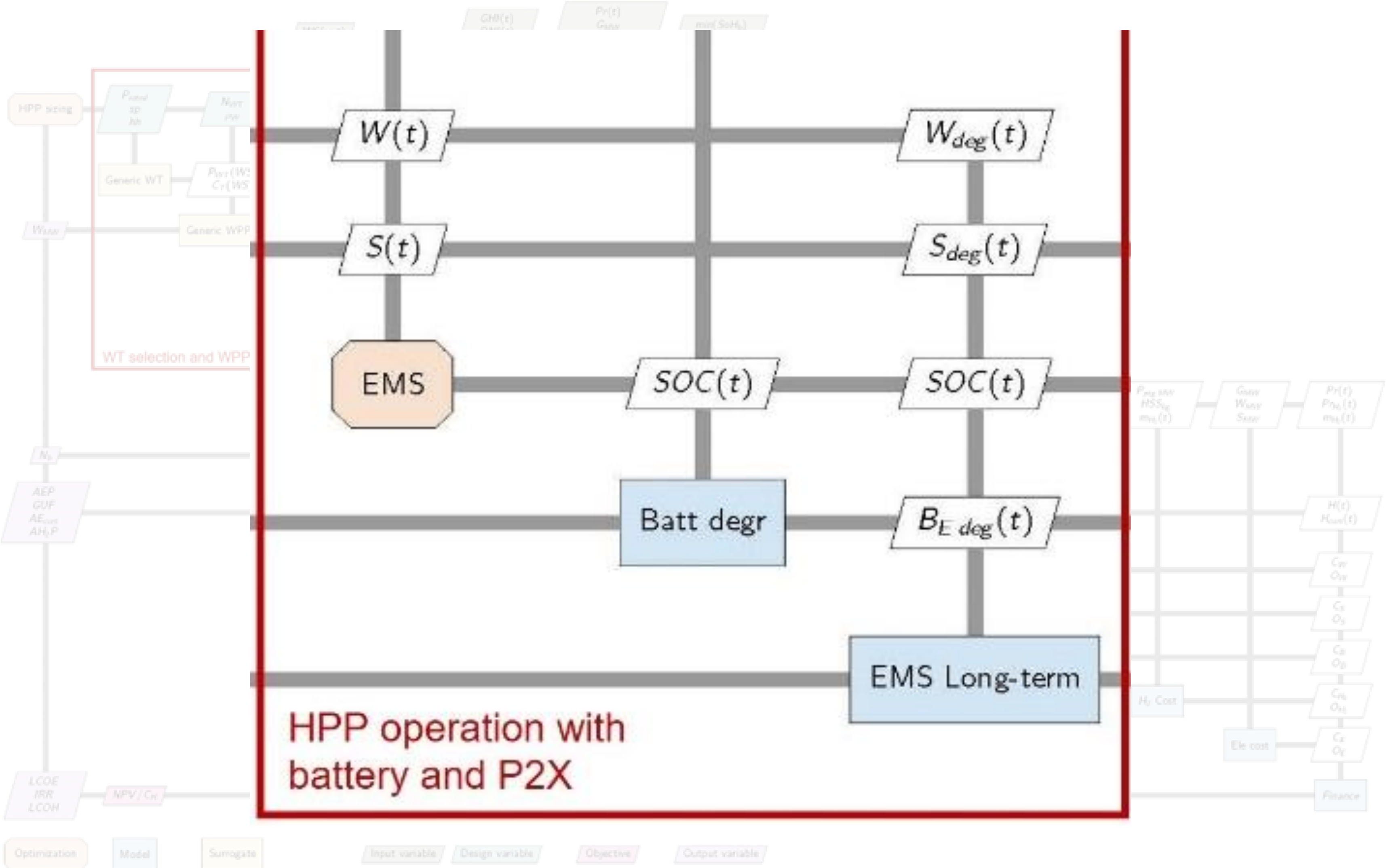


EMS solves the operation for one (or 2, 3) year(s) under new conditions (no degradation of PV, Wind, Battery). This operation is repeated for the full lifetime.

Battery degradation model evaluates the evolution of battery health (loss energy capacity over time).

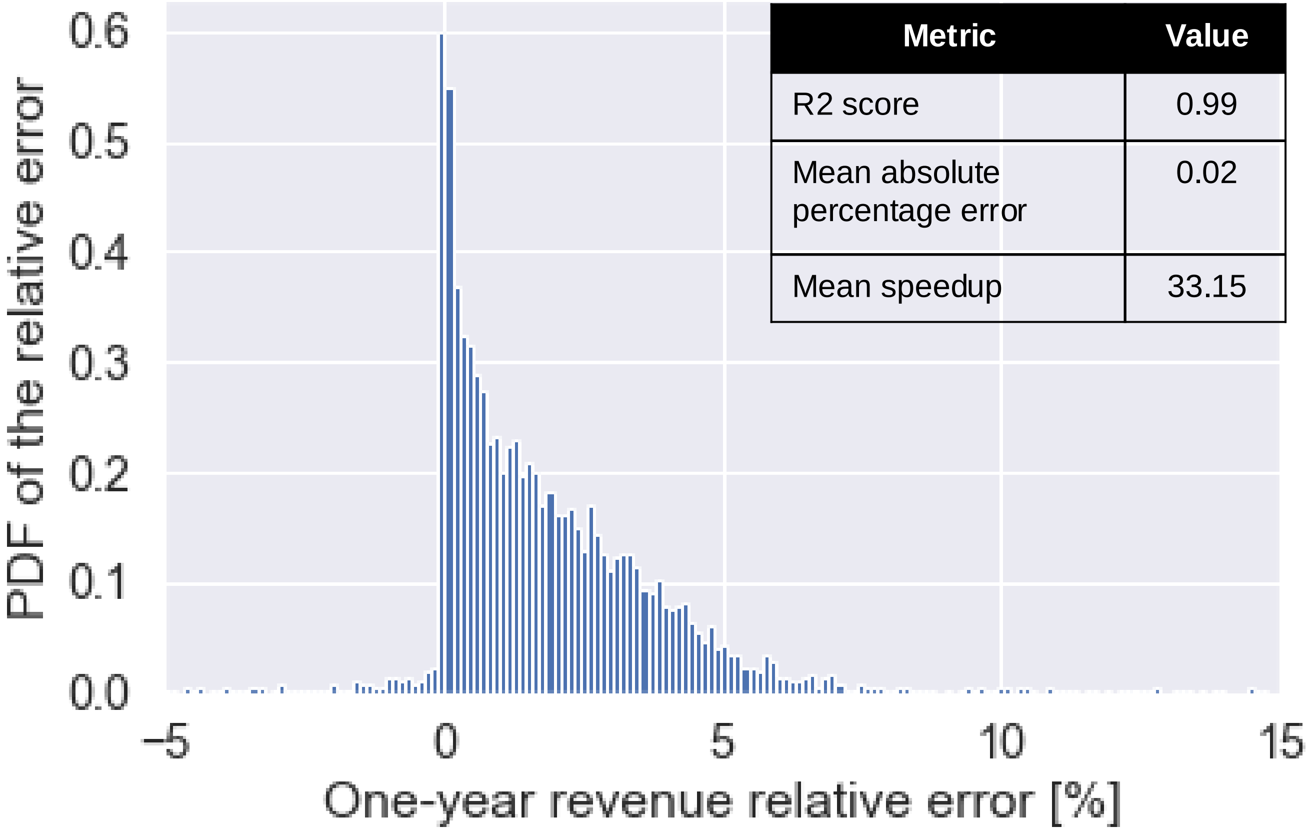
EMS Long-term is a correction of the idealized operation to account for degradation of Battery, PV, and Wind.

Murcia Leon, Juan Pablo, et al. "HyDesign: a tool for sizing optimization for grid-connected hybrid power plants including wind, solar photovoltaic, and Li-ion batteries." *Wind Energy Science Discussions* 2023: 1-22.

Validation of EMS Long-term

- Compare the **EMS Long-term** (rule-based operation correction) with an actual EMS operation optimization using the same degradation evolution of the components:

- **EMS Long-term** is able to evaluate the lifetime cashflows with degradation in 1/33 of the time.



Metric	Value
R2 score	0.99
Mean absolute percentage error	0.02
Mean speedup	33.15

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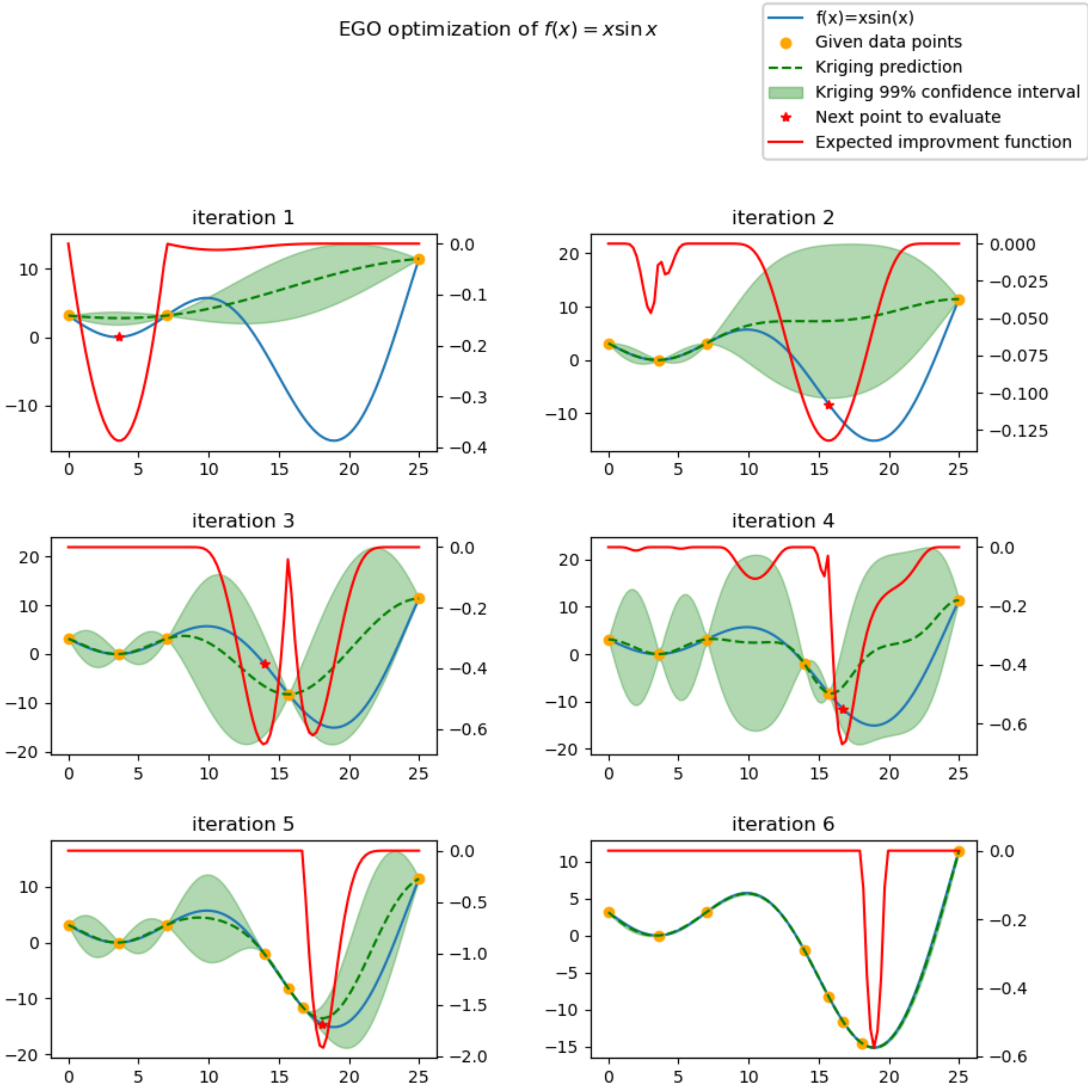
Sizing optimization using Parallel-Efficient Global Optimization (EGO)

- EGO: surrogate-based optimization [1]
  - Iterative process that suggests new model evaluation points with the objective of identifying the global optimal
  - Gaussian Processes surrogates provide uncertainty on surrogate's output.
  - Expected improvement can be evaluated based on current optimal using the GP on all the design space
  - New evaluation is done at the point of highest expected improvement

- Parallel-EGO [2] gives multiple evaluation points per iteration:
  - Evaluation points based on clustering EI(x), and providing the highest EI point per cluster
  - Add some extreme boundary evaluation points when optimal is changing
  - Add some refinement evaluation points when optimal is converging

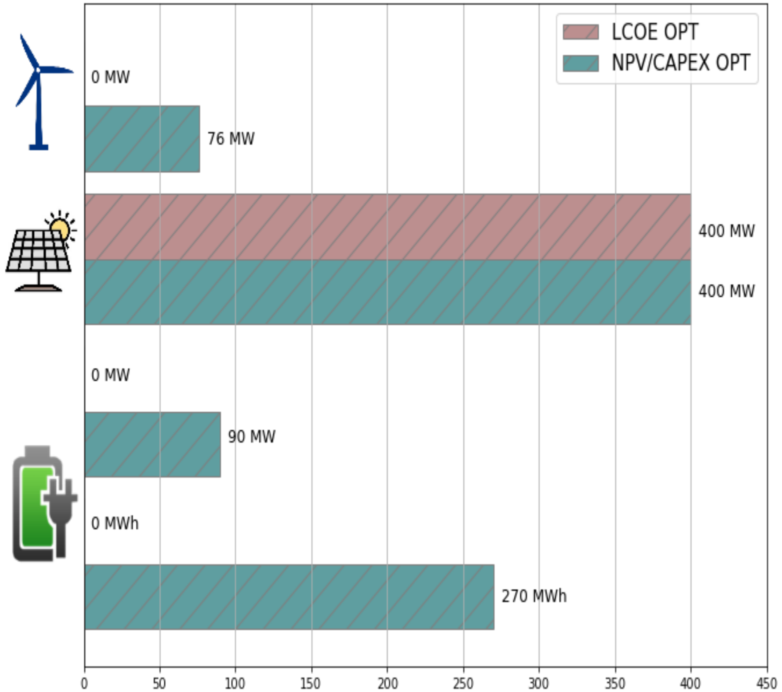


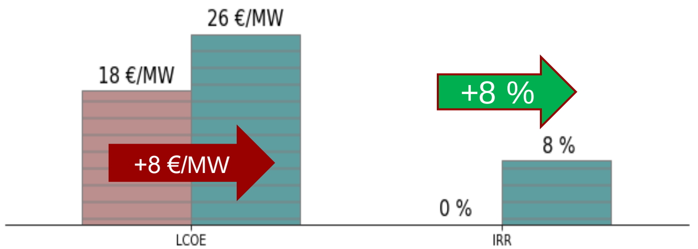
[1] Saves P. et al. "SMT 2.0: A Surrogate Modeling Toolbox with a focus on Hierarchical and Mixed Variables Gaussian Processes." *Advances in Engineering Sofware* 2024

[2] Murcia Leon, J. P. et al. "HyDesign: a tool for sizing optimization for grid-connected hybrid power plants including wind, solar photovoltaic, and Li-ion batteries." *Wind Energy Science Discussions* 2023: 1-22.

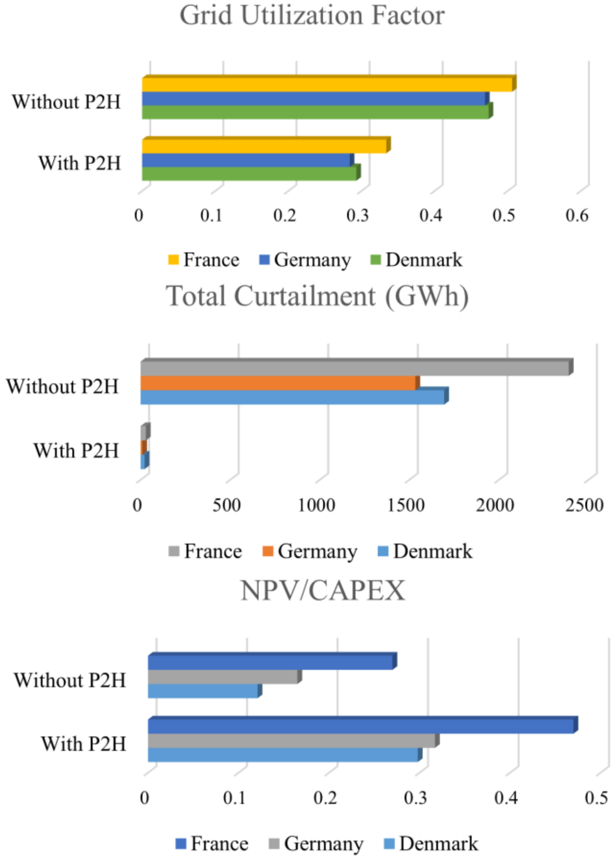
Key take aways about HPP design

LCOE based design selects cheapest generation and no storage





PtH2 based design reduce the grid utilization and can provide more revenues but depends on electrolyzer technology and H2 PPA



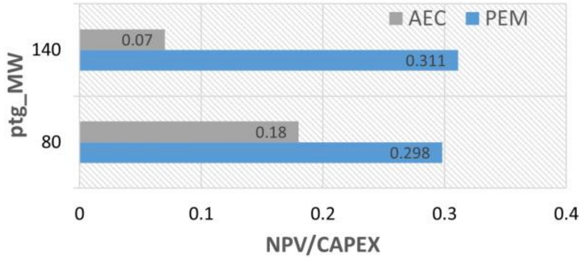


Table 1 HPP SIZING RESULTS FOR SITE IN DENMARK

H_2 PPA price	3 Euro/kg	5 Euro/kg	8 Euro/kg
NPV_over_CAPEX	0.1380	0.3125	1.3364
NPV [MEuro]	48.91	130.39	601.27
IRR	0.0677	0.0868	0.1752
CAPEX [MEuro]	354.41	417.29	449.93
OPEX [MEuro]	7.15	25.80	32.06
GUF	0.4746	0.2017	0.1067
annual H2 [tons]	110.12	12442.93	16418.87
grid [MW]	300	300	300
wind [MW]	360	360	360
solar [MW]	80	80	80
PtG [MW]	1	132	200
Battery Energy [MWh]	100	100	100
Battery Power [MW]	10	10	10
Total curtailment [GWh]	1600.21	0	0

Gupta, Megha, Kaushik Das, Mikkel Friis-Møller, and Juan Pablo Murcia Leon. "Assessment of hybrid power plant operation including P2H in future energy markets." (2023): 289-294.

Assumptions for HPP Sizing optimization

- Wind and Solar resources are user provided
  - At DTU we use **ERA5,** with mean wind speed scaled to match the Global Wind Atlas (GWA2 or GWA3).
- Generic WT and Wind plant wakes modeled with surrogates of DTU's **PyWake**
- Short-term Operation Optimization based on 1-3 years of weather data. MILP solved using **CPLEX**
- Detailed Battery degradation model evaluated over lifetime
- Actual Long-term (life-time) operation computed as a correction to idealized short-term operation
  - Accounts for degradation of battery, PV or electrolyzer
  - Accounts for forecast errors of wind, PV and market (in v1.4)
- Cost models: NREL's **WISDEM (Wind)**, and generic costs model for PV and battery.
  - Tech prices levels scaled to match **DEA Tech Catalogue or project partners costs data**
- Financial model based on **technology specific WACC**

HyDesign

Online documentation, with installation and Google Collab examples at:

https://topfarm.pages.windenergy.dtu.dk/hydesign/

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