DTU Wind Energy

WinGrid Scientific Workshop on Power System Balancing and Operation with Large Shares of Wind Power - session 2

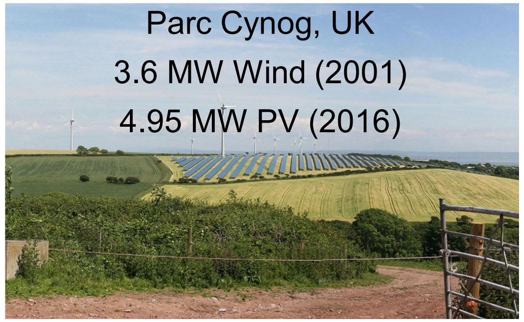
Kaushik Das, Technical University of Denmark

Hybrid power plants for future power systems

Overview of Hybrid Power Plants

VRE based Hybrid Power Plant

- Utility-scale grid connected HPP are large power plants (hundreds of MW) operated to maximize profit from market while required to provide grid ancillary services similar to any large power plant.



Renewables Now
News Research Trends Events Advertising

Solar

India to launch 2.5-GW wind-solar hybrid auction

RfS for 1200 MW ISTS-connected Wind-Solar Hybrid Power Projects in India (Tranche-II)

Start Date : 08/03/2019 End Date : 07/05/2019

RfS for Selection of Project Developers for setting up of 1200 MW ISTS-Connected RE Projects with assured Peak Power Supply in India (ISTS-VII)

Start Date : 01/08/2019 End Date : 17/10/2019

RfS for Selection of Project Developers for setting up of 1200 MW ISTS-Connected RE Projects with assured Peak Power Supply in India (ISTS-VII)

Press Information Bureau
Government of India
Ministry of New and Renewable Energy

MNRE issues National Wind-solar Hybrid Policy

KENNEDY ENERGY PARK

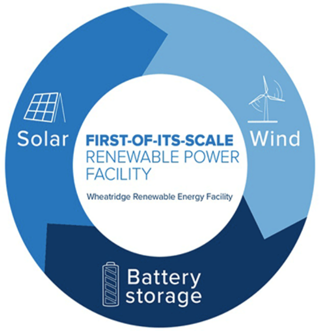
Windlab and Vestas installed first utility-scale Kennedy Energy Park HPP in 2018 in Australia

43.2 MW of V136-3.6 MW WTs, 15 MW of PV and 2 MW/4 MWh Li-Ion battery storage

All managed by Vestas customised control system

Wheatridge Renewable Energy Facility

North America's first major renewable energy facility combining wind, solar and battery storage in one location



Total HPP Cap = 380 MW
Wind = 120x2.5 = 300 MW (2020)
Solar = 50 MW (2021)
Battery = 30 MW, 120 MWh (2021)

MEGAVIND

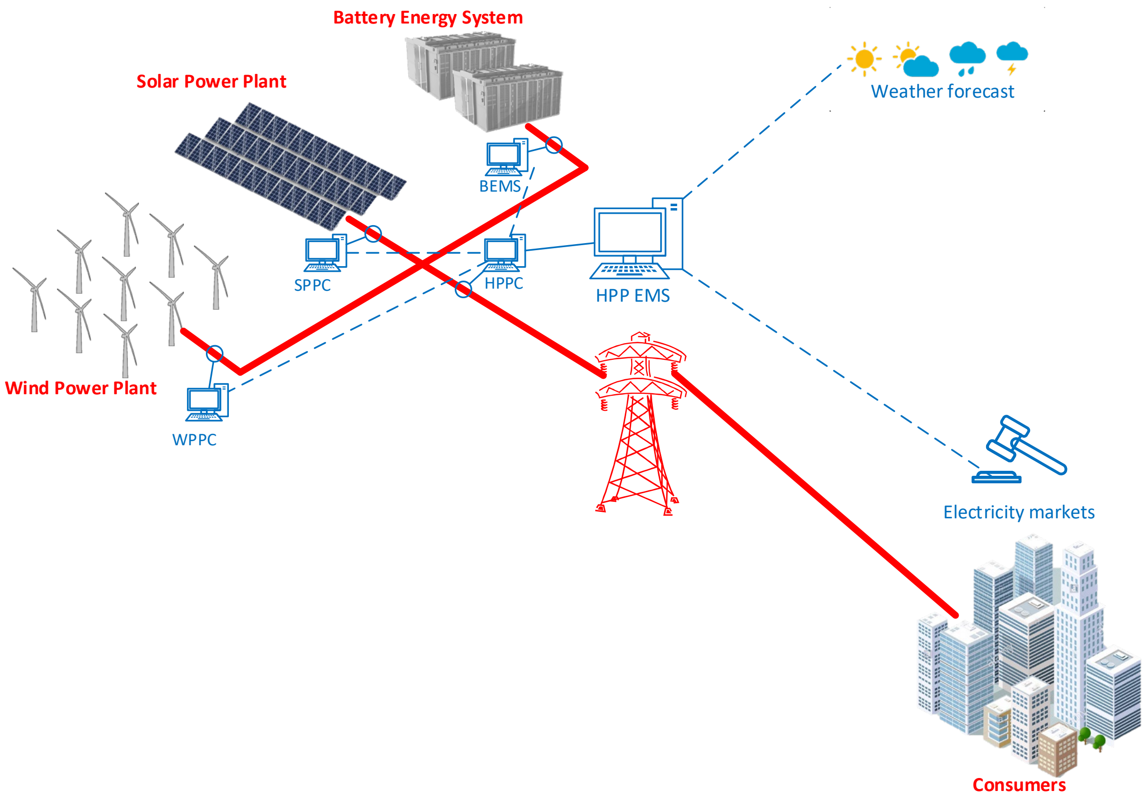
INCREASE THE SYSTEM VALUE OF WIND POWER

Today's wind turbines and wind farms are advanced electricity generation systems working in an increasingly integrated system that generates, stores, transmits and consumes energy. As described in the Megatrends, the build-out of the renewable energy capacity is moving towards technology-neutral tenders in which wind energy is competing head-to-head with other renewable technologies. Therefore, we are seeing companies moving towards delivering hybrid solutions consisting of e.g. wind, solar and storage facilities in order to best meet the demands for low cost, stable power generation and deliver reactive power and ancillary services.

The ability to fit into this new trend is a major innovation driver.

https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-renewable-hybrid-power-plants-benefits-and-market-opportunities.pdf
https://windeurope.org/about-wind/database-for-wind-and-storage-colocated-projects/

Hybrid Power Plant – Utility scale co-located grid connected

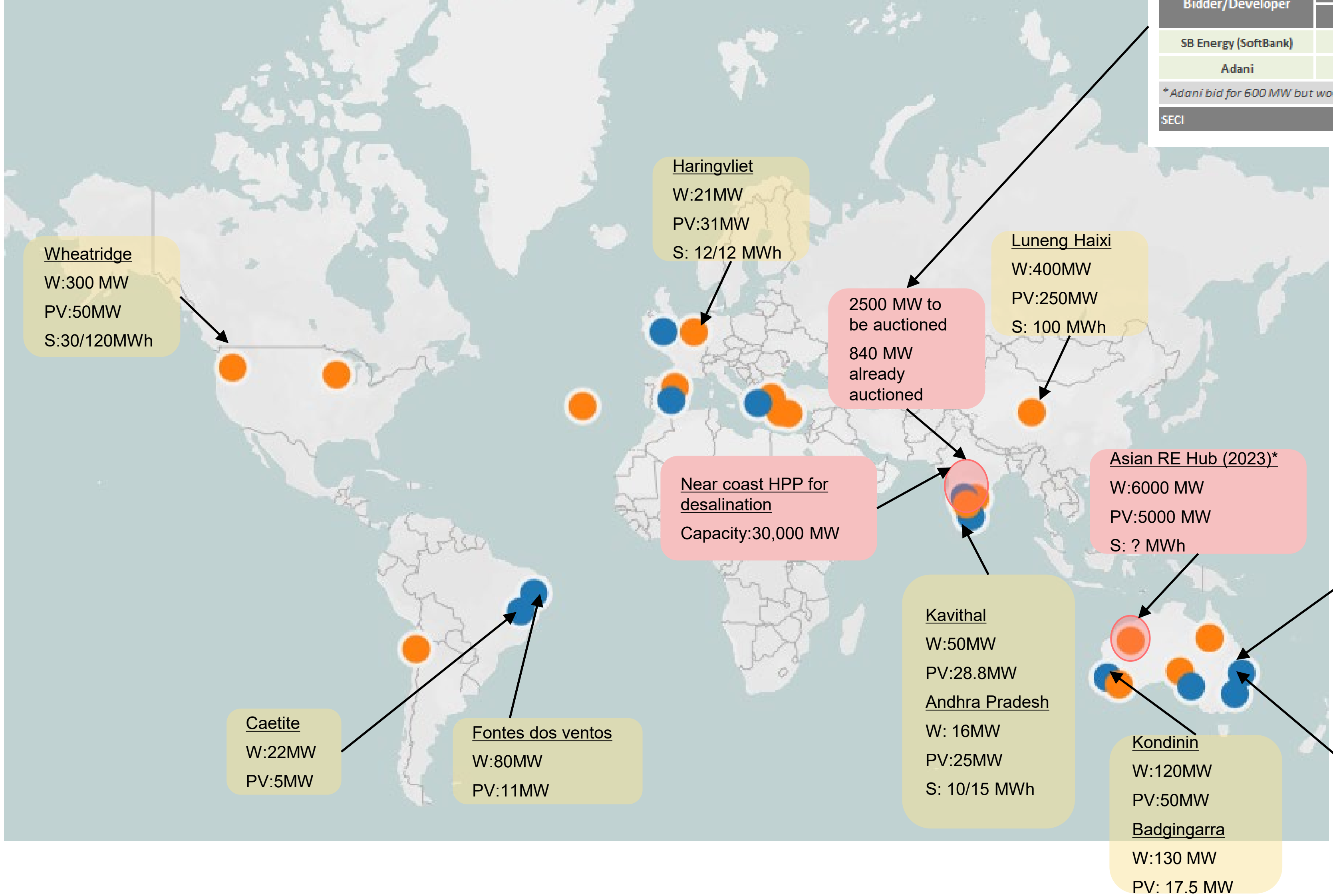


General Features:

- More than one generation sources involved
- All the assets are owned by same company so higher controllability
- Generally one common connection point to grid
- Motivation is to reduce cost / maximize revenue from different energy markets.
  - One common energy management system
- Control of electrical load is not of concern of the power plant owner as compared to traditional Hybrid Power Systems
  - Sometime even provide near baseload generation
- Many stakeholders involved

Hybrid (Wind + PV + Storage) Plants

Source: WindEurope



SECI: ISTS-connected Solar Wind Hybrid Projects — MERCOM India Research

Auction Results for 840 MW Solar Wind Hybrid Projects

Bidder/Developer	Capacity MW	Quoted Bids/Tariff (₹/kWh)	Quoted Bids/Tariff ($/kWh)	% Over Winning Bid
SB Energy (SoftBank)	450	2.67	0.0379	-
Adani	600 (390)*	2.69	0.0382	0.75%

*Adani bid for 600 MW but won only 390 MW — Note: $1 = ₹70.5

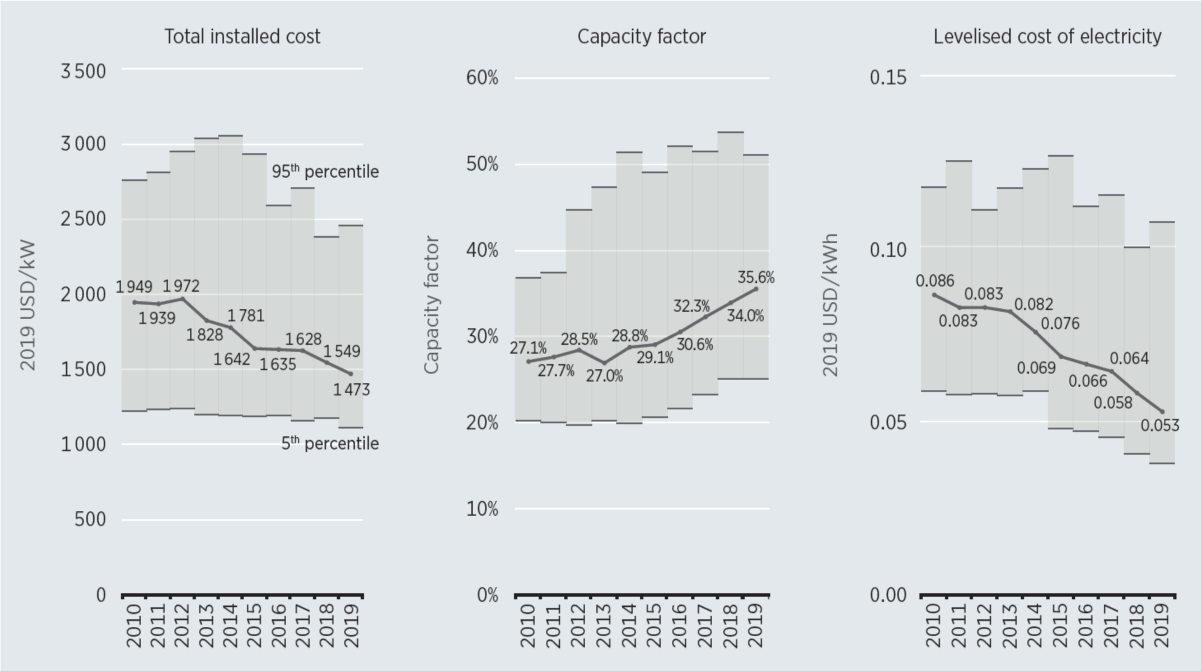
SECI — Source: Mercom India Research

Plant_Type

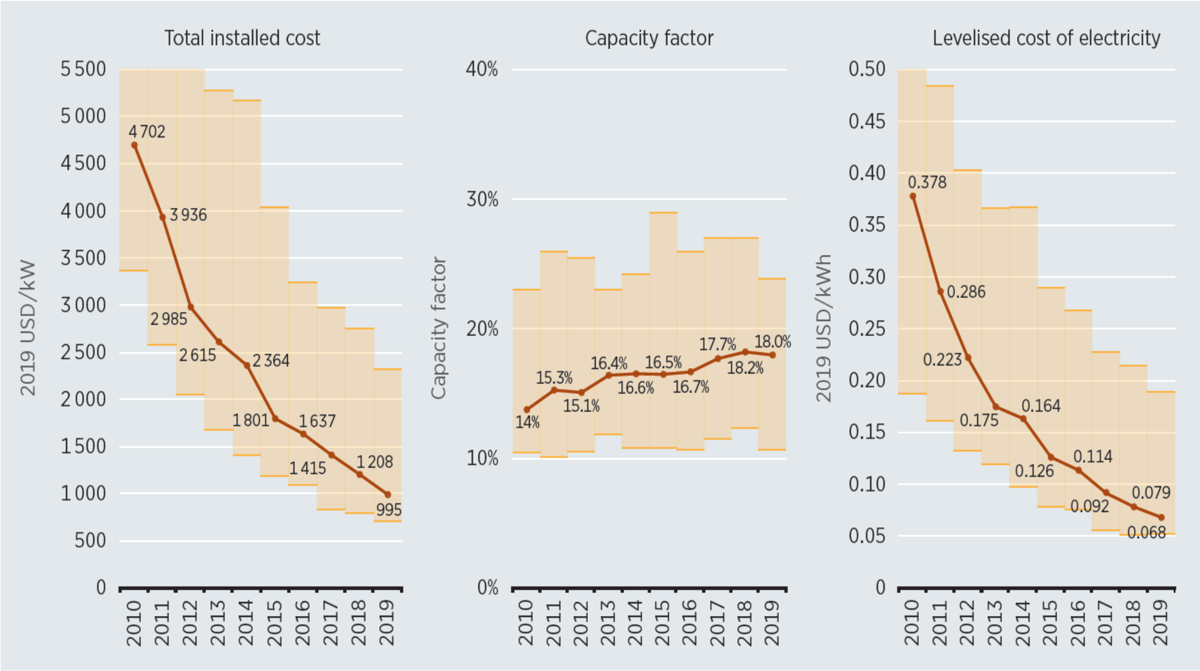
- Wind + PV
- Wind + PV + Storage

* https://asianrehub.com/

Motivations for HPP



Global weighted average total installed costs, capacity factors and LCOE for onshore wind, 2010-2019



Global weighted average total installed costs, capacity factors and LCOE for PV, 2010–2019

Source: IRENA Renewable Cost Database.

Motivations for HPP – System Operators/Society

- Optimal utilization of land
- Delayed requirement for transmission infrastructure reinforcement
- Improved grid stability and security
- More RES integration with same grid connection
- More flexibility allows for decommissioning of fossil-fuel based generators
- Reduced curtailment means more value of renewable energy

Advantages/Values of HPP – Owners/Developers

- **Cost reduction and Revenue increase**
  - Infrastructure
    - Reduction in land cost
    - Optimal use of electrical infrastructure and other infrastructure (e.g. access roads) saves costs
  - Project Development
    - Joint permitting process reduces risks and costs
    - Shared resources reduce internal costs
    - Joint site development reduces costs for e.g. soil investigations & weather measurements
  - Park Performance
    - Less fluctuating production increases electrical infrastructure utilization
    - Storage increases flexibility and number of accessible markets (Energy market, ancillary services market)
    - Reduction of forecast error using storage

Reduction in variability

Increase in availability

Increase in capacity factor

Reduction in cost

Increase in revenue

Increase in ancillary service capability

Increase of lifetime of the wind turbine

[1] Paulina Asbeck (Vattenfall), "Next-Gen Generation System: The symbiotic relationship of solar, wind & storage hybrid power plants", 17th Wind Integration Workshop, 2018

Others

- Wind turbine load and control and lifetime
- Storage lifetime assessment and control
- Wind farms wakes and control
- Grid interaction and stability assessment
- Offshore applications

Integration to Energy Systems

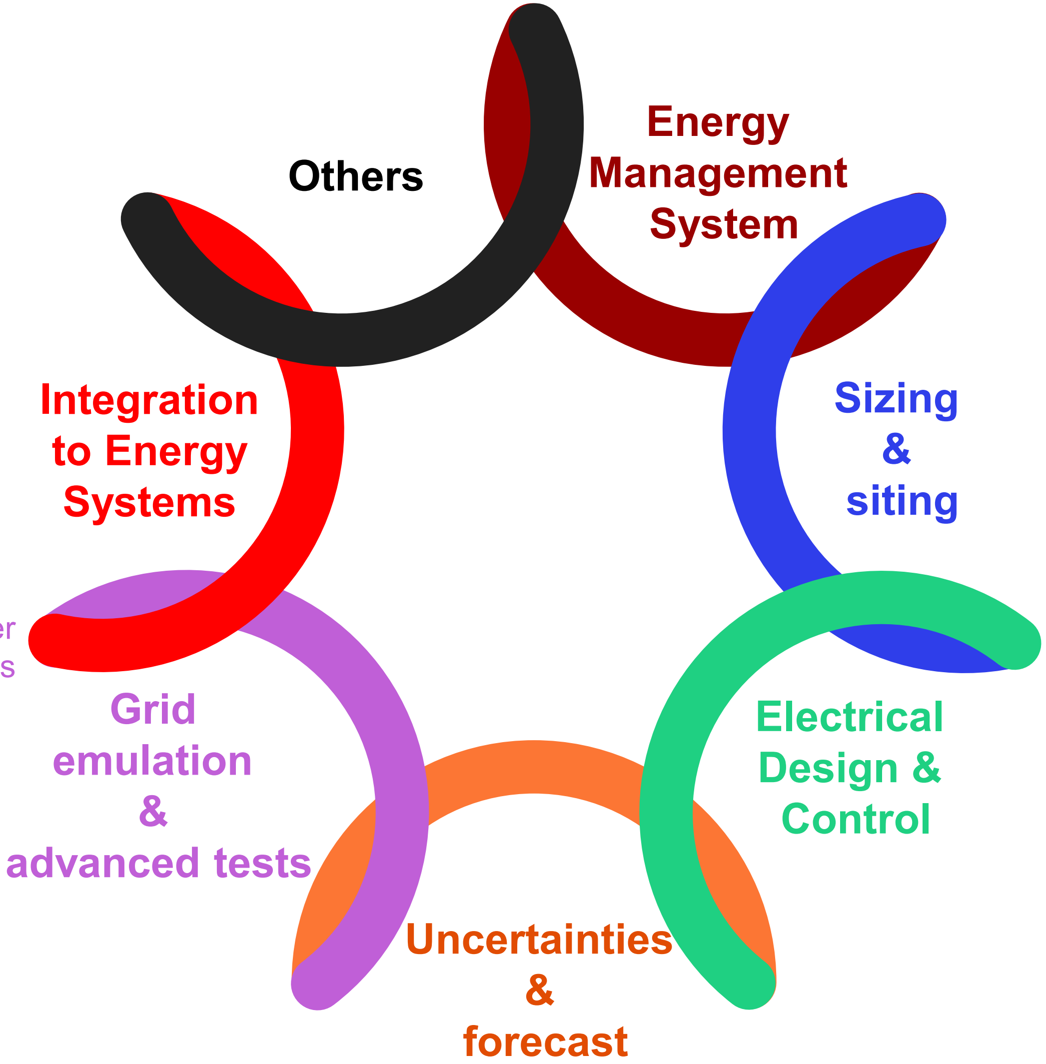
- Co-operation with other energy sectors
- Power2X
- Co-ordinated Control
- Load Balancing

Grid emulation & advanced tests

- Emulation of future converter dominated power systems using CGI and / or synchnonus condenser to emulate grid
- Development of new test methods / grid codes
- Validation of models

Uncertainties and forecast

- Variability for combined wind-solar-storage
- Market forecasts
- Hybrid power forecast
- Real time power simulation
- Assessment of flexibility & grid services



Energy Management System

- Optimal operation on markets: energy markets, grid service markets and capacity markets considering uncertainties, component lifetime

Sizing and siting

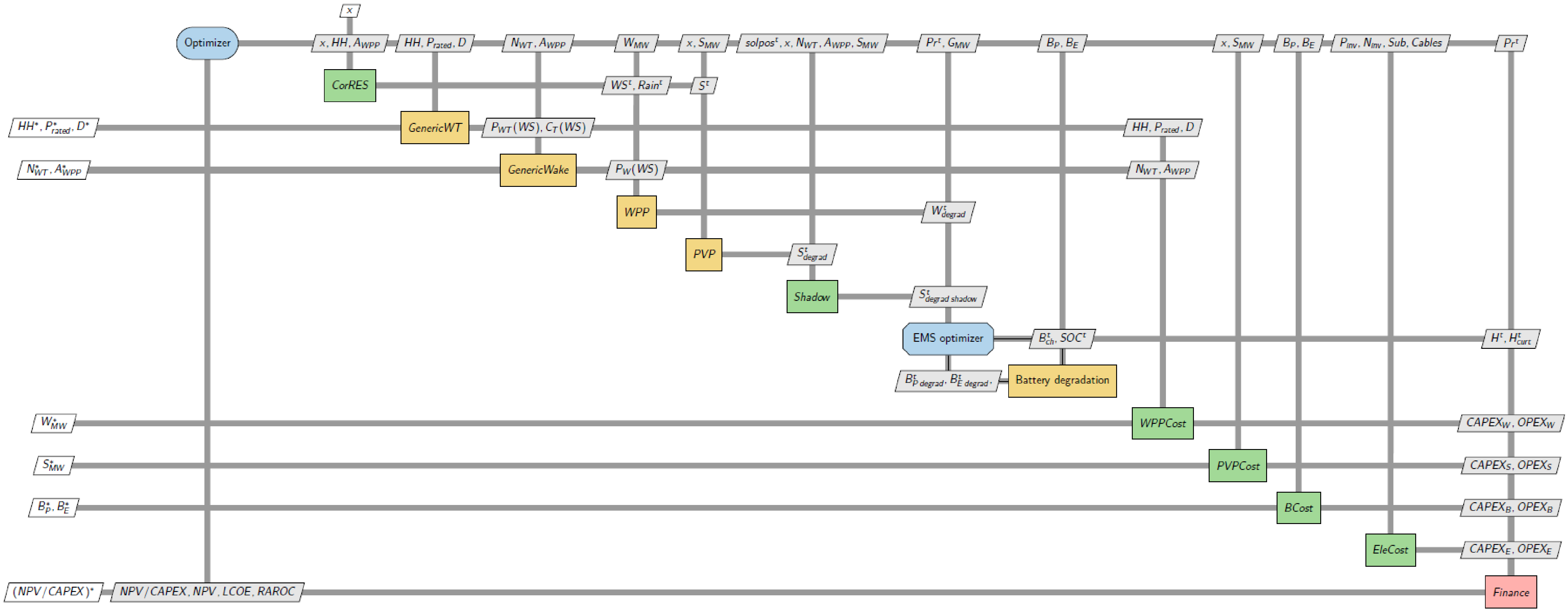
- Resource assessment
- Physical Design Optimization
- Selection / hybridization of storage technologies
- Optimal sizing of wind-solar-storage
- Hybridization of existing wind or solar plants

Electrical Design and Control

- Optimal electrical design – utilization of wind turbine DC links and inverter
- Use of electrical auxiliaries (supercapacitor, chopper, FACTS)
- Hierarchical control / Distributed control
- Grid services
- Blackstart capability

Sizing Example

Sizing Optimization



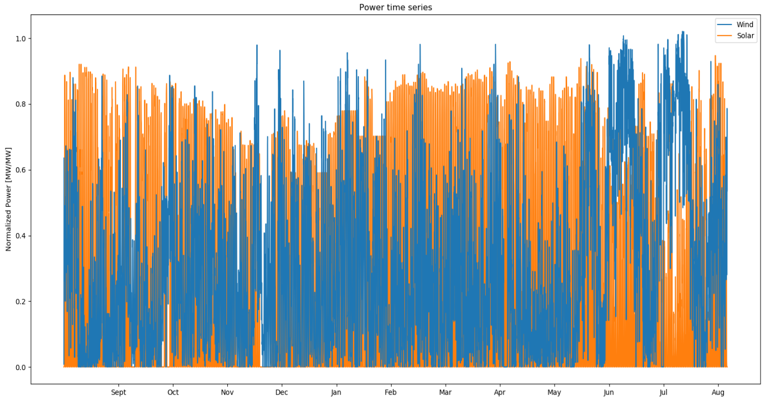
Case study

Power Purchase Agreement

- Peak/Off- peak fixed tariffs according to awarded tende
- 25 years contract
- Six peak hours every day

PPA requirement

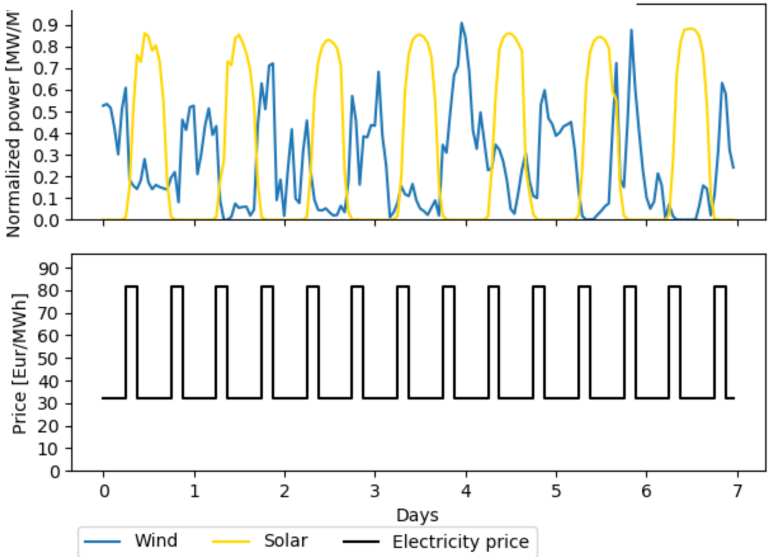
- Out of possible 9 peak hours (6-9, 18-24); HPP should provide peak power for 6 peak hours
- 6 peak hours will be communicated by the system operators 1 day before operation



Solar CF	Wind CF
23.5 %	29.5 %

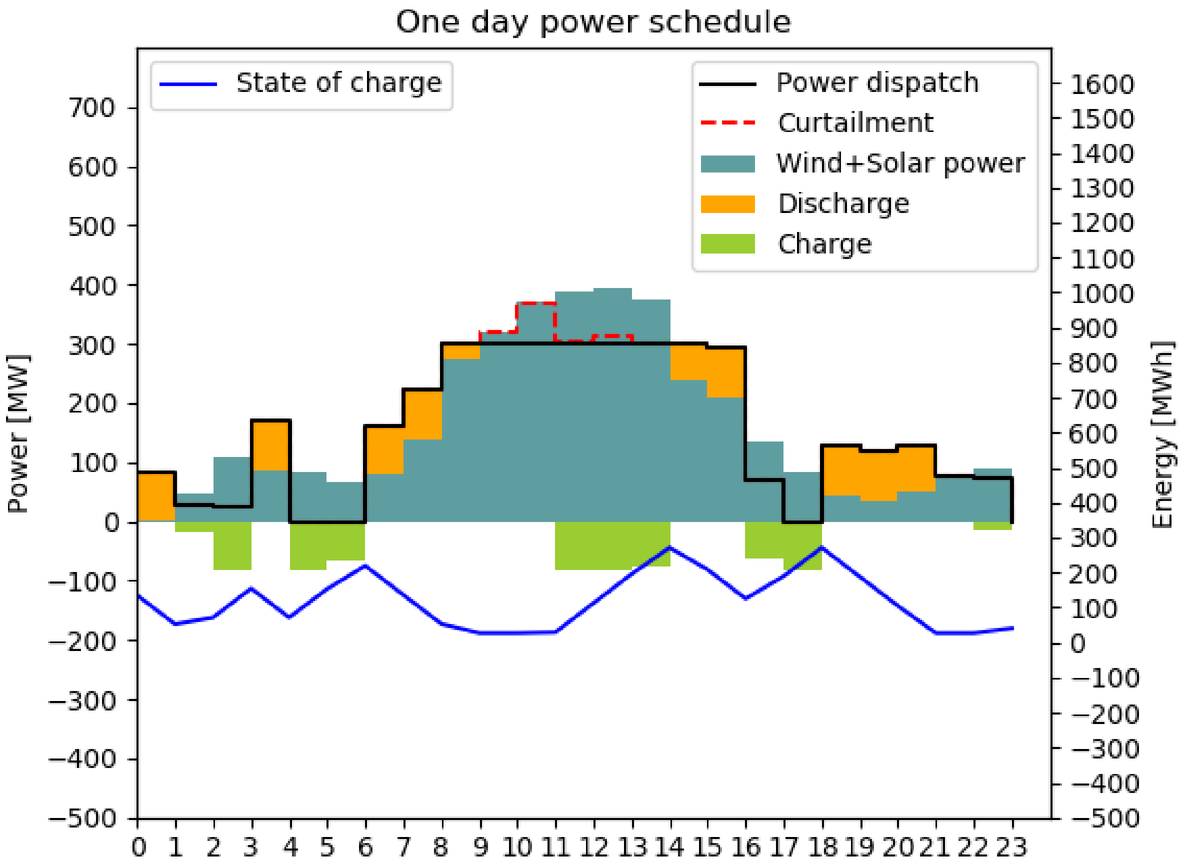
Winning Bid

Peak Tariff [EUR/MWh]	Off-Peak Tariff [EUR/MWh]	Peak Hours
81.5	32	6-9 18-21



Results

Base case



Optimal sizes of HPP technologies

Contract Capacity
= 300 MW

	Capacity	Unit
Wind	171	MW
Solar	378	MW
Battery energy	271	MWh
Battery power	83	MW

Alessandra Cossu "Optimal sizing of hybrid power plant" *Master Thesis, DTU Wind Energy, 2020*

Results

Comparison of case studies

	Solar Contracted capacity	Wind Contracted capacity	Wind Solar Optimized	**Optimal Solution**	Unit
Wind	-	300	129	171	MW
Solar	300	-	347	378	MW
Battery energy	-	-	-	271	MWh
Battery power	-	-	-	83	MW
Potential wind-solar energy at nominal capacity	617	775	1047	1219	GWh
HPP Annual energy production	617	775	1026	1199	GWh
Capacity factor	23	29	39	46	%
Full load hours	2057	2584	3421	3997	Hours
Total curtailment	0	0	21	20	GWh
Potential wind-solar energy curtailed	0	0	2	2	%
LCOE	29	38	32	39	EUR/MWh
NPV	37	36	72	82	MEUR

Contract Capacity = 300 MW

Location: India, Telangana region

Solar CF	Wind CF
23.5 %	29.5 %

Performance metrics

	Base case	Unit
Potential wind-solar energy at nominal capacity	1219	GWh
Maximum potential energy at contracted capacity	2628	GWh
HPP Annual energy production	1199	GWh
Total energy discharge	227	GWh
Capacity factor	46	%
Full load hours	3997	Hours
Total curtailment	20	GWh
Potential wind and solar energy curtailed	2	%
Capacity factor during peak hours	54	%
Capacity factor during off-peak hours	43	%

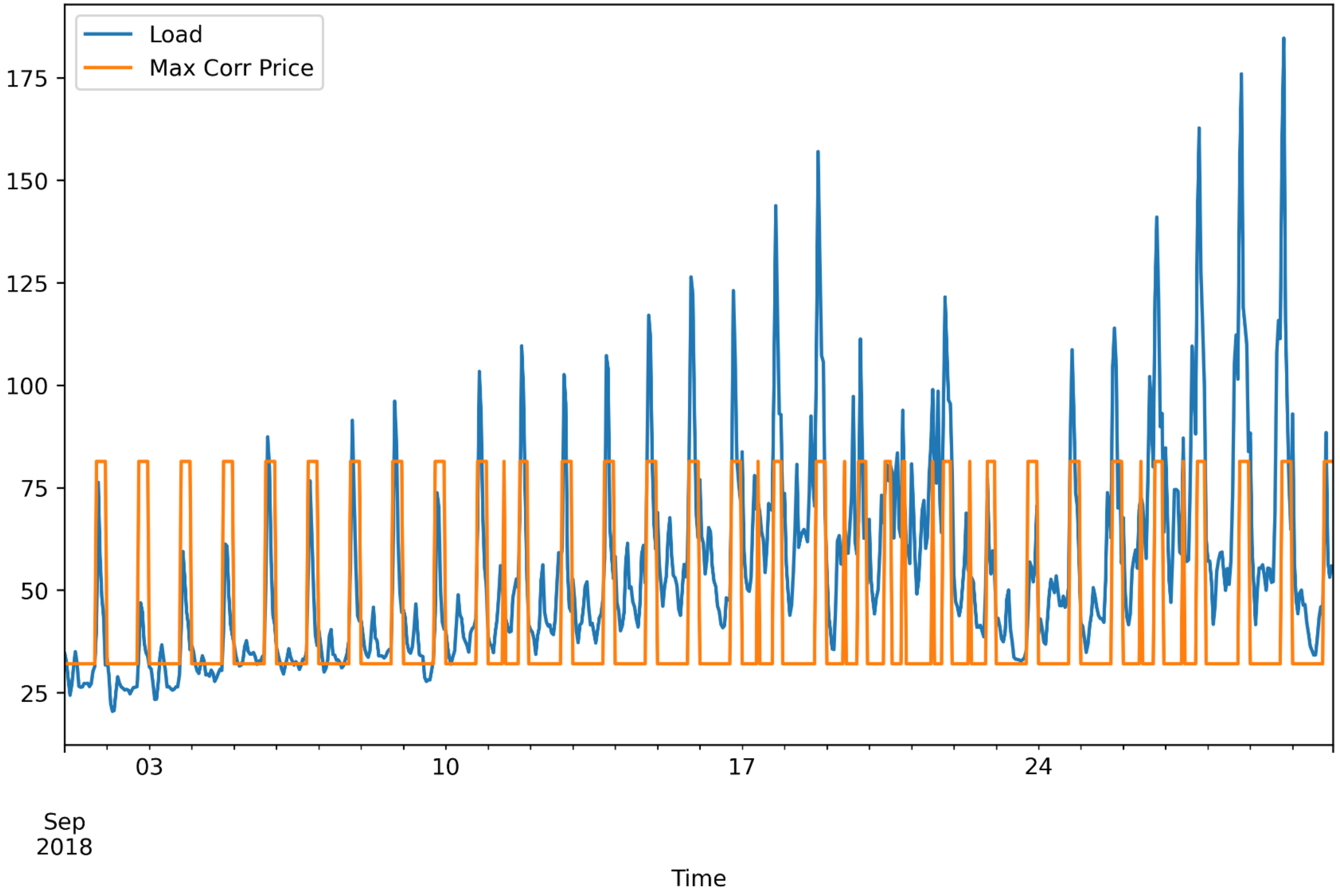
Comparison with different price profile inputs

	Base case	Market Prices	Evening peaks	Unit
Wind rated capacity	171	0	316	MW
Solar rated capacity	378	377	210	MW
Battery energy capacity	271	0	0	MWh
Battery power rating	83	0	0	MW
Potential wind-solar energy at nominal capacity	1219	775	1248	GWh
HPP Annual energy production	1199	761	1225	GWh
Capacity factor	46%	29%	47%	%
Full load hours	3997	2536	4084	Hours
Total curtailment	20	14	23	GWh
Potential wind and solar energy curtailed	2%	2%	2%	%
CAPEX	488	233	485	MEUR
IRR	9%	11%	8%	%
LCOE	39	29	36	EUR/MWh
NPV	82	95	51	MEUR

Sensitivity analysis of optimal sized HPP to price model

Main Indian Electric Market Case

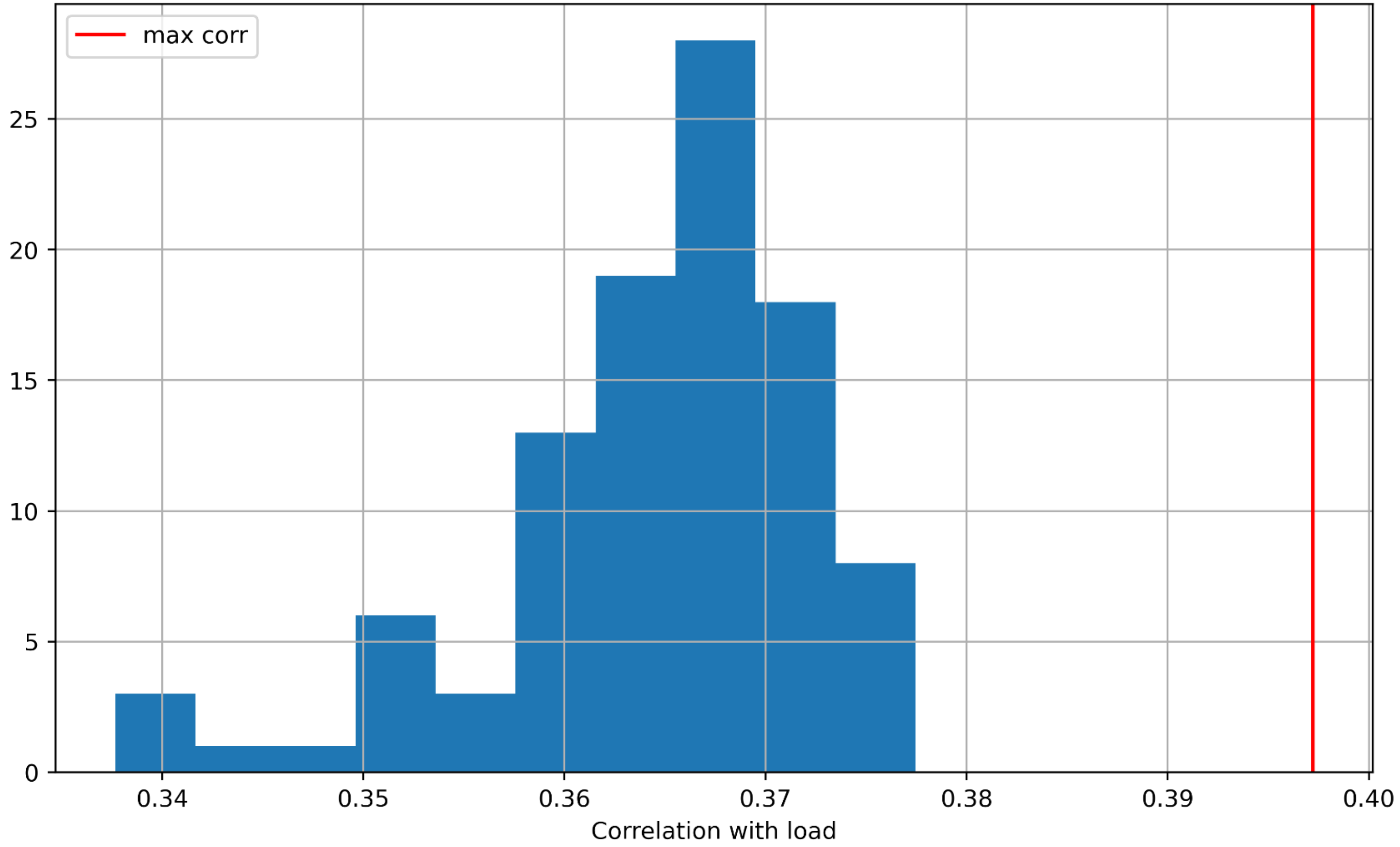
Indian Electric Market Main Case



Indian Electric Market Main Case

- 6 peak hours per day
- Peak prices occur at only 9 possible hour: 9-12 or 18-24
- Load can be modelled using historical electricity prices
- Max correlation price is the valid price (with 6 peak hours) that maximizes the correlation with the load

Build a stochastic model for the price

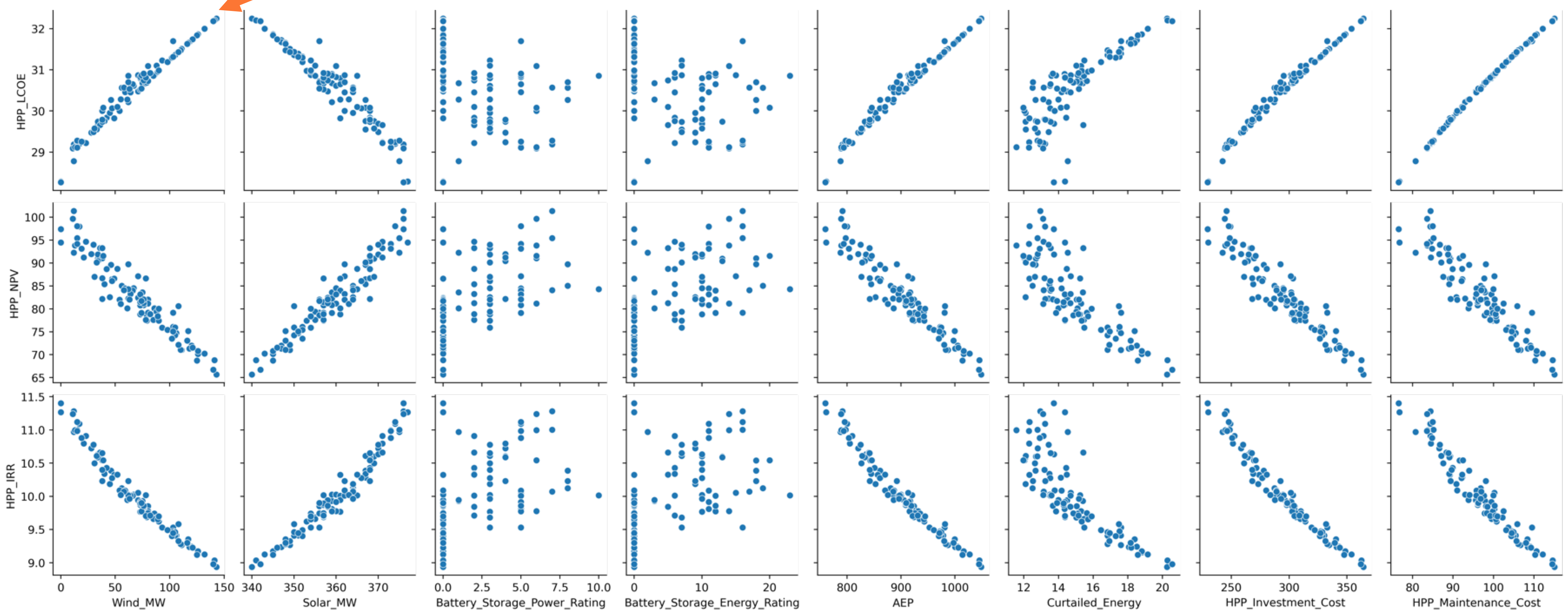


From the max correlation price

- Randomly select a weekday and weekend-day per month.
- Repeat the same day for all the week-days/weekend-days in the price time series
- The model is stochastic, a seed number controls the realization
- Different price signal can be obtained
- Peak/no-peak prices are fixed

How is the sizing optimization changing for different prices

Each point is a HPP optimized for a different price model realization (seed)



Additional Uncertainties

- Weather. Year-to-year variability in Wind, solar and load. 30+ yrs of weather in CorRES
- Peak/no-peak price levels
- Costs: Wind CAPEX and OPEX, solar CAPEX and OPEX, battery CAPEX and OPEX
- Financial parameters: discount rate, inflation
- Energy management system: Forecast errors in the future wind/solar resources and prices affects the actual performance of the HPP plant.
- Reliability and availability: Component sizing
- Technology: Choice of wind turbine, tracking vs non-tracking, choice of storage etc.

Impact of reliability on optimal sizing of hybrid power plant

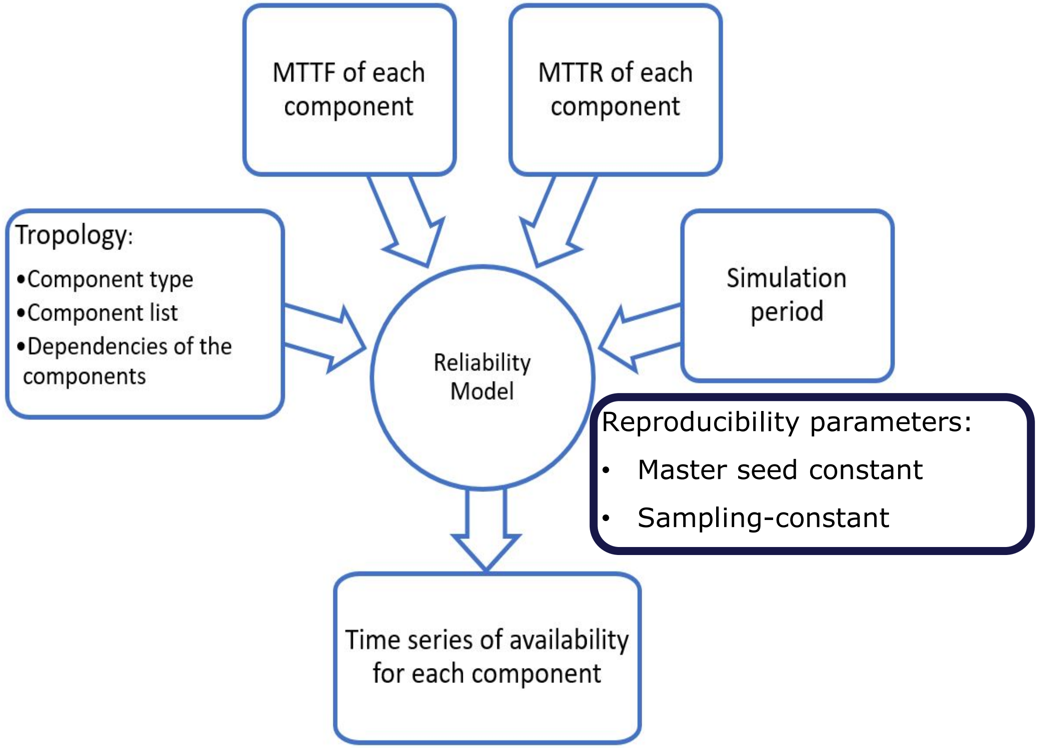
Reliability model

- Metrics
  - Availability

- Parameters
  - Failure rate, λ
  - Mean Time to Failure (MTTF)
  - Mean Time to Repair (MTTR)

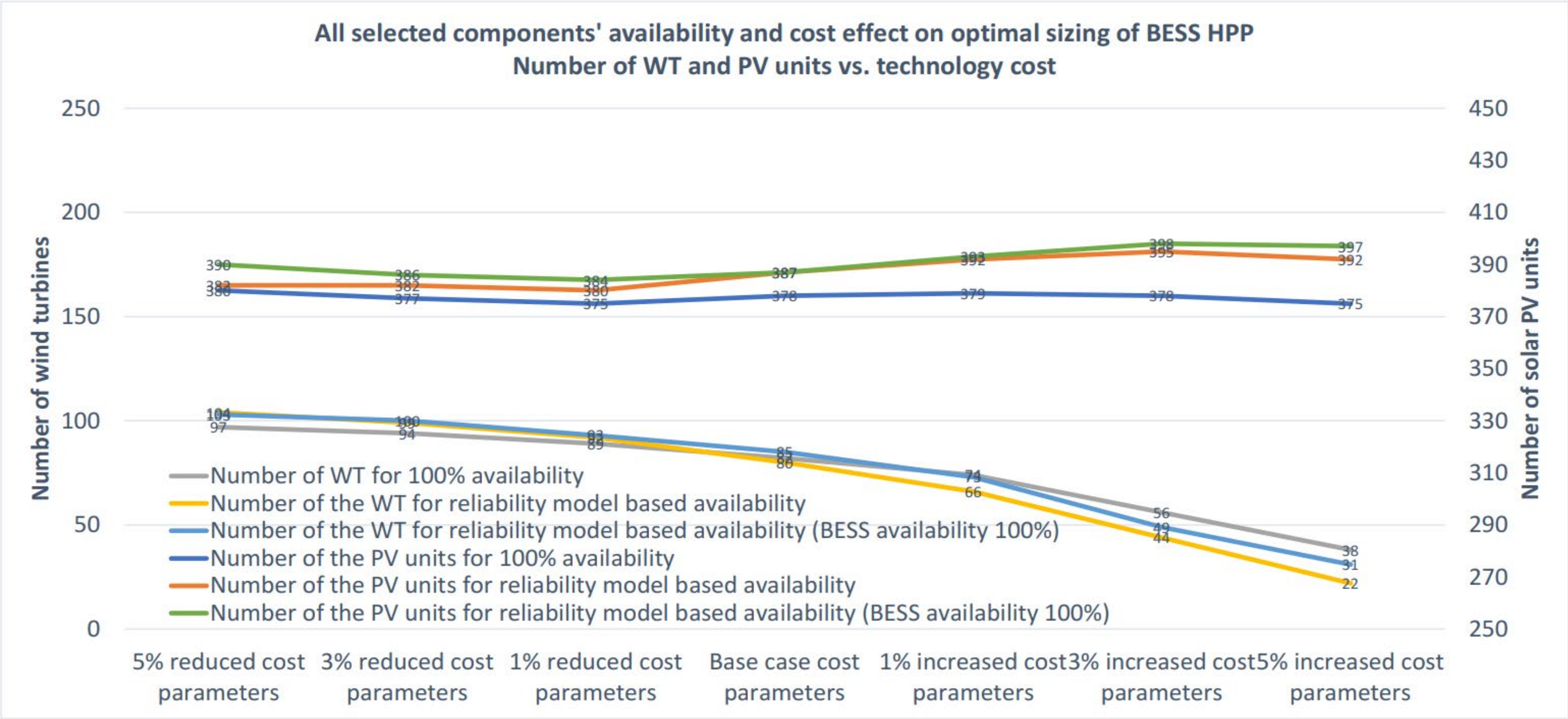
- Assumption for reliability mode

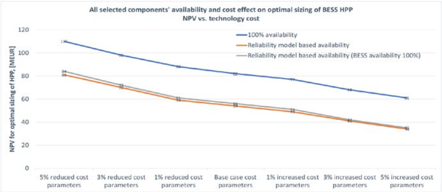
- MTTF ⇨ PDF of TTF
- MTTR ⇨ PDF of TTR

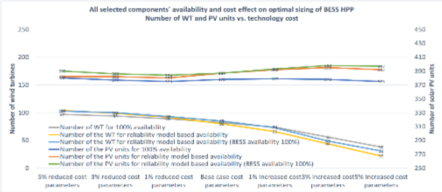


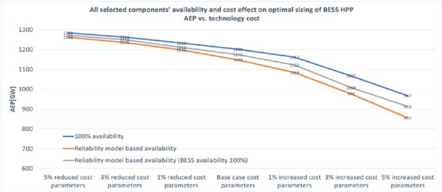
Wind+Solar+BESS HPP -

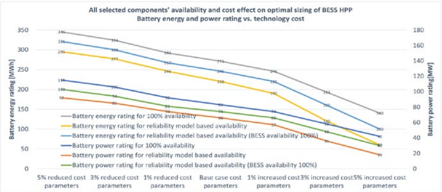
Impact of all selected components’ availability









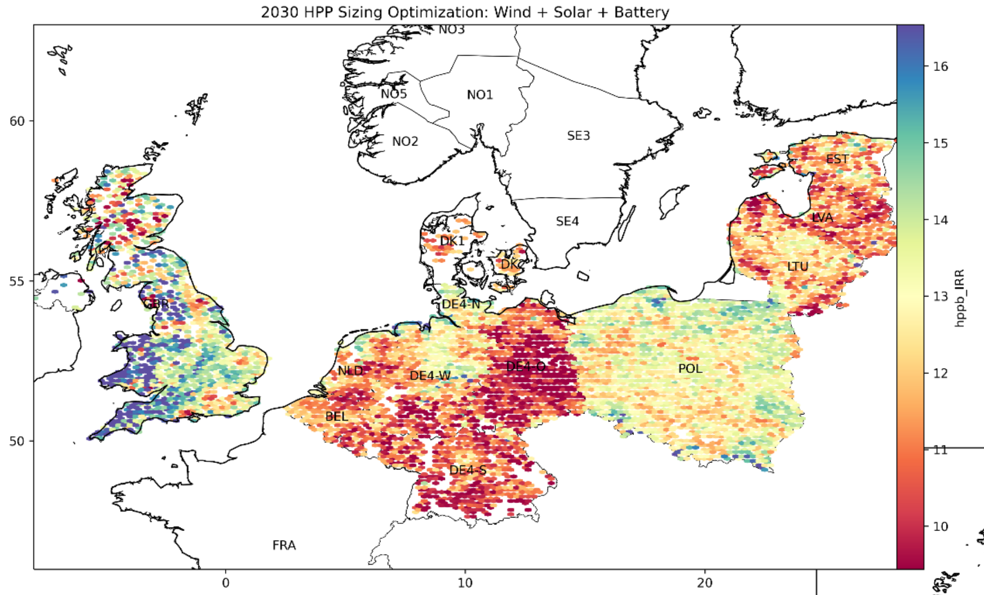


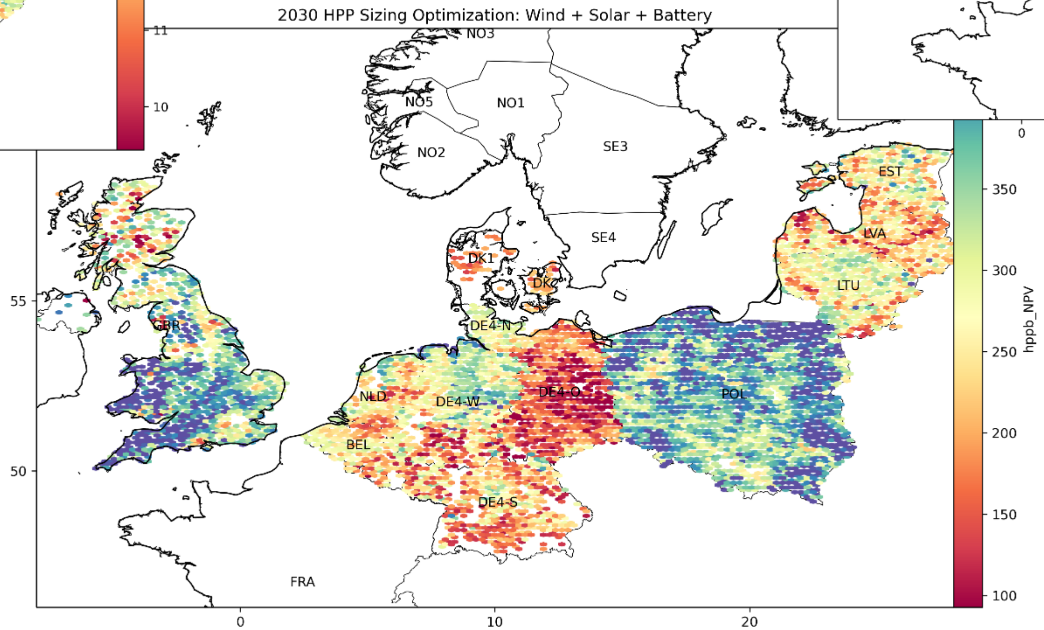
Open Questions

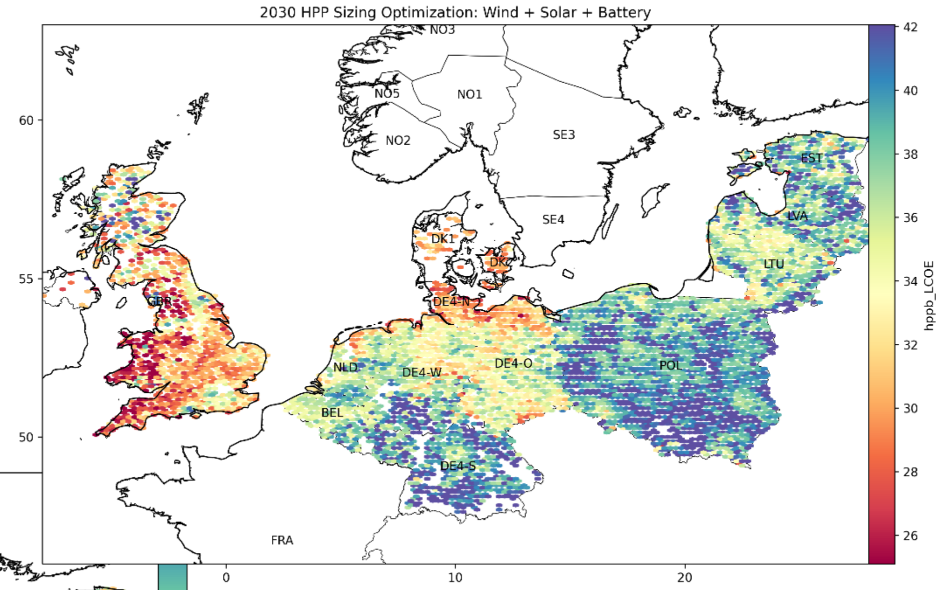
- How to include the following in sizing and physical design in terms of -
  - Resources
    - Correlations and uncertainties
    - Climate change
  - Market
    - Different types of energy markets
    - Uncertainties
    - Markets beyond electricity
  - Sharing of infrastructure, development and planning costs
  - Physical interactions between technologies
    - Shadow flickers
    - Change in wind flow due to heating up by solar panels
  - Shared electrical collection system
  - Cognizance of smoothening of different market values with large share of HPPs

Large scale Analysis

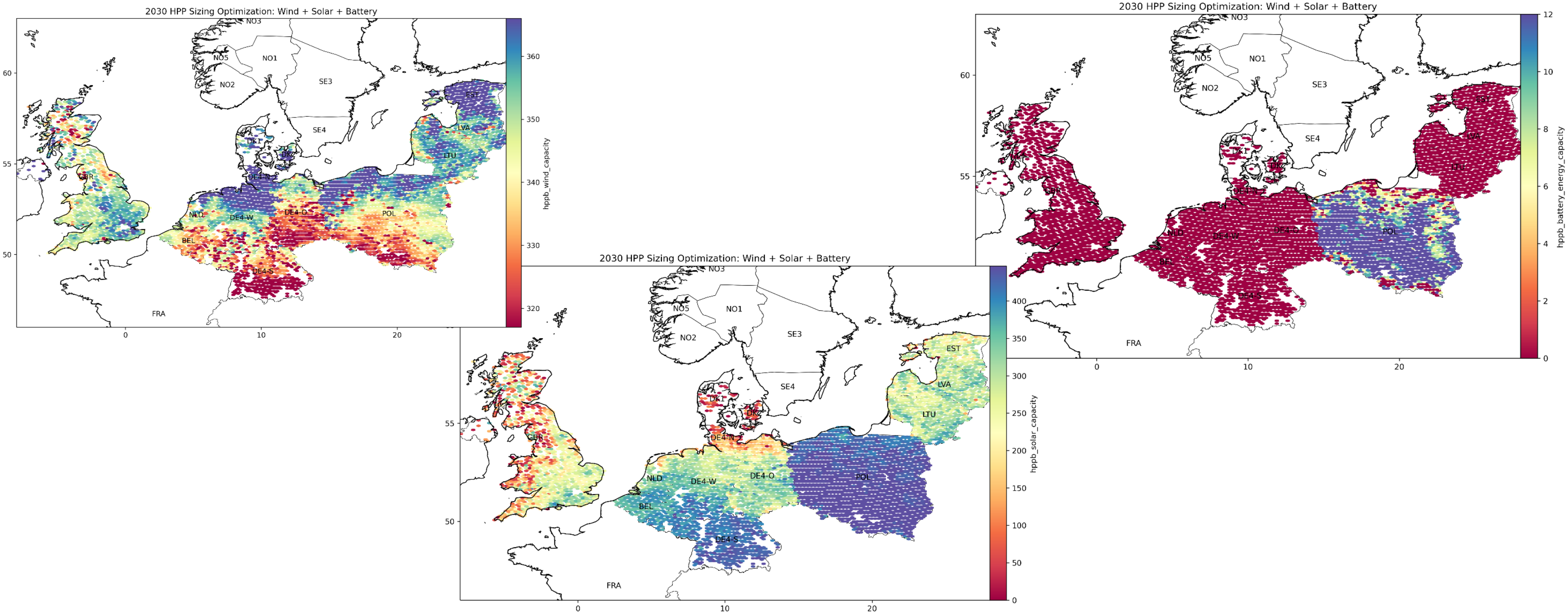
Internal Rate of Return, Net Present Value and LCoE







Wind Capacity [MW], Solar Capacity [MW], BESS [MWh]



Open Questions

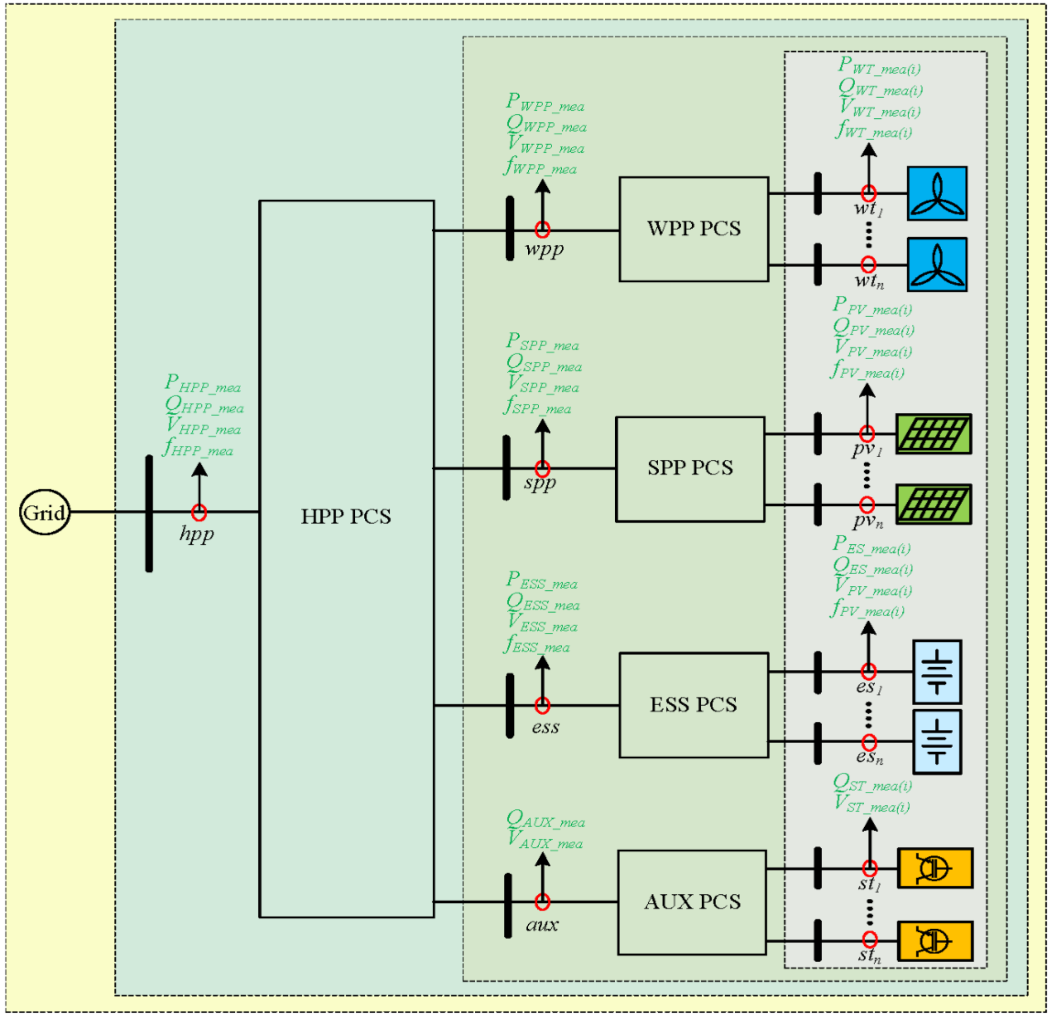
- How these maps change when we consider other markets and flexibilities?

- How does large deployment of HPPs impact the market operations?

- For larger deployment of HPPs, what plays the biggest role?
  - Costs
  - Regulations
  - CO_2 taxes
  - ….

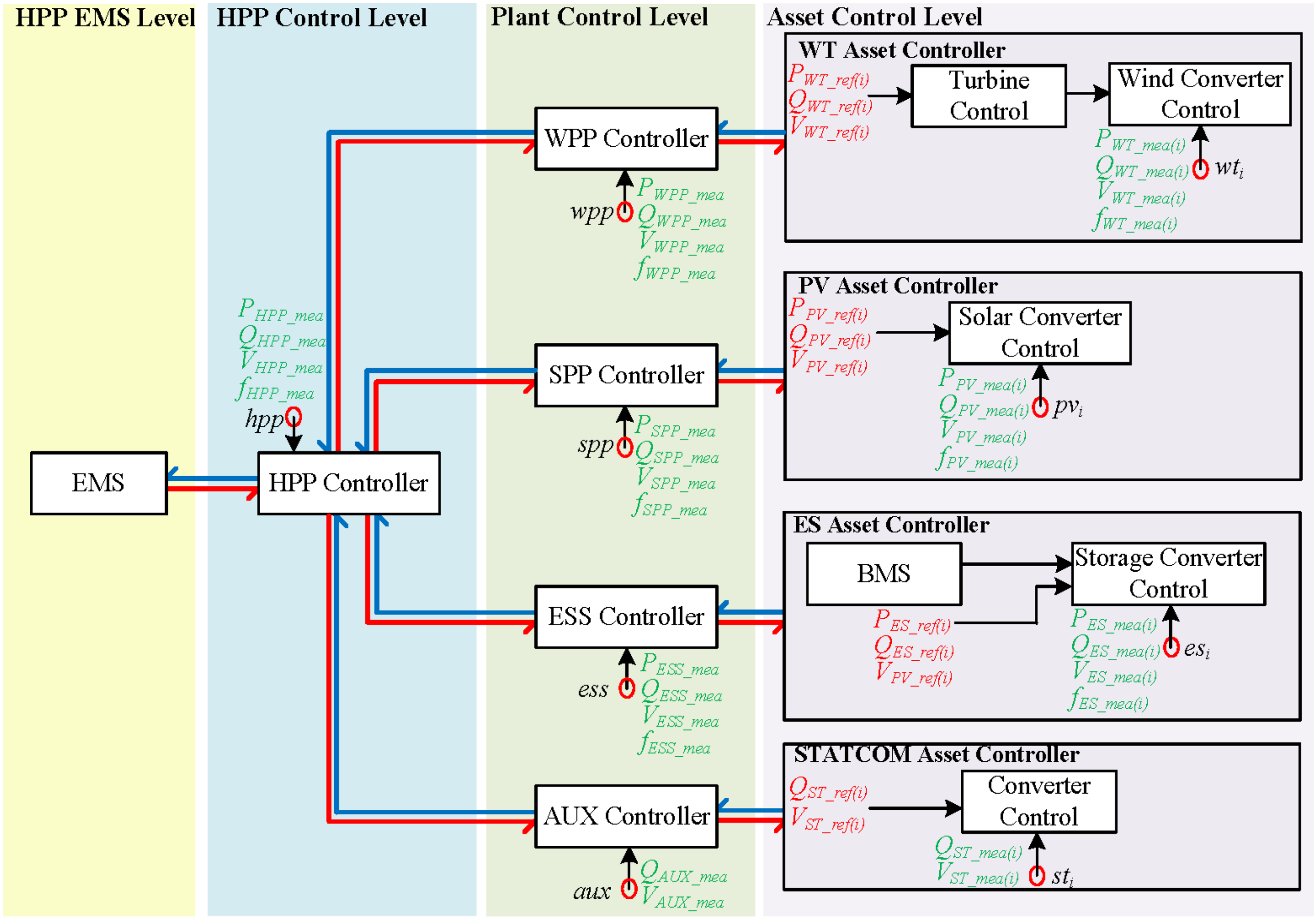
Control Architecture

HPP Layout



- Co-located AC HPP consisting of one WPP, one SPP and one ESS
- Multiple measurement points at the asset terminals and plant POCs

Control Architecture



Red – signals from higher to lower control level

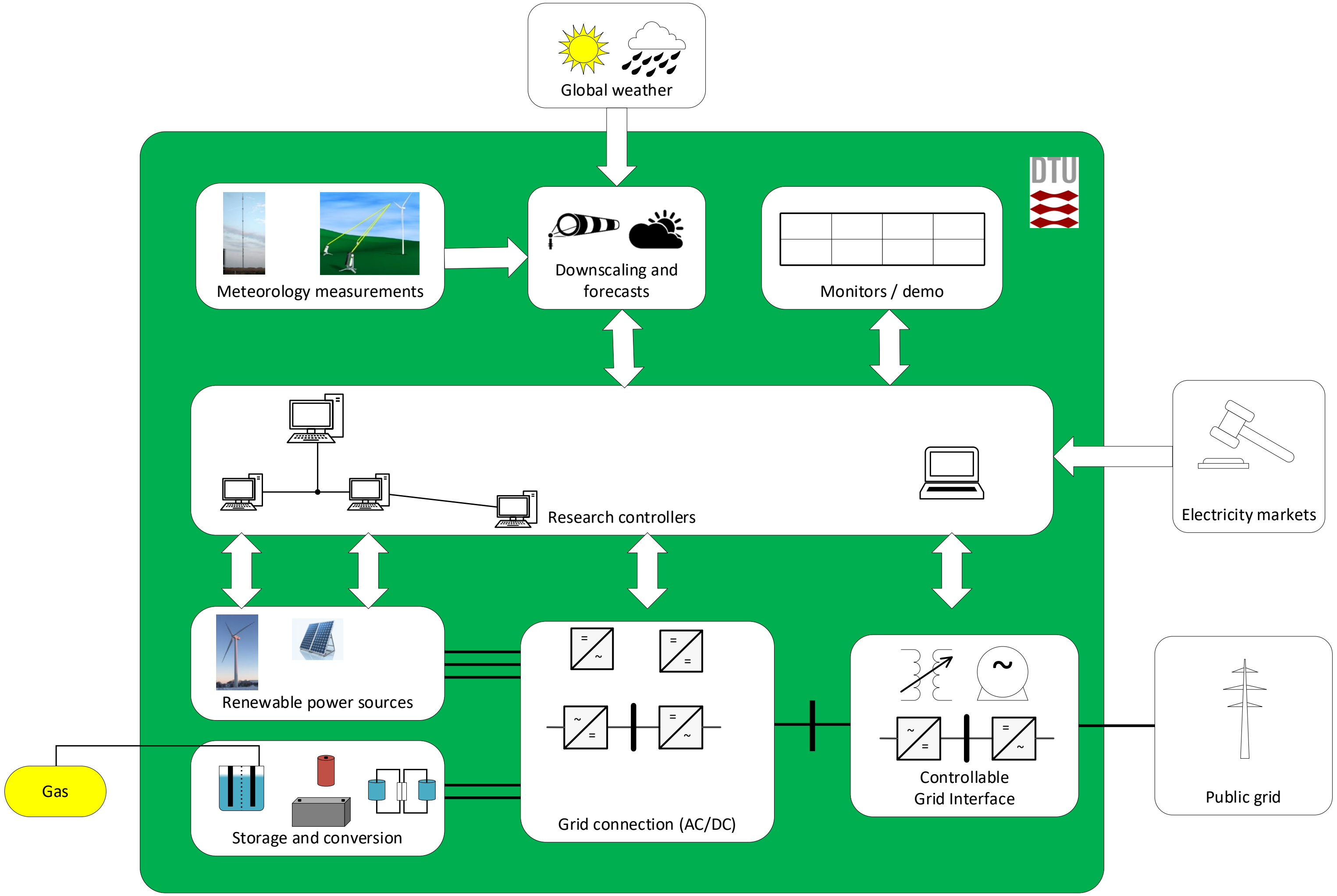
Blue – signals from lower to higher control level

- Challenges
  1. Coordination of multiple plant controllers
  2. Management of multiple hierarchies
  3. Robustness against communication failures (especially for time-sensitive functions, such as frequency service provision)

Research Infrastructure

DTU Hybrid Wind Power Plant Facility – under development

- Grid connected wind-hybrid power plant (wind / solar / storage)
- Open research controllers
- Power collection and grid connection (AC / DC)
- Controllable grid interface
- Connection to external information (weather forecasts, markets)

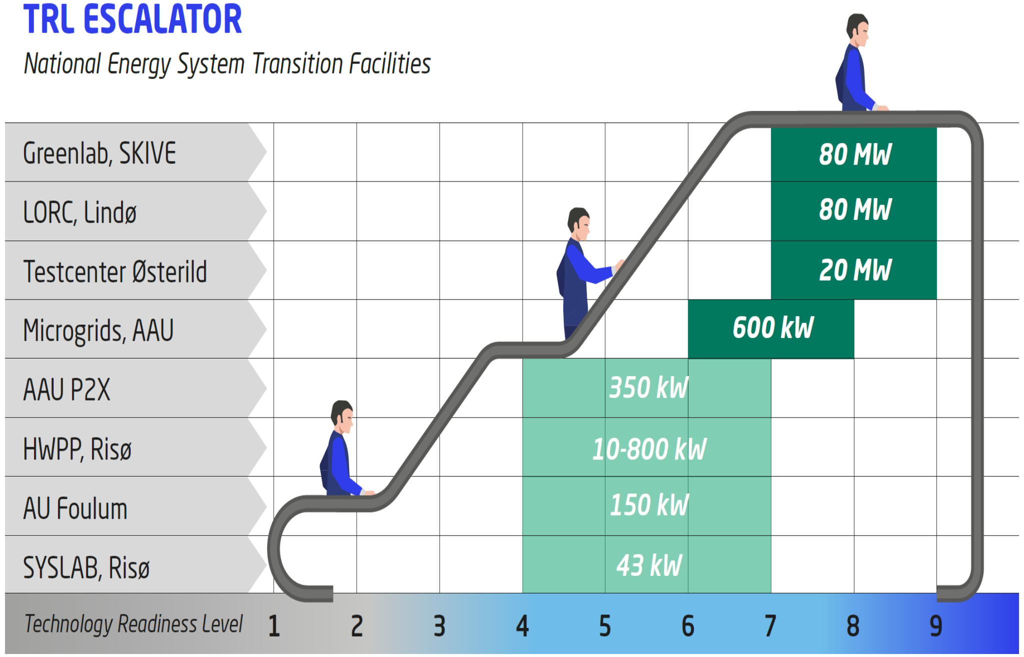


DTU

National Energy System Transition Facilities

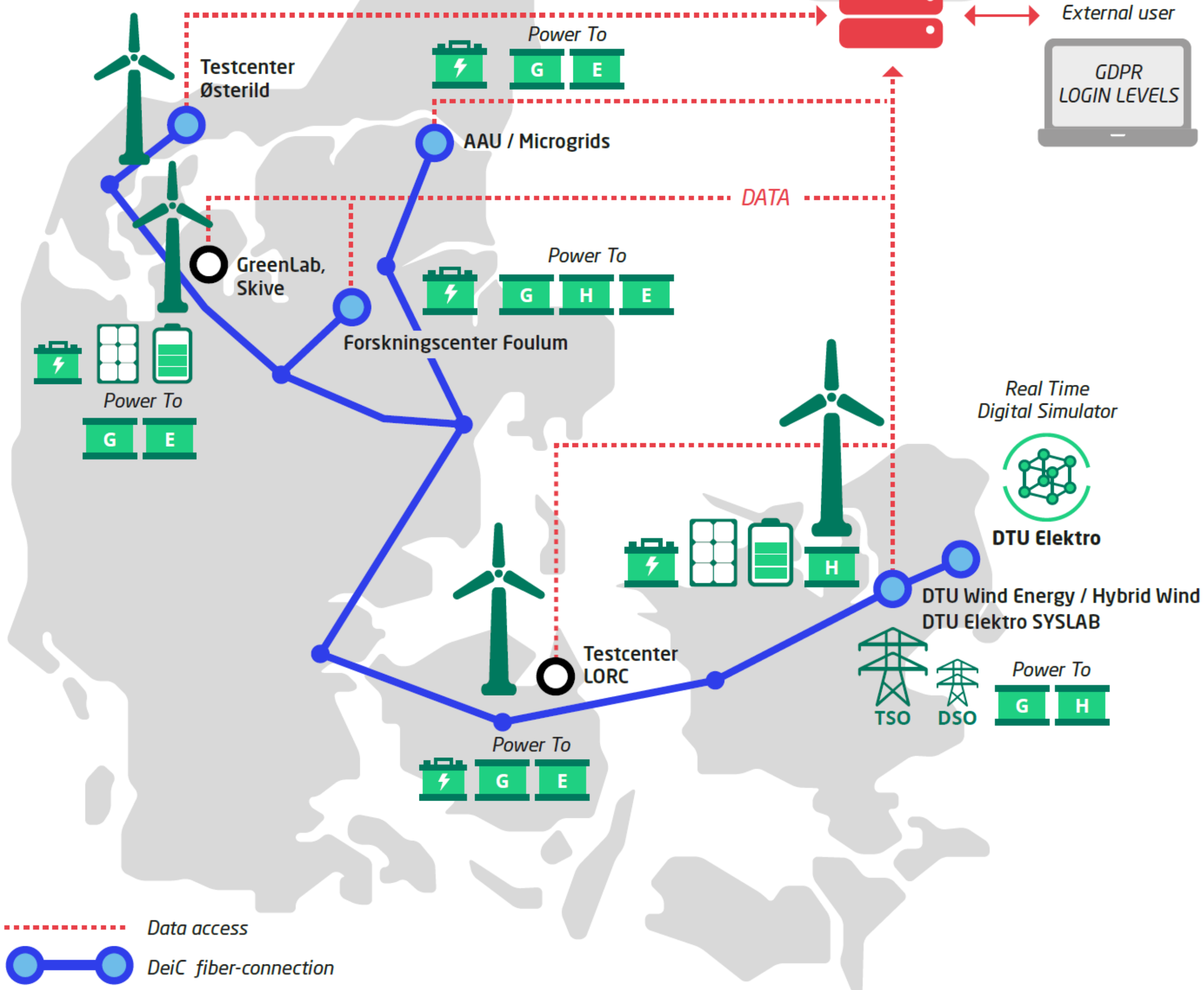
TRL ESCALATOR

National Energy System Transition Facilities



NEST digital infrastructure

A DeiC fiber network between testfacilities, laboratories and data-exchange with external users.



Open Questions

- How to stack different services in HPP controller?
- How the reliability between EMS and HPP controller impacts the operation?
- Which services should be assigned to which assets?
- How to hybridize already available plants in terms of control?
- How to develop grid codes, test and standards for HPPs?

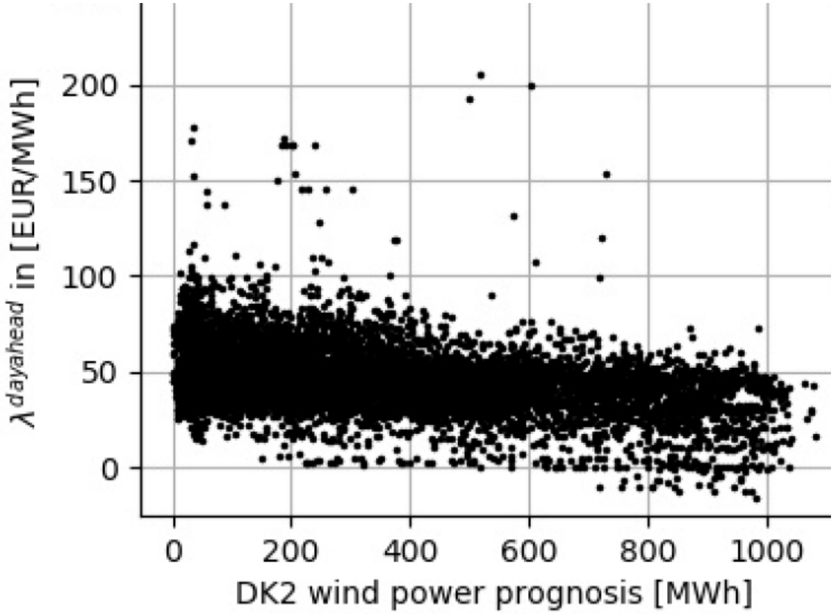
Energy Management System

Motivation for HPP in Energy Market

Market structure in Nordic

- Lowering cost of solar and storage technology
- Increased requirement of flexibility
- Increased share of RES in congested power systems
- Different markets around the globe opening up with specific requirements
- Reduced grid connection and DEVEX

Negative correlation between price and wind production

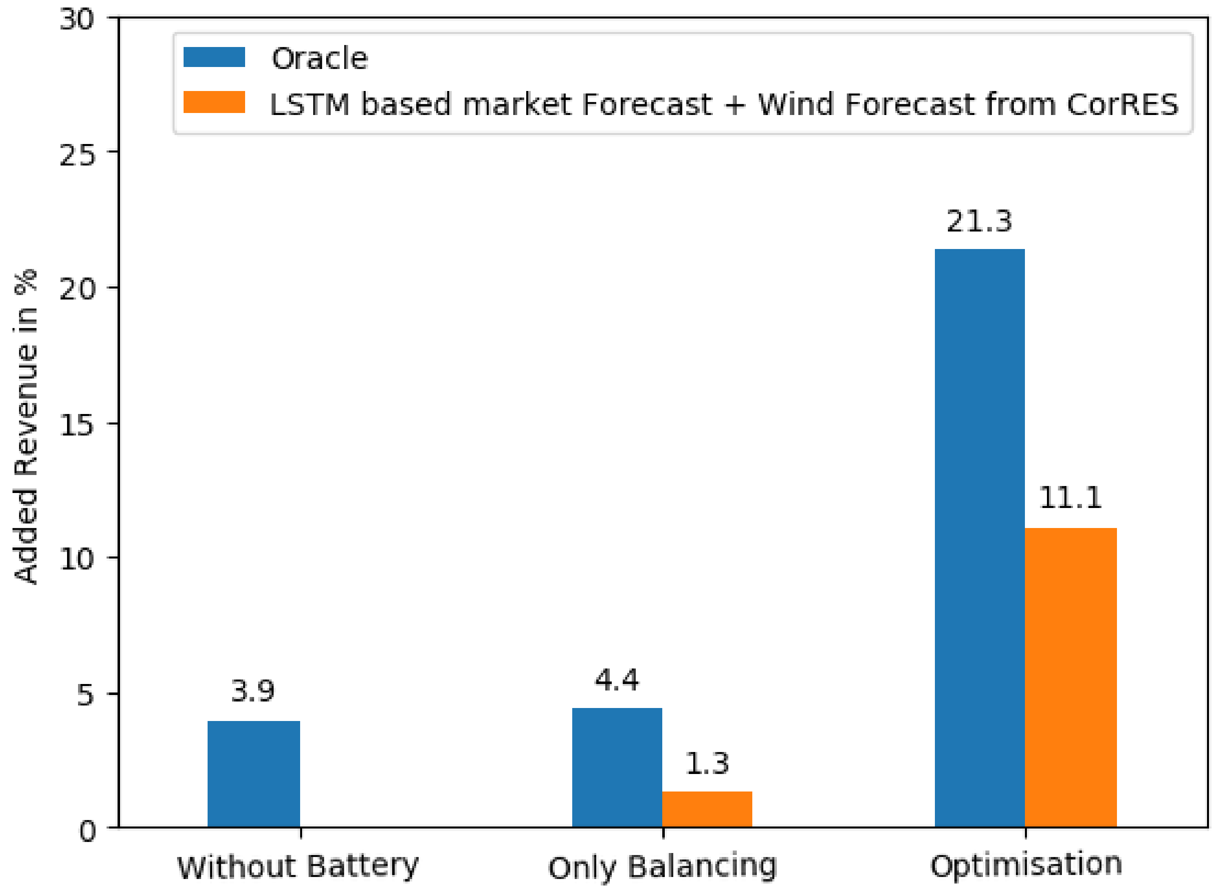


- Can storage play a role in increasing the revenue of the WPP thereby helping the society in green transition?
- On which type of market(s) storage plays the major role thereby determining the strategy of HPP energy management system?

Study Case - Value of day ahead optimisation

HPP PARAMETERS

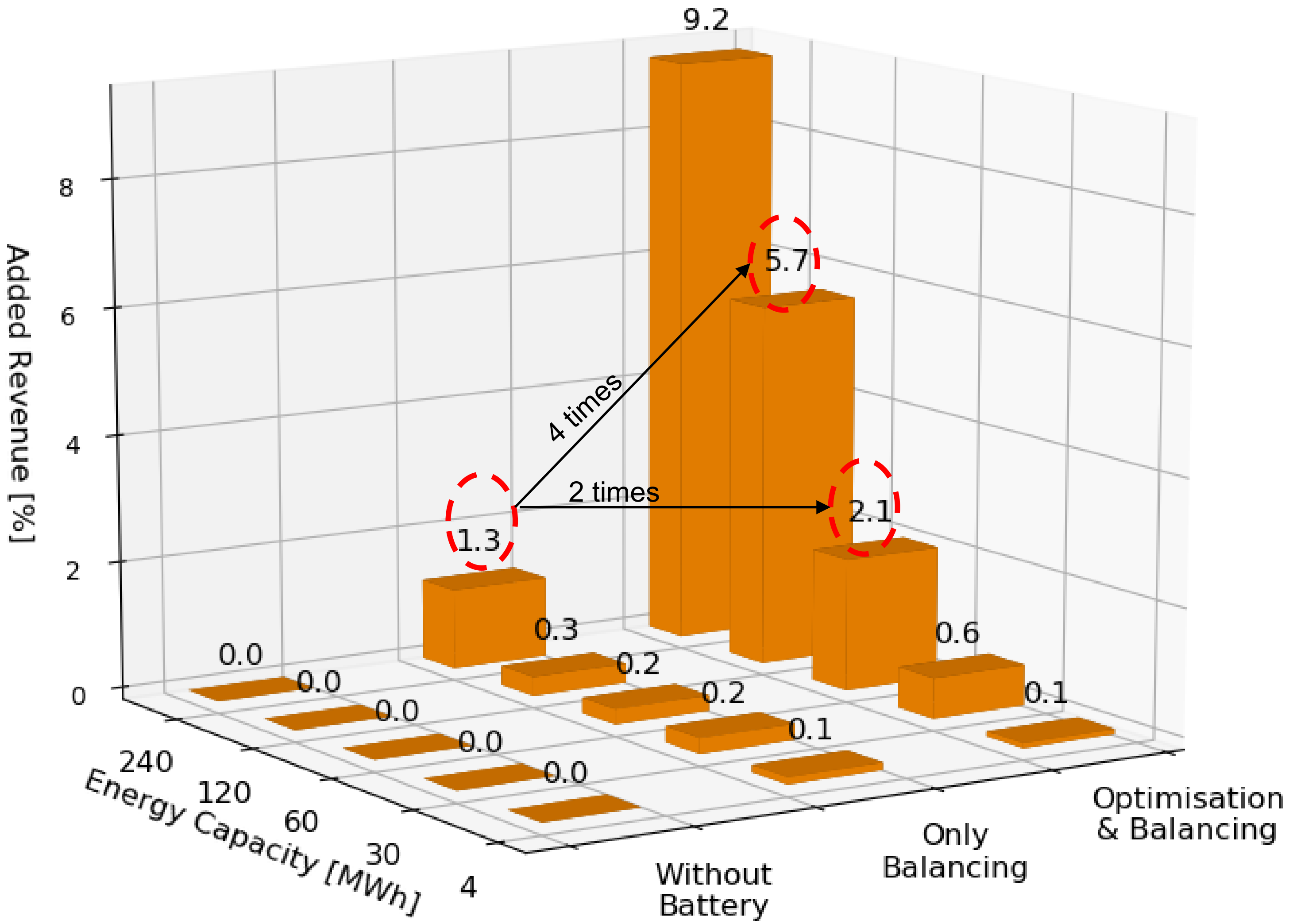
Name	Value	Unit
P_{max}^{HPP}	51	MW
P_{wind}	51	MW
P_{max}^{BESS}	34	MW
SOC_{max}	245	MWh
SOC_{min}	0	MWh
$SOC_{startOfYear}$	$50\% \cdot SOC_{max}$	MWh
η_{char}	0.95	MW/MW/hour
η_{dis}	0.95	MW/MW/hour
η_{leak}	0	MW/MWh/hour



- Storage used only for balancing doesn't add much revenue compared to allowing for day ahead optimization
- Quality of forecast play a major role (revenue up by another 10% as demonstrated by "Oracle" case)

Sensitivity studies of power energy ratio of the storage

- Added revenue is higher considering day-ahead optimization even with smaller battery capacity as compared to balancing
- Exponential increase in revenue with increase in energy capacity



Discussion

- Results have shown that storage system could be managed in several ways and that scheduling the production based on the market price forecast is the most effective.

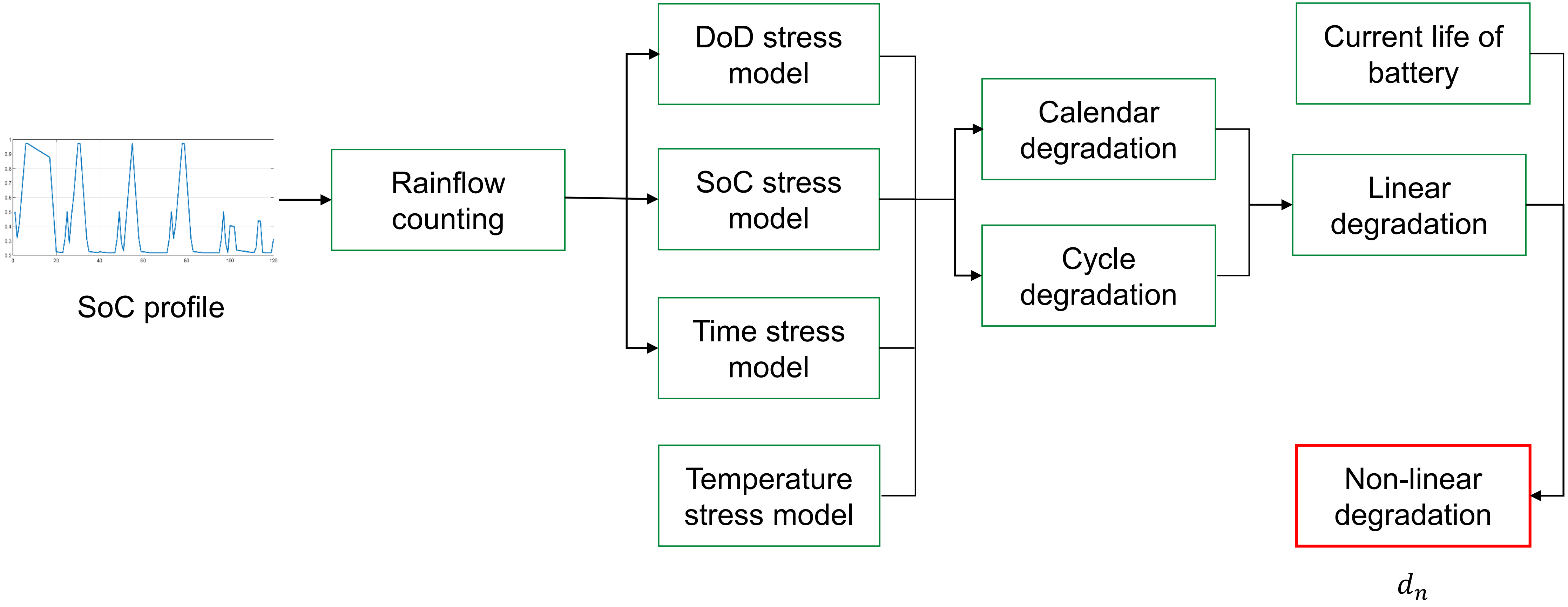
- Applying integrated bidding strategy for both day ahead markets and balancing markets eventually increases the revenue by more than 10% as compared to the case without battery.

- The most efficient technique relative to revenue and lifetime maximisation is to value the remaining energy rather than constraining the SOC goal to a given value.

- Lifetime considerations plays important role when choosing the battery capacity.

- Since, battery lifetime and cost plays a crucial role in the optimal decision of battery dispatch, it will be natural choice to include the battery cost and lifetime in future research of hybrid power plant's profit maximization.

Battery Degradation



Case study

- Wind power: Nord Pool, 2013-2020
- Spot Price: Nord Pool, 2013-2020
- Wind power plant: 100MW
- Battery parameters
  - Battery price[1]: 113€/*kWh*
  - $P^{max} = 30\ MW$
  - $E^{BESS} = 150\ MWh$
  - Degradation parameters[2]

TABLE I
DEGRADATION MODEL PARAMETERS

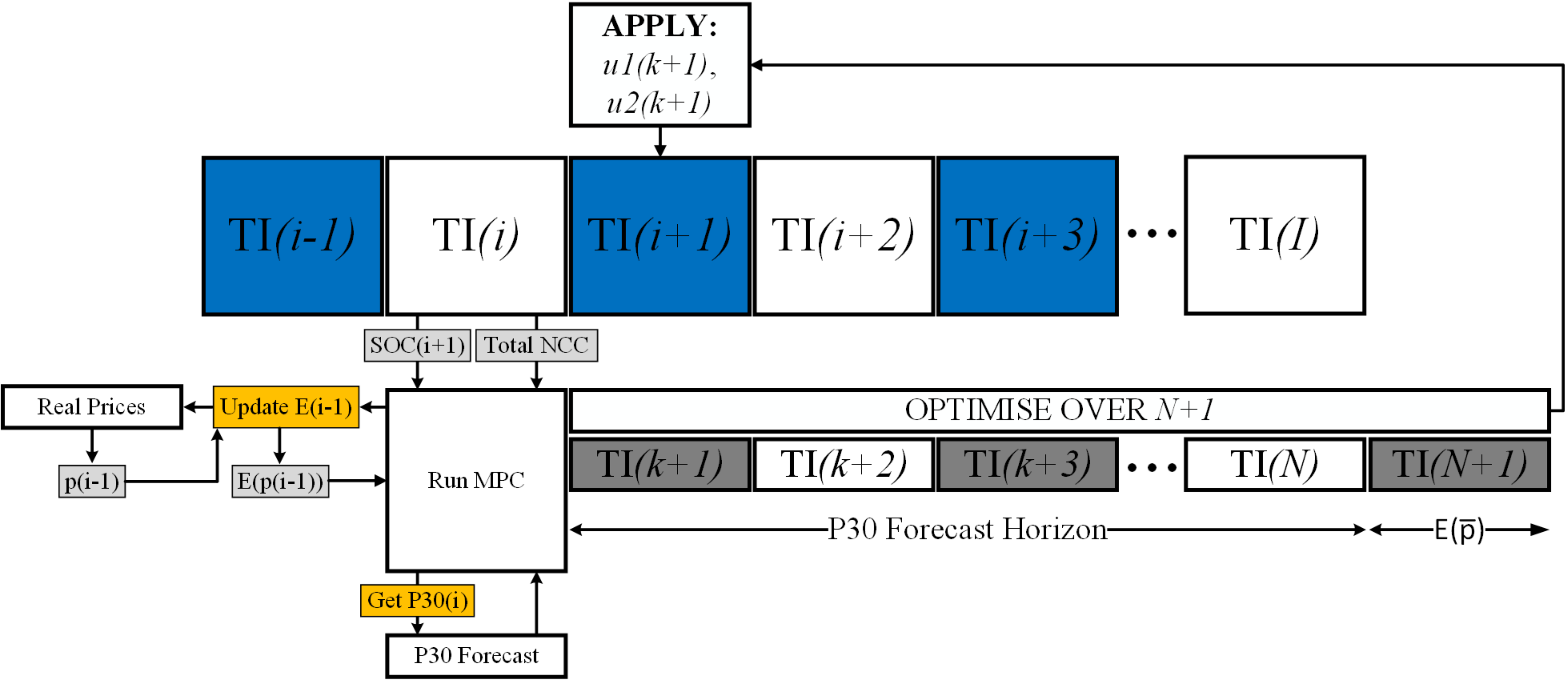
Nonlinear Degradation Model			
α_{sei}	5.75E-2	β_{sei}	121
DoD Stress Model			
$k_{\delta 1}$	1.40E5	$k_{\delta 2}$	-5.01E-1
$k_{\delta 3}$	-1.23E5		
SoC Stress Model			
k_{σ}	1.04	σ_{ref}	0.50
Temperature Stress Model			
k_{T}	6.93E-2	T_{ref}	25°C
Calendar Aging Model			
k_{t}		4.14E-10/s	

1. https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/
2. Xu B, Oudalov A, Ulbig A, et al. Modeling of lithium-ion battery degradation for cell life assessment[J]. IEEE Transactions on Smart Grid, 2016, 9(2): 1131-1140.

HPP v.s. only WPP

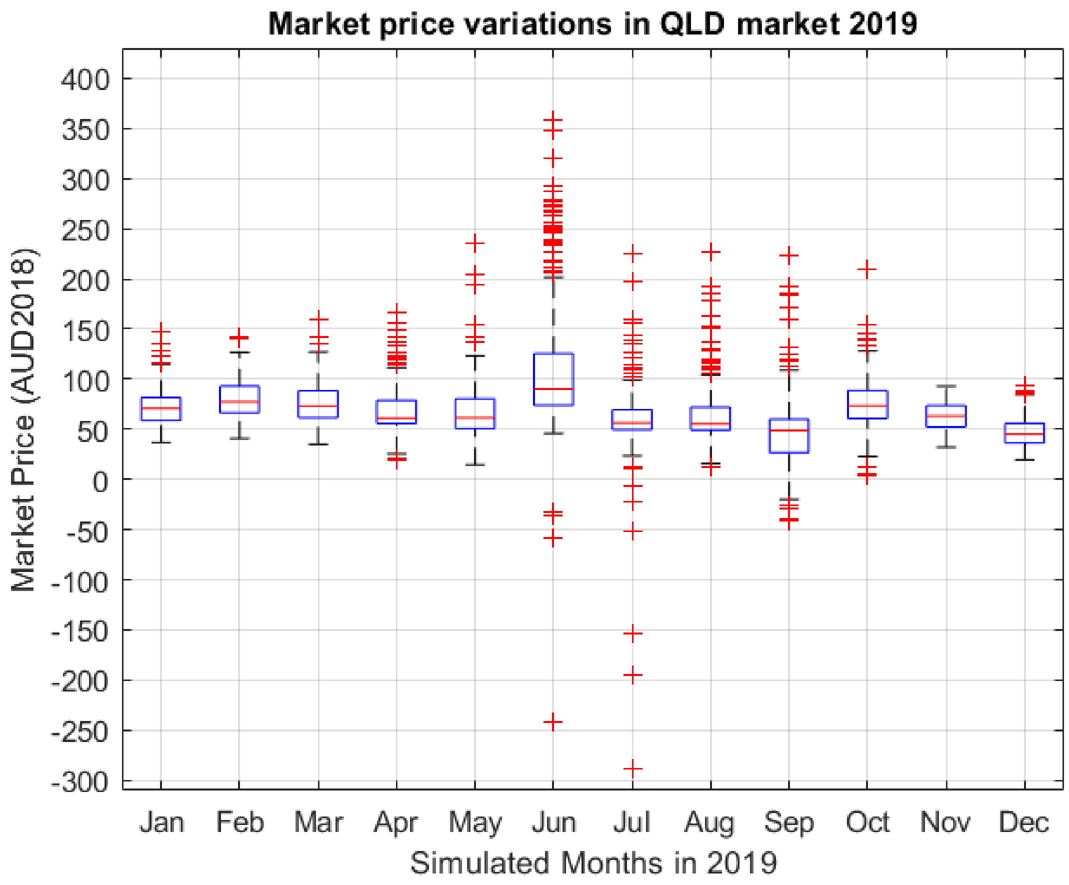
	HPP (weight factor=0)	HPP (optimal weight factor=150)	WPP
Revenues (million €)	63.8	60.3	61.5
Degradation costs (million €)	24	11.4	0
Profits (million €)	39.8	48.6	61.5

Energy Management System – Example Case: Australian market



[1] Johannes Moolman, "Potential of Hybrid Power Plant in Australian Grid", Master Thesis, DTU Wind Energy, 2019

Market Price Variations in QLD in 2019



Results

QLD

Infeasible: NPV = AUD -5.25 million

QLD: Sensitivity Analysis

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Inflation Index	1	1.02	1.0404	1.061208	1.082432	1.104081	1.126162	1.148686	1.171659	1.195093	1.218994	1.243374	1.268242	1.293607	1.319479	1.345868
Discount factor	1	0.909091	0.826446	0.751315	0.683013	0.620921	0.564474	0.513158	0.466507	0.424098	0.385543	0.350494	0.318631	0.289664	0.263331	0.239392
CAPEX (AUD)	5.32E+06															
Revenue (AUD/yr)	0	9639.929	8591.737	7657.519	6824.884	6082.784	5421.376	4831.886	4306.494	3838.23	3420.882	3048.915	2717.393	2421.919	2158.573	1923.862
DCF (AUD)	-5.32E+06	9.64E+03	8.59E+03	7.66E+03	6.82E+03	6.08E+03	5.42E+03	4.83E+03	4.31E+03	3.84E+03	3.42E+03	3.05E+03	2.72E+03	2.42E+03	2.16E+03	1.92E+03
NPV	-5.25E+06															

NSW

Feasible: NPV = AUD 19 million

NSW

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Inflation Index	1	1.02	1.0404	1.061208	1.082432	1.104081	1.126162	1.148686	1.171659	1.195093	1.218994	1.243374	1.268242	1.293607	1.319479	1.345868
Discount factor	1	0.909091	0.826446	0.751315	0.683013	0.620921	0.564474	0.513158	0.466507	0.424098	0.385543	0.350494	0.318631	0.289664	0.263331	0.239392
CAPEX (AUD)	5.32E+06															
Revenue (AUD/yr)	0	3217272	2867444	2555654	2277767	2030095	1809354	1612615	1437268	1280988	1141700	1017558	906914.5	808301.7	720411.5	642078
DCF (AUD)	-5.32E+06	3.22E+06	2.87E+06	2.56E+06	2.28E+06	2.03E+06	1.81E+06	1.61E+06	1.44E+06	1.28E+06	1.14E+06	1.02E+06	9.07E+05	8.08E+05	7.20E+05	6.42E+05
NPV	1.90E+07															

SA

Infeasible: NPV = AUD -1.62 million

SA

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Inflation Index	1	1.02	1.0404	1.061208	1.082432	1.104081	1.126162	1.148686	1.171659	1.195093	1.218994	1.243374	1.268242	1.293607	1.319479	1.345868
Discount factor	1	0.909091	0.826446	0.751315	0.683013	0.620921	0.564474	0.513158	0.466507	0.424098	0.385543	0.350494	0.318631	0.289664	0.263331	0.239392
CAPEX (AUD)	5.32E+06															
Revenue (AUD/yr)	0	489908.6	436638.6	389161	346845.8	309131.7	275518.5	245560.1	218859.3	195061.8	173851.8	154948.2	138100	123083.8	109700.3	97772.12
DCF (AUD)	-5.32E+06	4.90E+05	4.37E+05	3.89E+05	3.47E+05	3.09E+05	2.76E+05	2.46E+05	2.19E+05	1.95E+05	1.74E+05	1.55E+05	1.38E+05	1.23E+05	1.10E+05	9.78E+04
NPV	-1.62E+06															

VIC

Feasible: NPV = AUD 1.12 million

VIC

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Inflation Index	1	1.02	1.0404	1.061208	1.082432	1.104081	1.126162	1.148686	1.171659	1.195093	1.218994	1.243374	1.268242	1.293607	1.319479	1.345868
Discount factor	1	0.909091	0.826446	0.751315	0.683013	0.620921	0.564474	0.513158	0.466507	0.424098	0.385543	0.350494	0.318631	0.289664	0.263331	0.239392
CAPEX (AUD)	5.32E+06															
Revenue (AUD/yr)	0	2189795	1951689	1739473	1550332	1381758	1231513	1097605	978257.9	871887.7	777083.5	692587.8	617279.6	550160.1	490338.8	437022.1
DCF (AUD)	-5.32E+06	2.19E+06	1.95E+06	1.74E+06	1.55E+06	1.38E+06	1.23E+06	1.10E+06	9.78E+05	8.72E+05	7.77E+05	6.93E+05	6.17E+05	5.50E+05	4.90E+05	4.37E+05
NPV	1.12E+07															

Discussion

- Hybrid Power Plant is an evolving technology
- Many open research questions
- Industries – ‘wait and watch’ policy for first movers
- Value quantification is still a open question but looks optimistic with fast declining costs of solar and storage
- Value is definitely beyond LCoE (peak power plants, round-the-clock PP, grid services)
- Hypothesis- Value may be much enhanced with sector coupling

All DTU publications on HPP: https://files.dtu.dk/u/1ZkU87OZFLDHmRTz/HPP%20DTU%20Publications?l

Appendix

Definitions and concept of HPP

- ESIG
  - **Co-Located Resource**: Multiple technologies at a common point of interconnection and participating as separate resources
  - **Hybrid Resource**: A combination of multiple technologies that are physically and electronically controlled by the plant's owner/operator and participating as a single resource
- Wind Europe in Position paper, 2019
  - **Hybrid Power Plant**: Power-generating facility that converts primary energy into electrical energy and which consists of more than one power-generating modules connected to a network at one connection point.

Definitions and concept of HPP

- ESB Networks, EirGrid, Northern Ireland Electricity Networks, System Operator Northern Ireland and the Grid Code Panel

  - A **Hybrid Site** to be any project that has multiple generating units or power generating modules which utilise multiple primary energy sources or technology types in generating/storing electricity and are electrically connected behind a single defined Connection Point to a licensed System Operator.

  - A **Hybrid Unit** is a single generating unit or power generating module which utilises multiple primary energy sources or technology types in generating/storing electricity and are electrically connected behind a single defined Connection Point to a licensed System Operator.