

MARKET-ORIENTED DISPATCH STRATEGIES FOR WIND-STORAGE CONFIGURATIONS USING DAY-AHEAD FORECASTING SIGNALS



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4th International
Hybrid Power Systems Workshop

22 - 23 May 2019

Crete, Greece



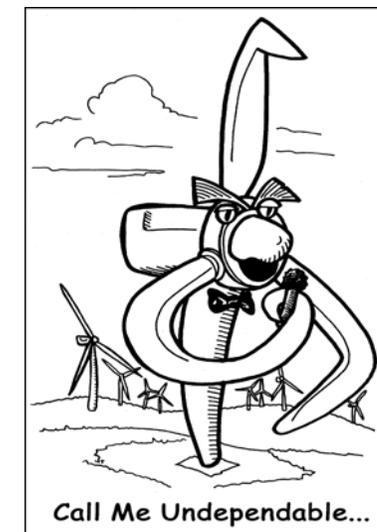
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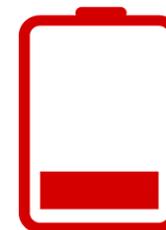
energynautics
solutions for sustainable development

- INTRODUCTION
- PROBLEM POSITION
- METHODOLOGY
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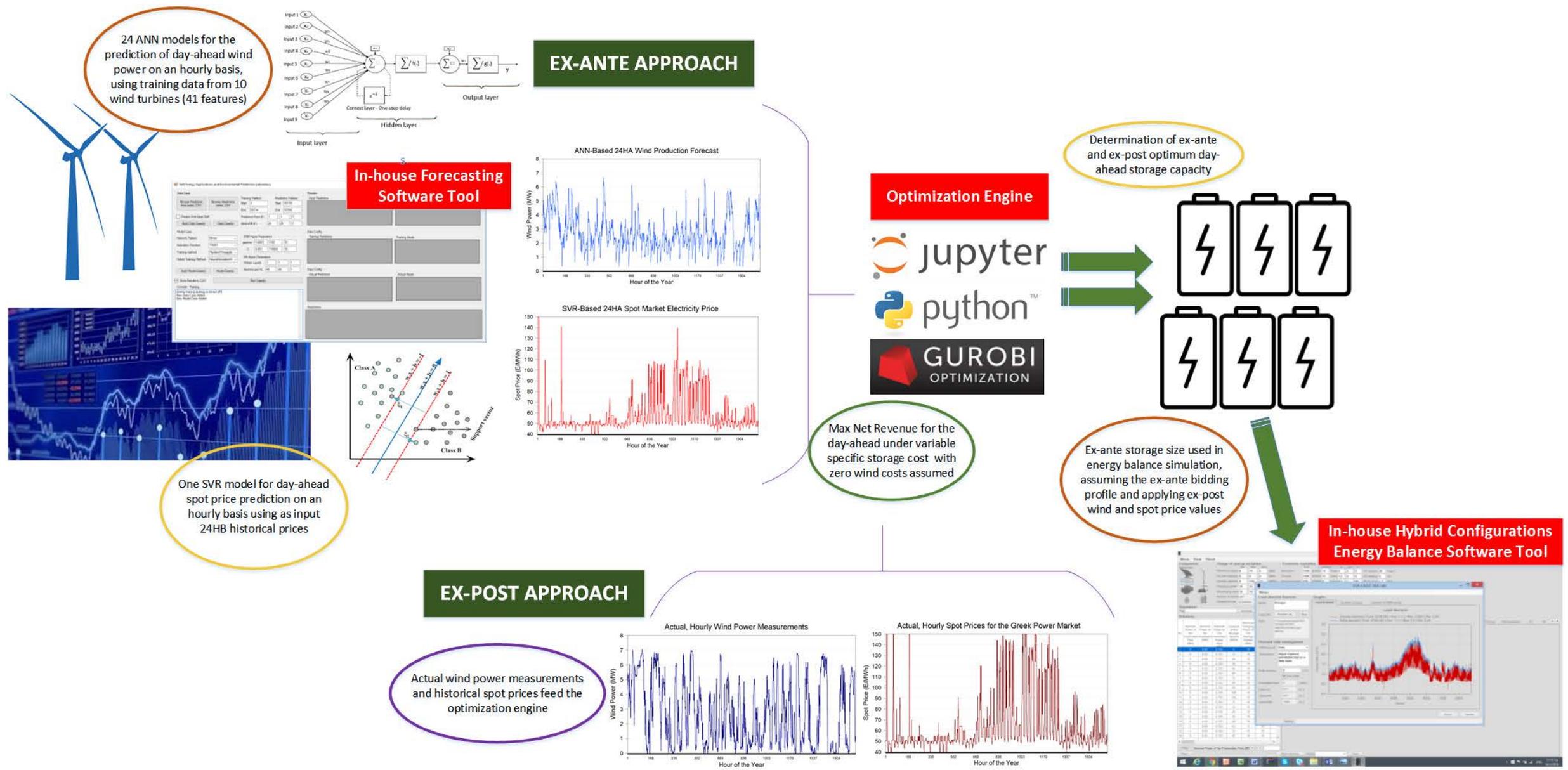
- **Stochastic character** of wind power generation entails **limitations on the shares of wind energy** in electricity systems and **challenges further market integration**
- New wind parks are called to cope with **more dynamic pricing schemes**, with the traditional feed-in-tariffs **gradually phasing out**
- **Concerns and local opposition** to the further expansion of the wind energy sector, even in progressed energy markets
- Increased interest for **advanced bidding strategies** that capture the elements of **storage and forecasting**



- **Dynamic pricing** on the basis of spot market prices is assumed
- Evaluation of a **price-following dispatch strategy** for **wind-storage** configurations with the use of **day-ahead forecasting results** and **ex-post, historical data** for **wind energy production** and **spot electricity prices**
- Forecasting results generated through the training and validation of **Artificial Neural Networks (ANNs)** and **Support Vector Regression (SVR)** models
- **Optimum bidding offers** and **storage size** determined in relation to **storage costs' variation**

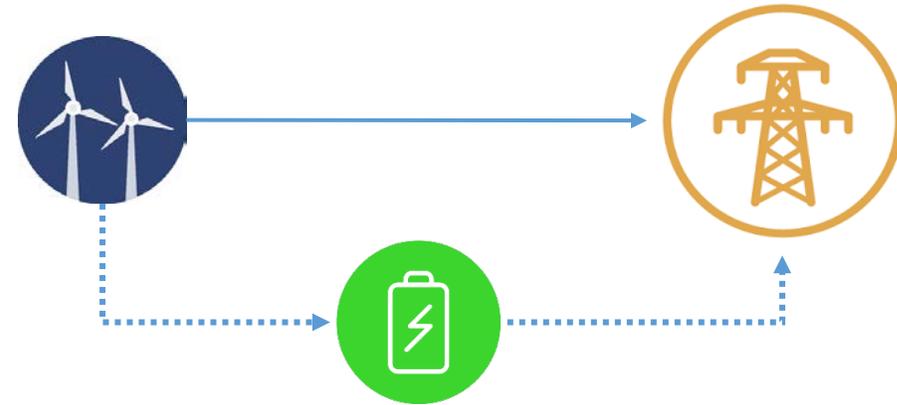


Methodology



Methodology

- **Ex-ante problem solution**, employing also forecasting algorithms in order to produce the respective **day-ahead profiles** for wind power generation and spot electricity prices
- **Ex-post also approach** considering **historical data** for wind energy production and spot electricity prices
- **Predicted / actual profiles** of wind power generation and spot electricity prices used to inform an **optimization engine**
- Maximization of **daily net revenues** with the optimizer generating the **respective optimum storage capacity** on a daily basis, including depreciation cost of storage



$$\text{Maximize} \left\{ \left\{ \sum_{i=1}^h (ESS^d_i \cdot Sp_i + WP^g_i \cdot Sp_i) \right\} - \frac{ESS_{cap} \cdot c_{ESS} \cdot h}{h_{life}} \right\} = NR$$

$$WP_i^g + ESS_i^c = WP_i^t$$

$$SOC_i = SOC_{i-1} + ESS_i^c \cdot \eta_c - ESS_i^d \cdot \eta_d^{-1}$$

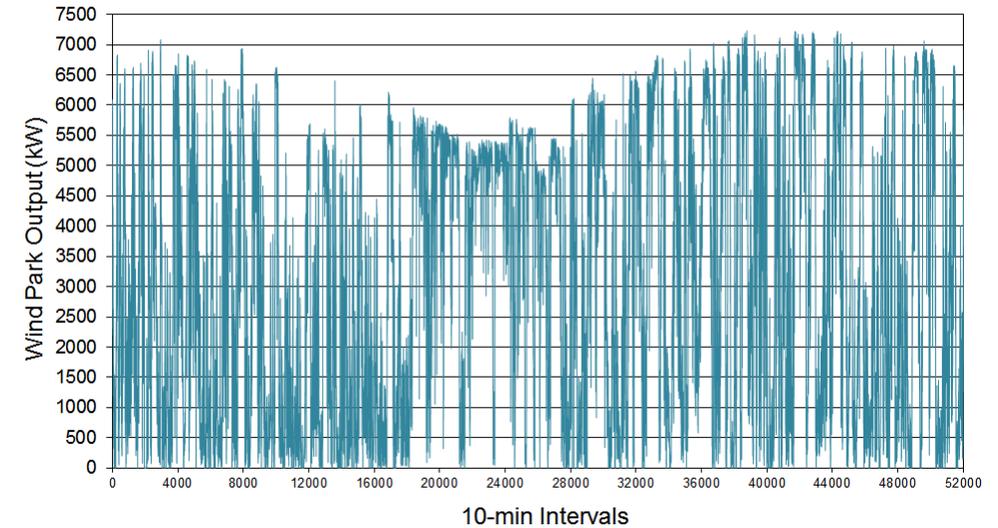
$$SOC_{\min} \leq SOC_i \leq ESS_{cap}$$

$$ESS^d_i; ESS^c_i \leq ESS_p$$

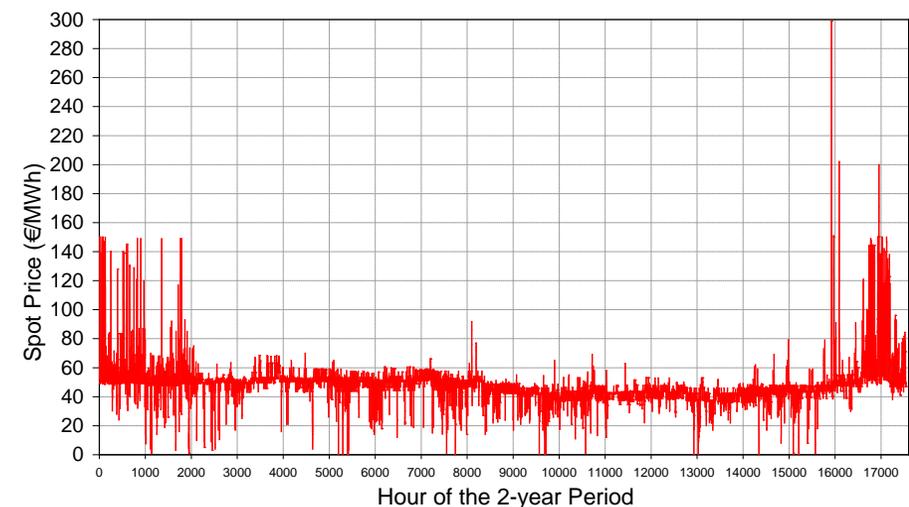
Case Study – Input Data

- Wind park examined located in the Greek mainland and employs a total of **10 wind turbines** of **750kW** each (Neg Micon NM44)
- Detailed, full-year dataset made available, including measurements of **actual wind energy production** and **ambient temperature**, as well as **wind speed and direction at hub height** for all 10 wind turbines
- Long-term average **wind speed** of the wind park estimated at **~9.3m/s**, which leads to an average **capacity factor** exceeding **38%**
- Historical **spot price time series** for the Greek power market

Wind Power Generation Data Series
for the 7.5MW Euboea Wind Park (2016)



Spot Electricity Prices for the Greek Power Market (2015-2016)



Case Study – Forecasting Techniques

- Different prediction horizons applied, i.e. from **1 to 24h ahead**, while for the training of the models a total of **41 features** were fed into the input layer
- Measurements for each of the 10 wind turbines, i.e. **wind speed, wind direction, power generation, ambient temperature** together with an indicator of time
- 7,152 hourly values used for the training of the models (**~80%**) and 1,632 for the models' validation (**~20%**)
- **24 ANN models** for wind power using as input the “ t_0-1 , t_0-2 and t_0-3 ” values & a **single SVR model** for the case of spot prices using as input the “**t-24**” value

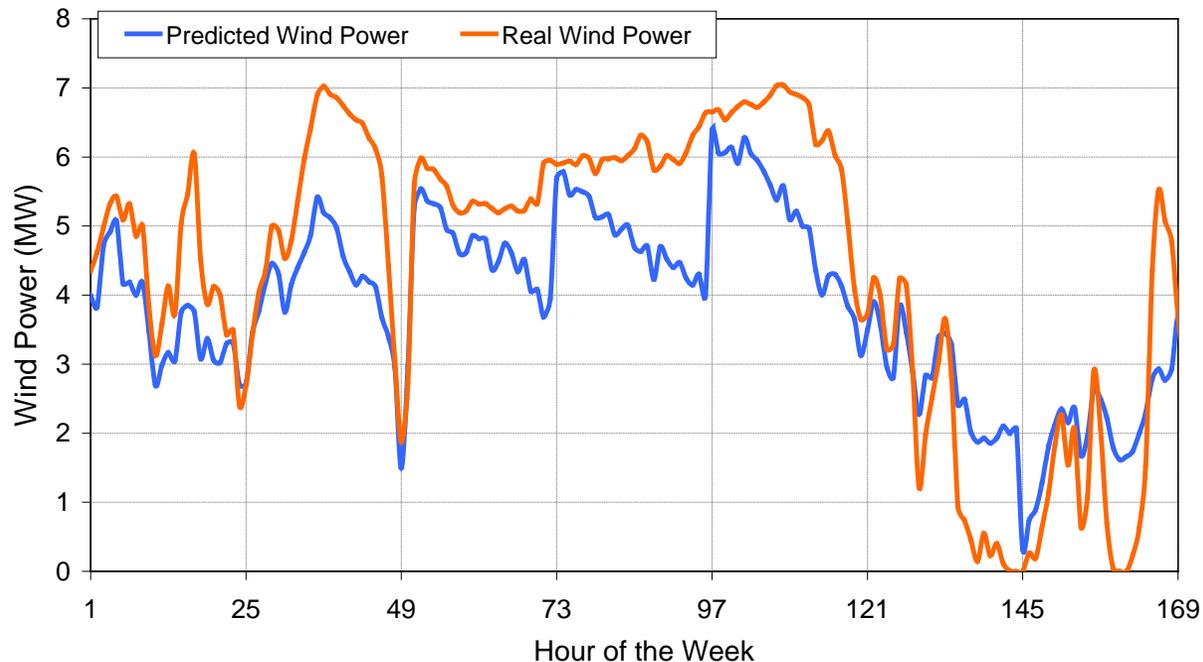
Property	Selected Options
Architecture	Elman
Training Method	Resilient propagation
Hidden Neurons	70
Activation Function	tanh

Method	Parameter	Index	1HA	6HA	12HA	24HA
ANN	Wind power	R ²	99.52%	94.84%	88.94%	87.32%
		IA	99.71%	95.32%	85.85%	64.99%
			24HA			
SVR	Spot price	R ²	99.70%			
		IA	92.59%			

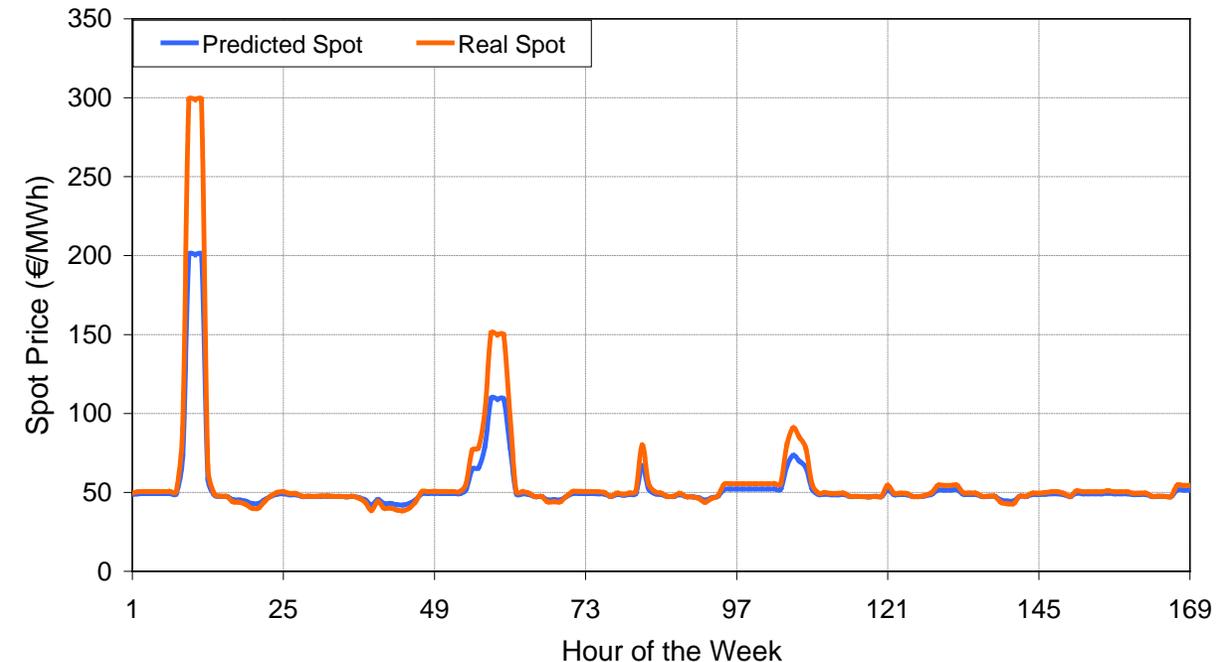
Application Results – Forecasting

- ANNs **mainly underestimate** the actual wind power generation, with the models' performance decaying for > 6 hours ahead
- Forecasted CF_f equal to **35.9%** vs $CF_r=36.4\%$
- Due to the cyclic pattern of the spot price profile, **SVR faces no observable decay**
- Average spot price $Sp_{av-r}=64.88\text{€/MWh}$ for the actual values and $Sp_{av-f}=57.76\text{€/MWh}$

Predicted Vs Actual Wind Power Measurements_1-24HA



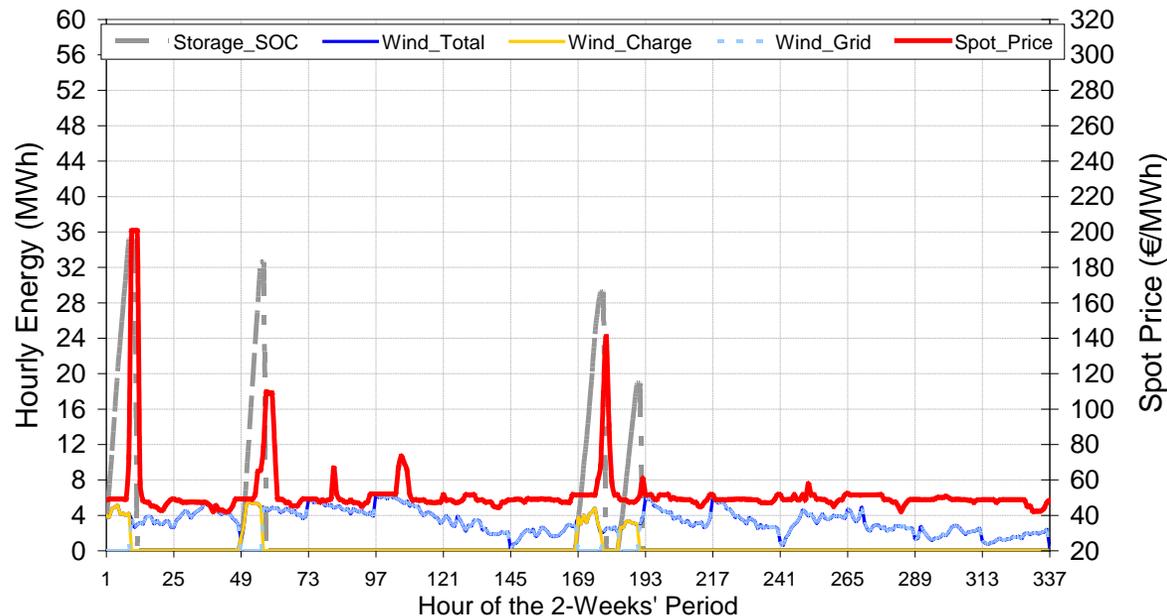
Predicted Vs Actual Spot Electricity Price_1-24HA



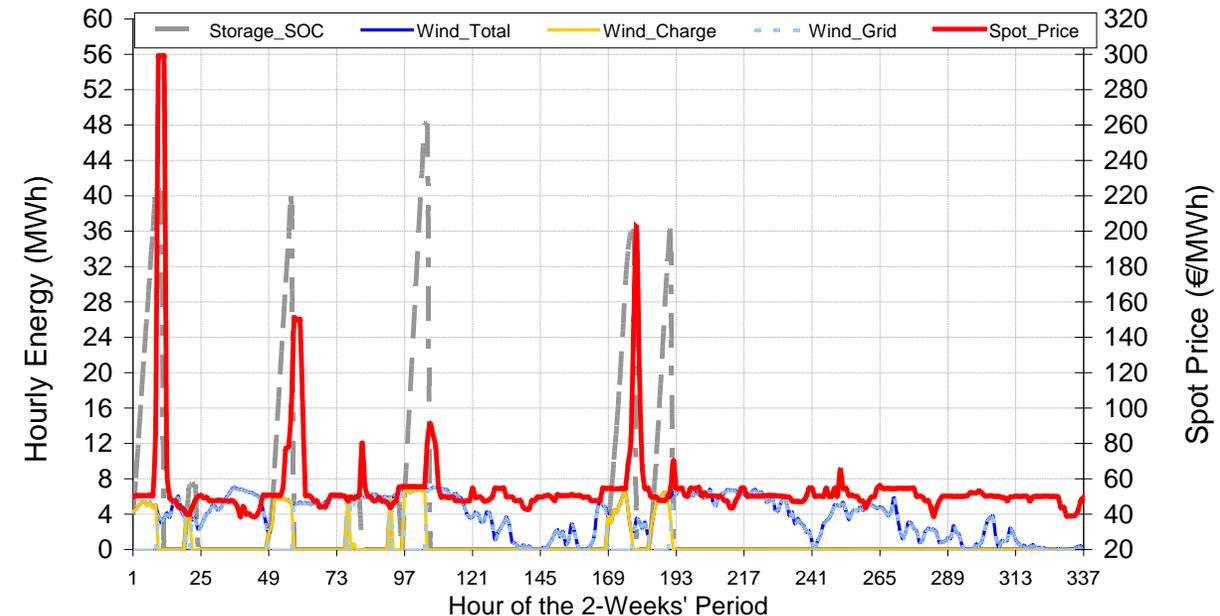
Application Results – Optimum Bidding Storage

- In view of considerable **increase in the spot price**, the solver introduces the **appropriate storage capacity** which is set to fully cycle (charge and discharge) within the given day time window
- Forecasting models developed **underestimate the actual wind power generation and spot prices** for the examined two-weeks' period → the optimum daily storage capacity **becomes higher** in the case of applying the **ex-post approach**
- Simulation is repeated for different **specific storage cost scenarios (50-250€/kWh) @1C**

Energy Balance Analysis for the Day-Ahead Optimum Storage Capacity $c_{ESS}=100\text{€/kWh}$ **Ex-Ante Bidding Approach**



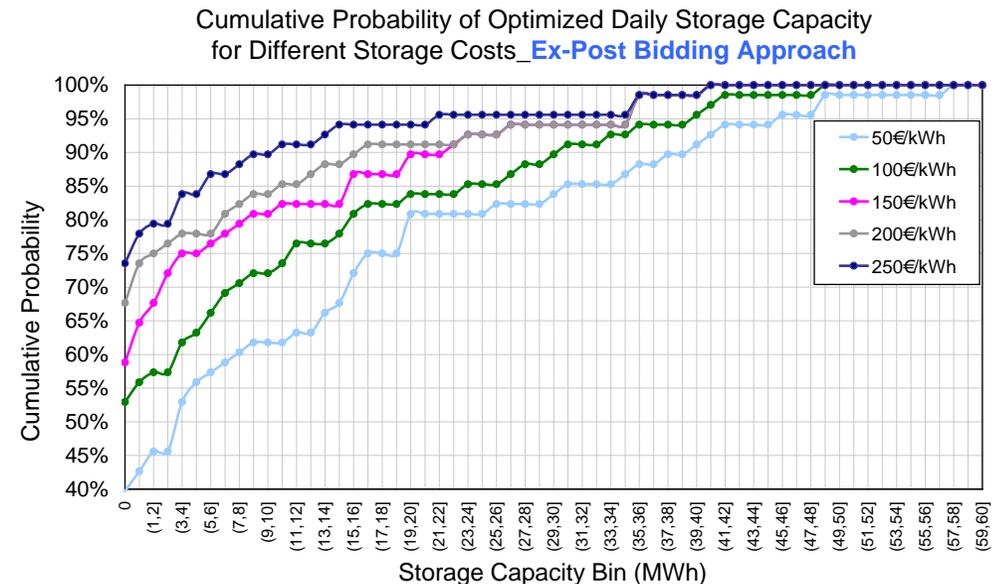
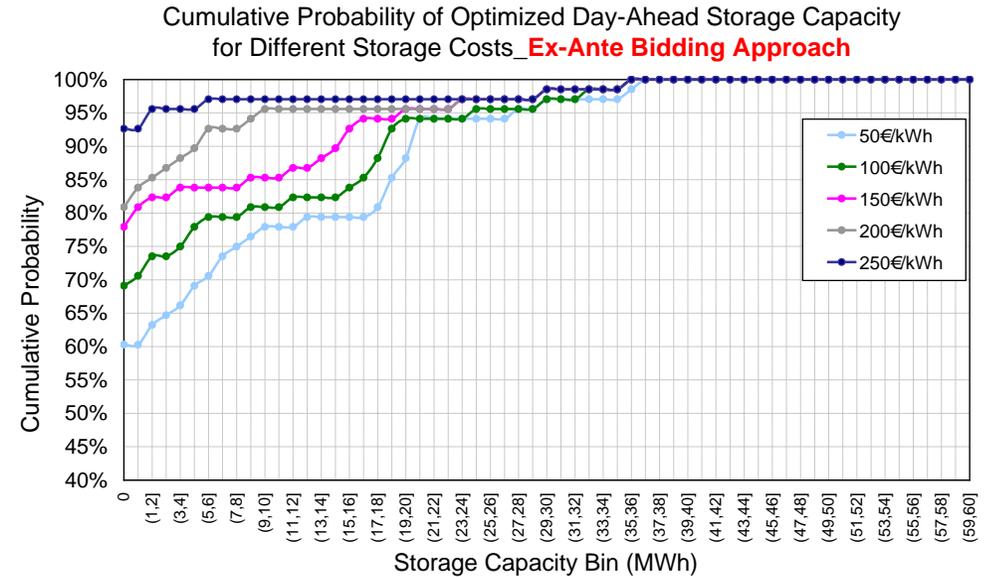
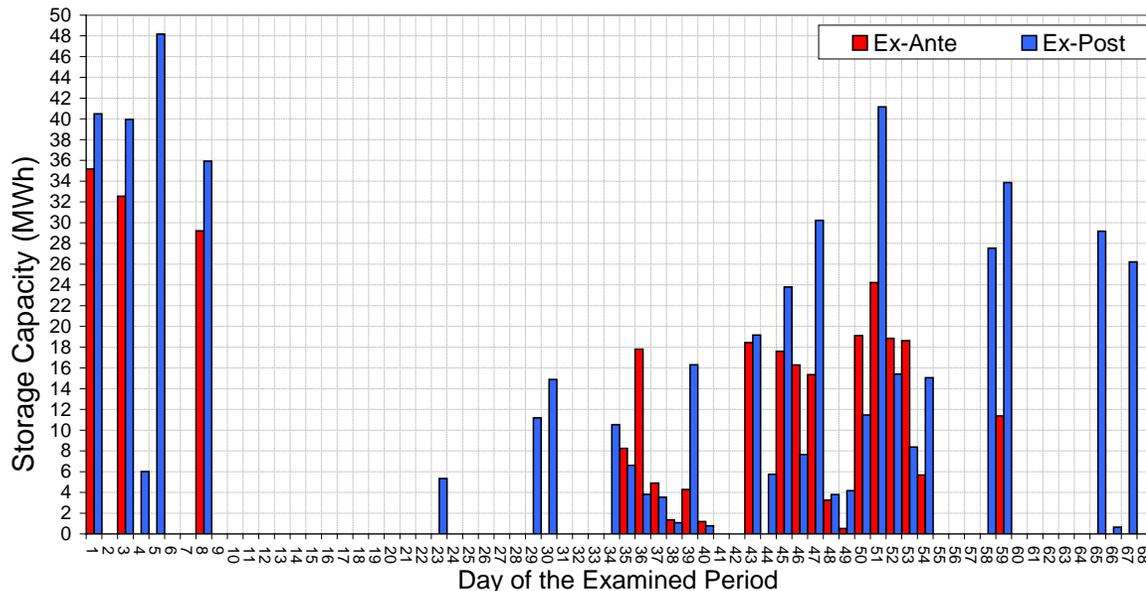
Energy Balance Analysis for the Daily-Basis Optimum Storage Capacity $c_{ESS}=100\text{€/kWh}$ **Ex-Post Bidding Approach**



Application Results – Optimum Bidding Storage

- Although for most days the **ex-post approach produces higher storage capacity**, there are instances where the **inverse behavior is illustrated** → overestimation of the actual wind power generation
- For a considerable number of days, **no storage capacity is needed** → could leasing of variable storage capacity become an option?

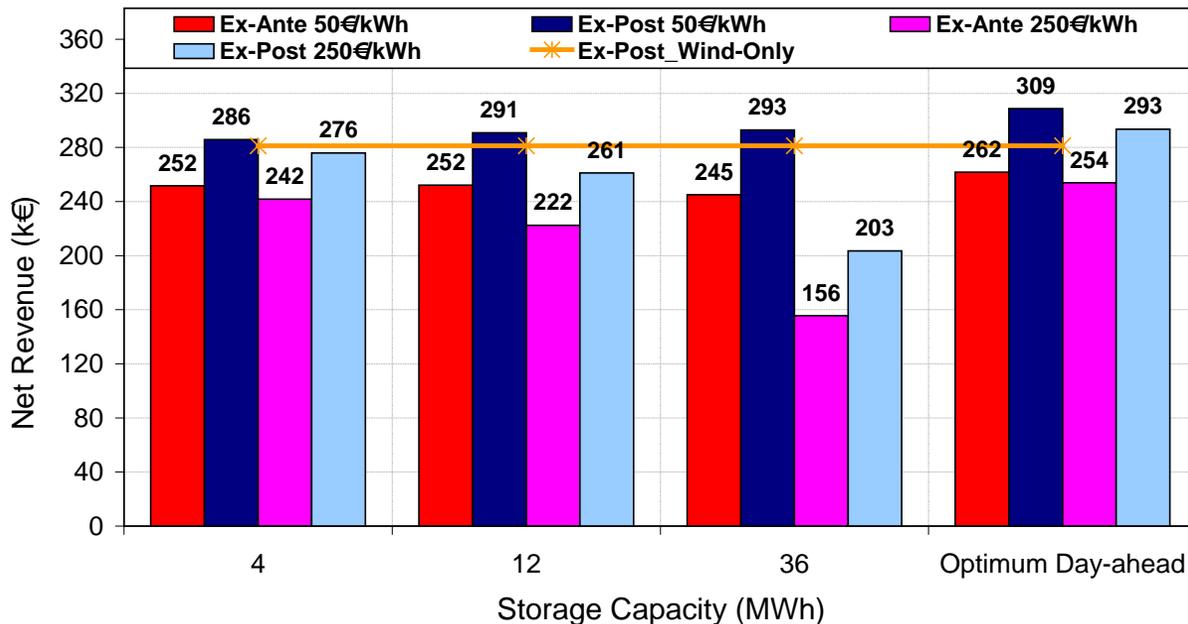
Comparison between the Ex-Ante & the Ex-Post Optimum Day-Ahead / Daily-Basis Storage Capacity $c_{ESS}=100\text{€/kWh}$



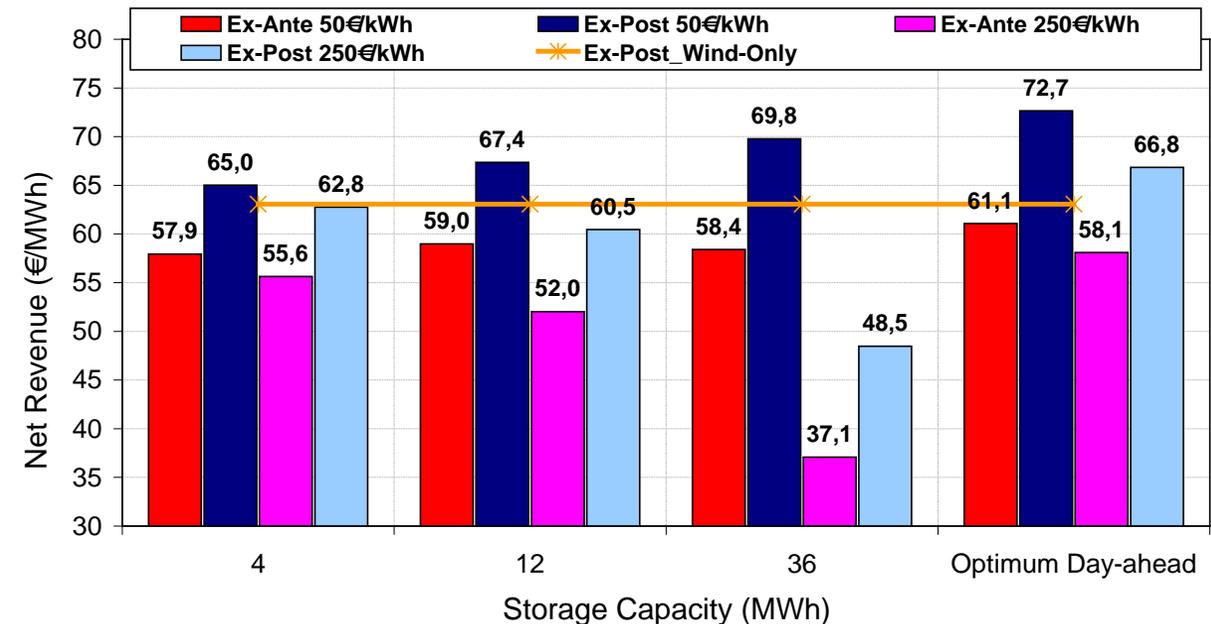
Application Results – Net Revenue

- **Appreciable difference** between the net revenue of **optimum, day-ahead, variable storage** and **fixed storage** options, which increases with the increase of fixed storage capacity
- Risk of imperfect prognosis incorporated in the ex-ante approach yields **considerably lower revenue expectations** and **discourages the adoption of higher storage capacity**, even in the case of low storage costs
- **High storage costs** (250€/kWh) suggest net revenue that is **lower than the wind-only case** for all fixed storage capacities examined, with the opposite occurring for the ex-post, optimized daily storage scenario

Comparison of **Total Net Revenue** for Fixed & Variable Storage Capacity Configurations



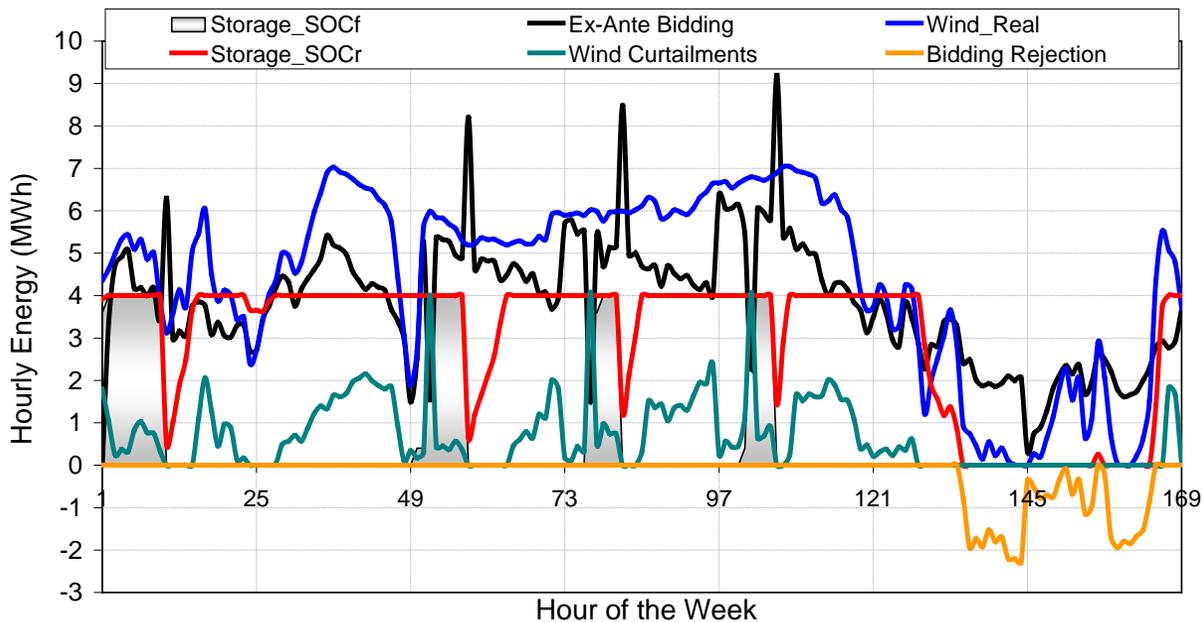
Comparison of **Specific Net Revenue** for Fixed & Variable Storage Capacity Configurations



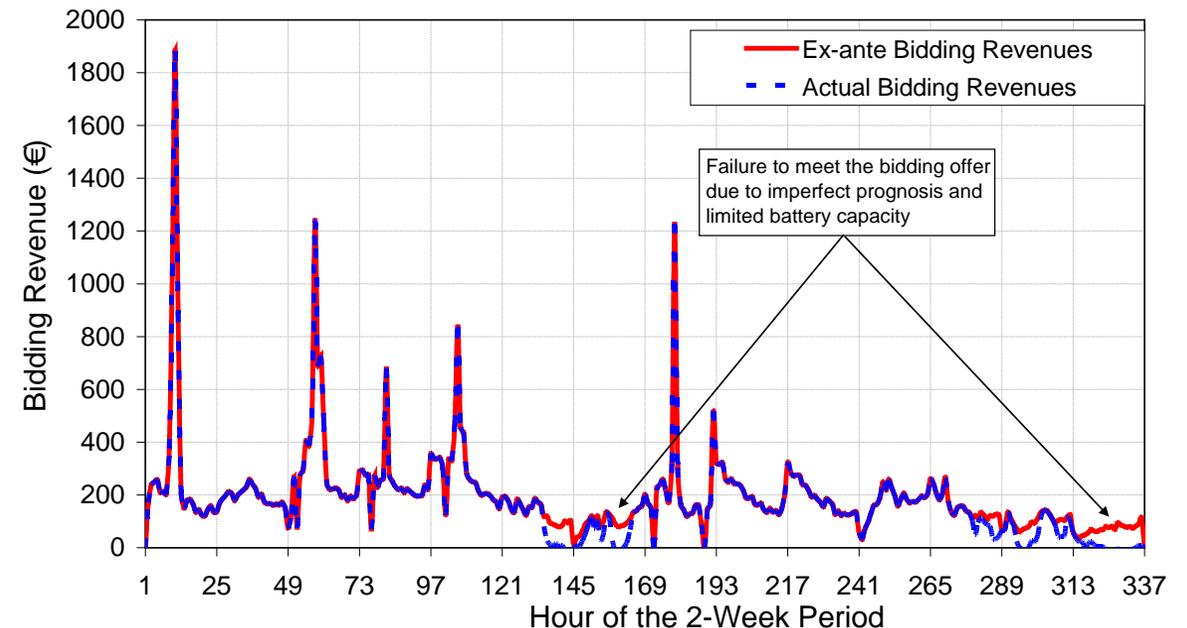
Application Results – Ex-Ante vs Real

- Letting the daily, **ex-ante generated bidding profile** of a given wind-storage configuration to encounter the **actual wind power and spot price conditions** → impact of imperfect prognosis is evaluated
- The dispatch profile adopted corresponds to the **optimized bidding offers** obtained from the optimizer under the **ex-ante approach**
- The **real (ex-post) wind power generation and spot price data** are used in order to compare the **resulting net revenue** of the two approaches

Application of the **Ex-Ante Bidding Profile** for the **Fixed ESS=4MWh**
Configuration under Actual Operation Conditions $c_{ESS}=100\text{€/kWh}$



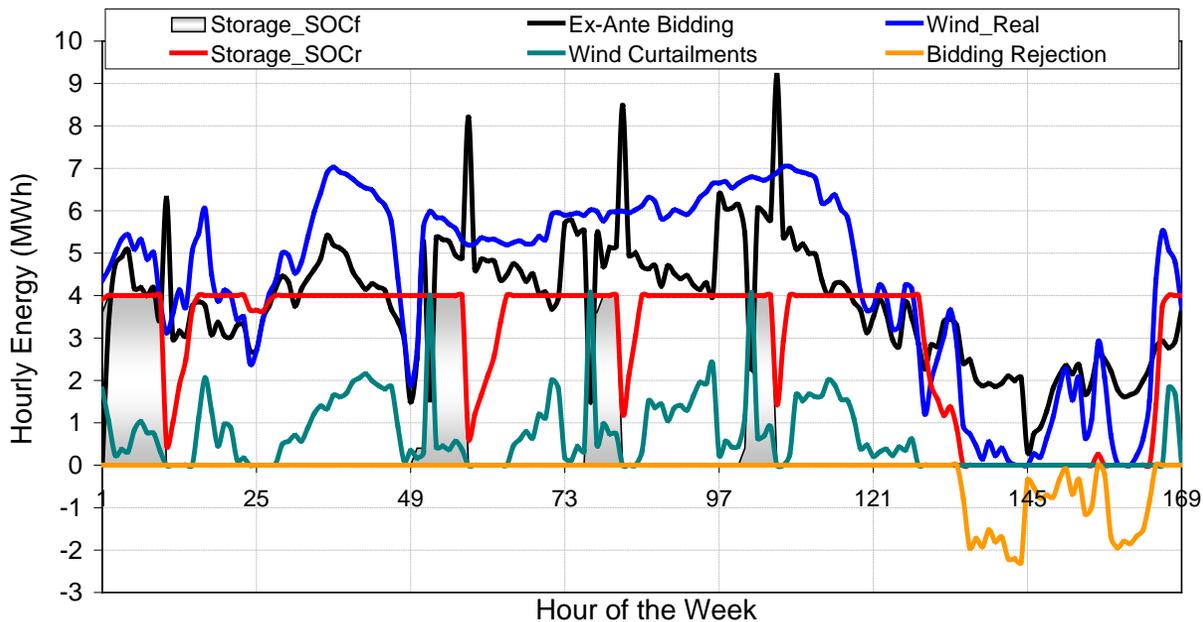
Comparison of the Estimated (Ex-ante) and the Actual Bidding Revenue for **Fixed ESS=4MWh** & $c_{ESS}=100\text{€/kWh}$



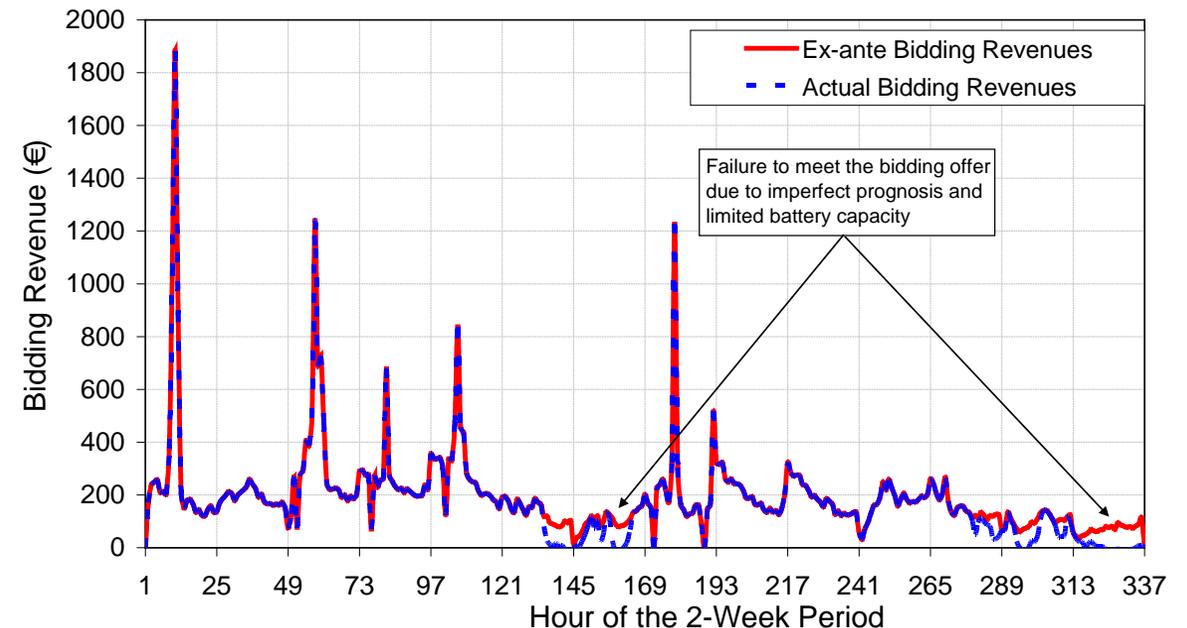
Application Results – Ex-Ante vs Real

- **Different cycling** of the storage component due to the **different wind profile adopted** (predicted vs real wind power generation)
- Generation of **excess wind energy** (or curtailments), as well as instances during which the day-ahead (ex-ante generated) **bidding offer is eventually not met** → a **penalty is triggered**
- Net revenue overestimated by **~18%** on the basis of the ex-ante approach; bidding rejections equal to **17%** of the **ex-ante bidding offers** and **wind energy excess** amounts to **15%** of **actual wind power generation**

Application of the **Ex-Ante Bidding Profile** for the **Fixed ESS=4MWh**
Configuration under Actual Operation Conditions $c_{ESS}=100\text{€/kWh}$



Comparison of the Estimated (Ex-ante) and the Actual Bidding Revenue for **Fixed ESS=4MWh** & $c_{ESS}=100\text{€/kWh}$



- The **spot price spread** of the Greek market discourages the use of wind-tied storage **for costs exceeding 100-150€/kWh**. This seems to completely rule out batteries for the time being
- Adoption of an ex-ante, 24 hours-ahead approach for the development of bidding offers introduces **considerable risk, not necessarily hedged by an ex-ante optimized storage component**, even at the daily interval
- Such risk needs to be quantified to allow for **rational storage oversizing**, evaluating also the **trade-off with the penalty cost** for bidding rejection
- Dispatch windows within the day, e.g. **intra-day or quarter-day dispatching**, may ameliorate the impact of **imperfect forecasting**, allowing also **minimization of the required storage capacity** on the basis of more intense cycling, especially for wind power applications
- **Variable storage capacity** on a daily interval challenges the concept of **storage leasing**, especially in the case of large-scale storage infrastructure

Thank you for your Attention



Acknowledgment: This research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme «Human Resources Development, Education and Lifelong Learning» in the context of the project “Reinforcement of Postdoctoral Researchers” (MIS-5001552), implemented by the State Scholarships Foundation.