Optimization of joint operation of fast and slow storage

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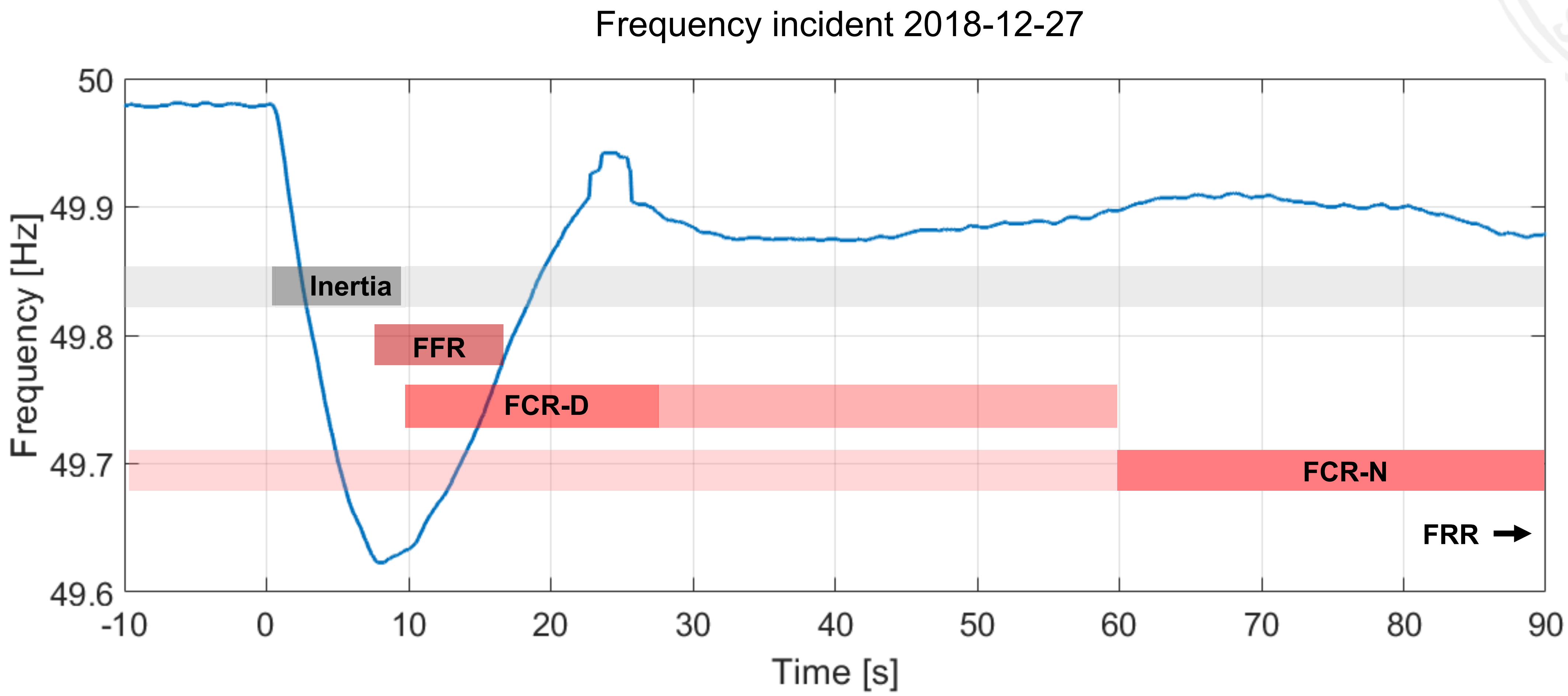

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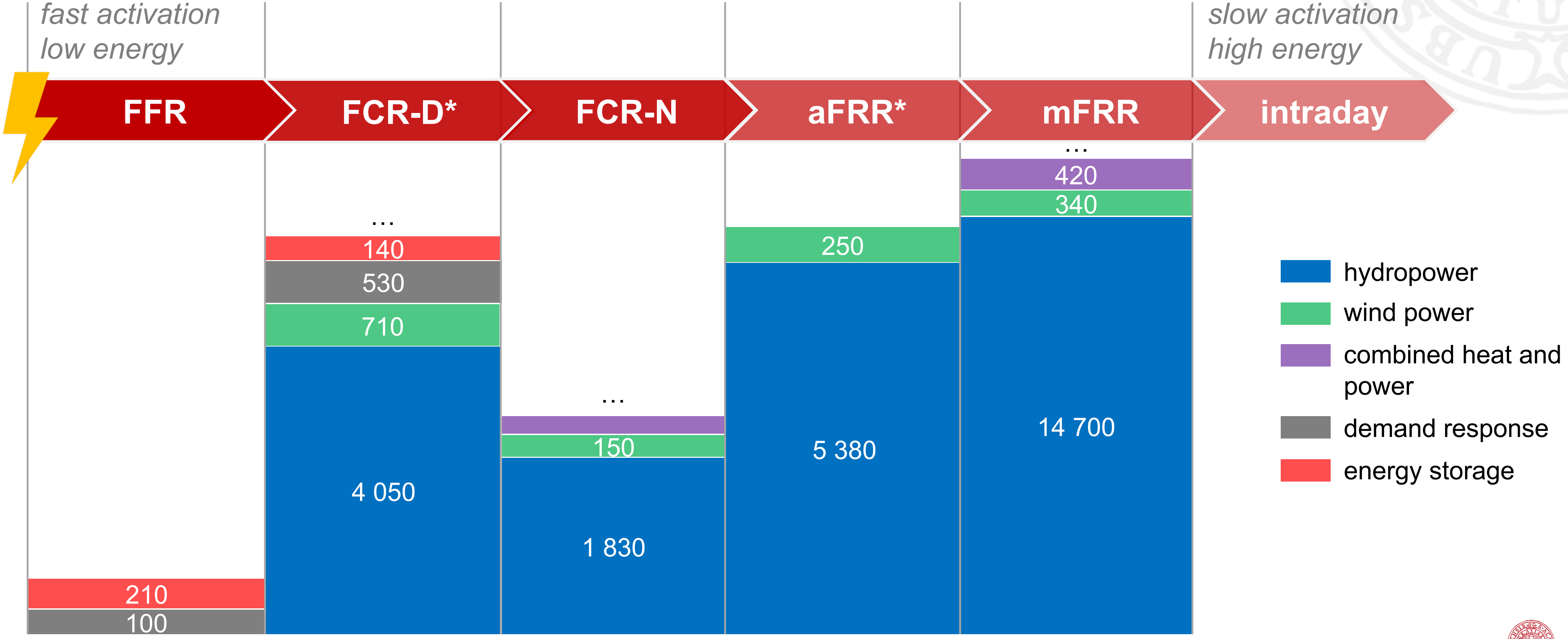
Prequalified frequency reserve capacity in Sweden



* includes both “up” and “down” reserves
source: Svenska kraftnät, data from 2024-04-01

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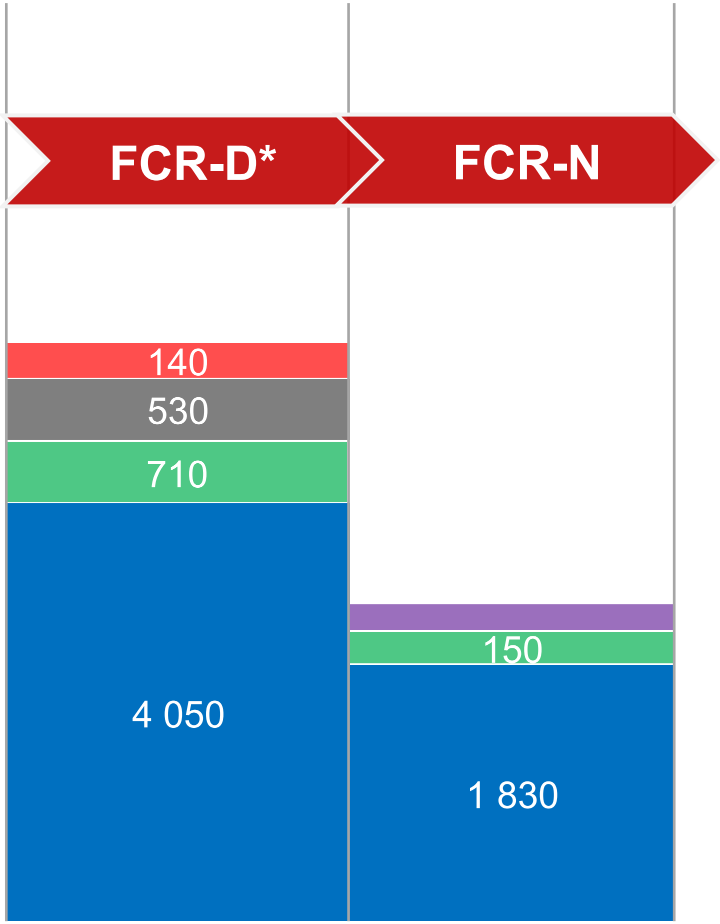
Prequalified frequency reserve capacity in Sweden



- New technical requirements entered into force in September 2023
- Hydropower currently responsible for 80% of FCR capacity
  - New speed requirements are an issue
- New technologies entering the markets
  - Continuous and more energy intense provision is creating difficulties

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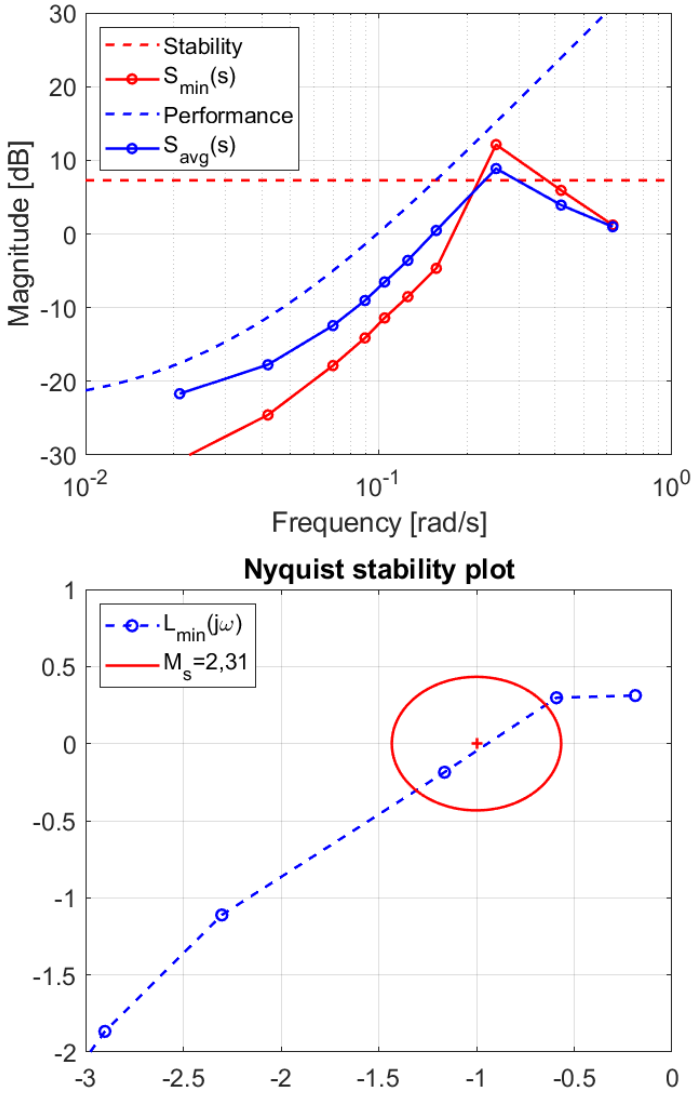
Let’s do an investment pre-study

FCR-N

Unit: Kaplan turbine
Nominal power: 24 MW
Nominal head: 23 m
FCR-N prequalification: 2,4 MW
FCR hours: 1 200 per year*
Projected income: 1 200 h x 56 €/MW** x 2,4 MW
= **161 280 € / year**

- New FCR-N requirement test is failed – no ability to continue to sell FCR-N



* assumed value
** average FCR-N price between 2021-2023, source: Svenska kraftnät

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FCR-N

- **Case 0:** Do nothing
- **Case 1:** Upgrade hydropower unit
- **Case 2:** Install a stand-alone energy storage system
- **Case 3:** Install a hybrid system with energy storage

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Case 0

- No investment is taken and the FCR-N provision is lost
- Cost:
  0 €/year
- Cashflow:
  0 €/year

Case 1 Upgrade hydropower unit

- The necessary performance upgrades for the hydropower unit are implemented
- Wide variety of scenarios depending on the improvement, some unit cannot achieve required performance
- Cost:
  ranging from several 10k up to several million €
- Cashflow:
  ???

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Case 2 Stand-alone storage system

- Installation of a stand-alone battery energy storage system with the same FCR-N capacity
- Required size*:
  P_s = 1,34 x 2,4 = 3,2 MW
  E_s = 2 x 2,4 = 4,8 MWh
- Expected lifetime[1]: 10 years
- Life-cycle cost[2]: 341 680 €/year
- Cashflow:
  -180 400 €/year

$$C = (c_p P_s + c_e E_s)\frac{i(1+i)^L}{(1+i)^L - 1} + c_f P_s$$

Table 3: Cost and lifetime parameters of storage technologies, taken from [13].

Parameter	Description	BESS	FW	SC
c_p	Capital cost per unit of power [€/kW]	257	624	315
c_e	Capital cost per unit of energy [€/kWh]	275	6 186	29 250
c_f	Fixed maintenance cost [€/kW-year]	7	5	1
μ	Round-trip efficiency [pu]	0.86	0.86	0.92
DoD	Depth of discharge [pu]	0.8	0.8	0.8
N_c	Number of full cycles	3 500	200 000	1 000 000
L_c	Calendar lifetime [years]	10	20	16

* interpretation of new FCR requirements, source: Svenska kraftnät
[1] Mongird et al.: An evaluation of energy storage cost and performance characteristics, Energies, 13, 2020
[2] Diaz-Gonzalez et al.: Energy storage in Power Systems, John Wiley & Sons, 2016

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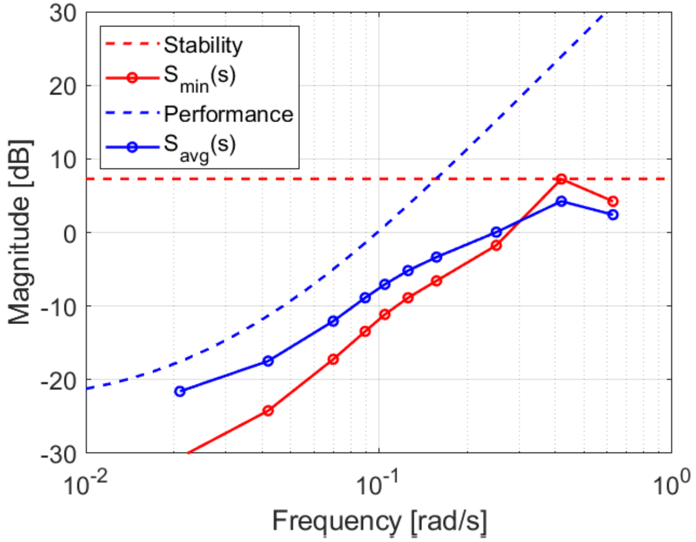
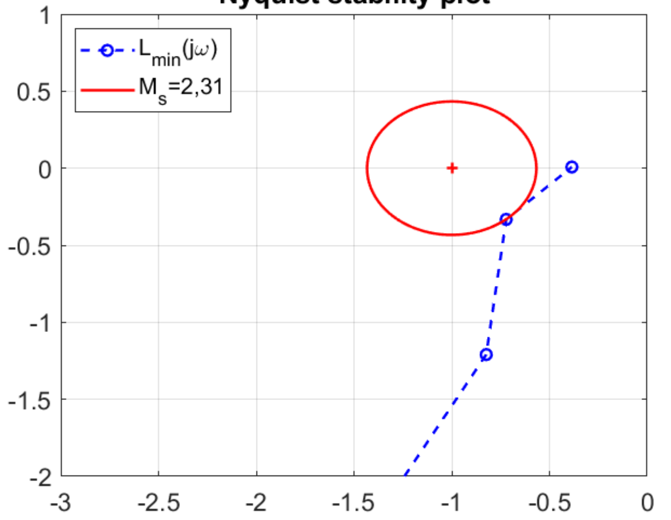
Case 3 Hybrid system with energy storage

- Enhancement of the hydropower FCR-N response with an energy storage system
- The method for the storage system control design and required size published in [3]
- Required size:
  P_s = 0,47 MW
  E_s = 0,01 MWh
- Expected lifetime: 1 year
- Life-cycle cost: 134 600 €/year
- Cashflow: **26 680 €/year**



Nyquist stability plot



[3] Laban, Norrlund, Lundin: Storage system design for improved primary frequency control from hydropower units, IEEE Transactions on Energy Conversion, 38, 2023

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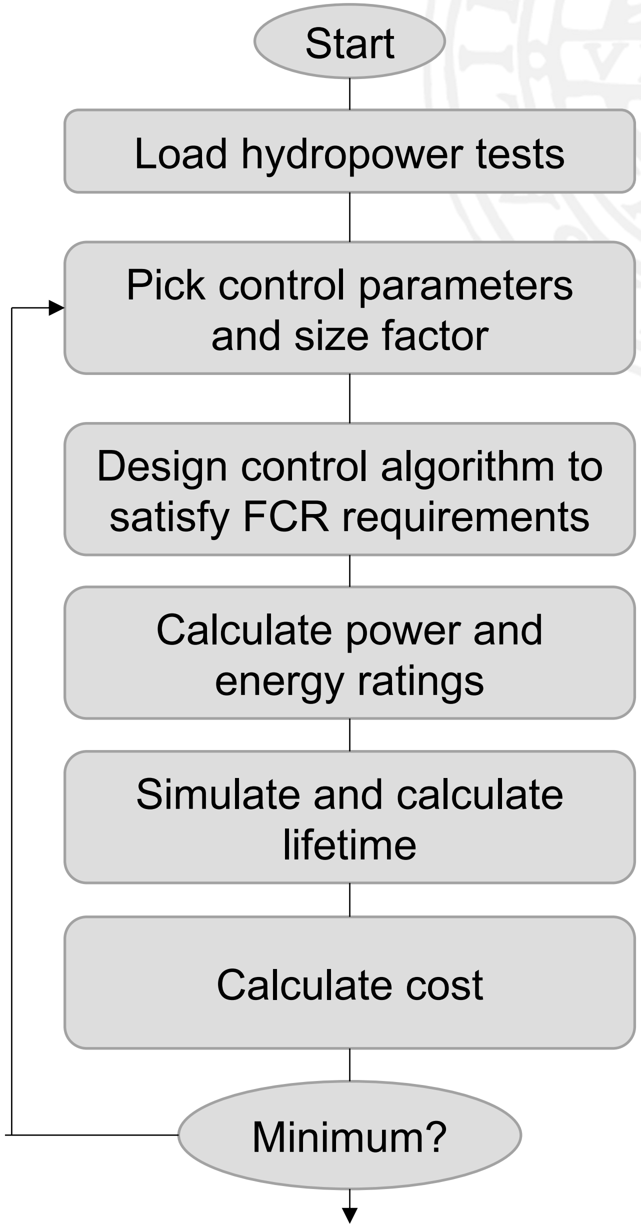
Case 3.1 Optimized hybrid system with energy storage

- The storage size is an optimization variable together with control parameters from [3]
- Consider: BESS, flywheels, supercapacitors
- Optimal size of **supercapacitor**:
  P_s = 0,28 MW
  E_s = 0,001 MWh
- Expected lifetime: 7 years
- Life-cycle cost: 8 400 €/year
- Cashflow: **152 800 €/year**



[3] Laban, Norrlund, Lundin: Storage system design for improved primary frequency control from hydropower units, IEEE Transactions on Energy Conversion, 38, 2023

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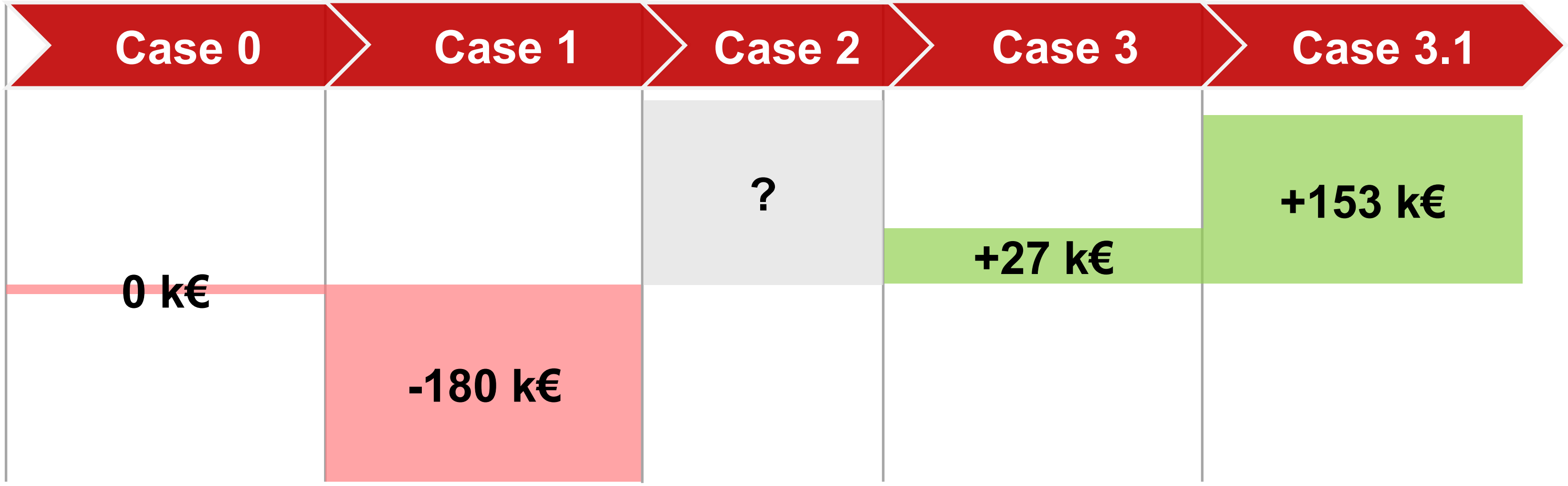
Conclusion

- The developed hybrid system design and optimization methods provide a cost-effective alternative to improve hydropower FCR response
- The hydropower + storage combinations plays to the strengths of both individual technologies
- Expanding the benefits: modifying the hydropower response to reduce mechanical wear and tear and stacking other services from the hybrid system



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Thank you!

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