OESTER
Offshore energy storage

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Brief description:	Summary of initial sizing of energy storage systems for the OESTER project.

Offshore energy storage

OESTER Result 1.1

Operational performance optimization strategies per storage option

1st report

EXECUTIVE SUMMARY

This report summarizes findings from the OESTER project regarding the optimal sizing and dispatch of Energy Storage Systems (ESS) that charge exclusively from the co-located wind farm. The study evaluates how three different storage technologies can enhance system-level Key Performance Indicators (KPI) under projected 2035 market conditions. Wind production is obtained from project partner Vattenfall for a farm representative of *Hollandse Kust Zuid* for the weather year 2019. Day-ahead price for the simulated year 2035 are procured from analytics company *Montel*.

The methodology employs a simplified power flow model to determine the optimal dispatch strategy and ESS sizing (rated power and energy capacity) simultaneously. The optimization problem prescribes a given improvement in system-level KPI over the baseline wind farm (without storage) and aims to minimize the overall capital cost of the ESS.

A distinctive feature of this approach is the inclusion of curtailment power as a design variable within the optimization framework, subject to operational constraints such as grid congestion, overplanting, or negative price episodes. The optimal solution only captures the share of baseline curtailment needed to meet the prescribed KPI improvements.

The study demonstrates that the optimal storage size depends highly on specific cost parameters that define the trade-off between power and energy sizing. The three technologies considered achieve the same system-level KPI using vastly different configurations and exhibiting different dispatch behaviours.

Increasing the volume of exported energy by means of energy storage is found to be 4 to 5 times more capital intensive than increasing the Value-Weighted Energy (VWE) exported, making curtailment capture a difficult use case to justify for energy storage.

The relation between storage system size and related system-level benefits is highly dependent on the assumed day-ahead prices. In the projected 2035 scenario, price cannibalization is driven primarily by solar production rather than wind oversupply. The resulting high capture rate of the reference farm (97 %) limits the arbitrage opportunity available to co-located storage. Under these conditions, energy storage is at least 46 % less cost-effective than overplanting as a means of improving VWE.

No cost-effectiveness optimum exists across the storage sizing range: for all technologies, each increment in installed capacity yields diminishing returns. A practical design envelope is defined between a minimum of +5 % VWE improvement threshold and an upper bound referenced to comparable commercial deployments. Within this envelope, VWE gains of +6 % to +8 % are achievable at moderate storage cost. Deployment-specific constraints, not addressed in this study, should be assessed before the size envelope is refined for each technology individually.

I. INTRODUCTION

A. OESTER context

OESTER [1] is a three-year initiative involving thirteen partners from the European offshore renewable energy sector, under the framework of Mission-driven Research, Development and Innovation (MOOI), by the Netherlands Enterprise Agency.

The core mission of the OESTER project is to mature, de-risk, and validate innovative offshore electricity storage solutions from technological, economic, environmental, and societal perspectives. The goal from the project is to deliver scalable solutions that can be deployed globally, supporting the rapid development of renewable energy systems. System flexibility across various time scales is being investigated in the project:

- Short-term storage: batteries integrated into wind turbine monopiles (*Verlume*)
- Medium-term storage: Hydro-Pneumatic Energy Storage (HPES) from *FLASC* and Underwater Pumped Hydro Storage (UPHS) from the *University of Groningen*, co-located within wind farms.
- Long-term storage: flexible pressurised alkaline electrolyser installed on offshore platforms directly connected to wind farms (*Battolyser Systems*)

B. Energy Storage Technologies

The key energy storage technologies, and their developer are listed below.

Verlume develops modular, scalable subsea battery systems. Within OESTER, the company is actively exploring the installation of stacked battery modules within the submerged section of offshore wind monopile foundations, distributing storage at each wind generator.

FLASC B.V. develops a Hydro-Pneumatic Energy Storage (HPES) system tailored for co-location with offshore wind, storing energy by pumping hydraulic fluid to compress a fixed volume of pre-compressed air. By leveraging the seawater as a natural heat sink, the technology achieves high round-trip efficiencies while offering a safe, battery-free alternative built on established offshore supply chains.

The Underwater Pumped Hydro Storage (UPHS) system investigated by the *University of Groningen* stores energy by pumping water into flexible bladders housed on the seabed. During discharge, the natural hydrostatic pressure of the surrounding water column, increasing with depth, drives the stored water back through artificially deep hydro-turbines to generate electricity.

C. General aim of Result 1.1

Result 1.1 focuses on optimally sizing Energy Storage Systems (ESS) for the technologies developed by OESTER project innovators. The goal is to maximize the system-level value of wind farms integrated with storage, referred to as *hybrid wind farms* in this document.

At this stage, the sizing process uses high-level techno-economic parameters provided by the technology developers, without full techno-economic optimization. The results of this sizing exercise will serve as input for the techno-economic optimization conducted in Result 7 of the project and which will account for higher fidelity cost and revenue estimations.

The objective of the present study is to determine an initial storage sizing for each of the three energy storage technologies (*Verlume*, *FLASC*, *UPHS system*), serving as a baseline for subsequent techno-economic analyses. In OESTER, a fourth technology is considered to investigate system-integration of offshore wind, an electrolyzer developed by *Battolyser Systems*. The sizing of the electrolyzer follows the same general framework but is the subject of a separate report.

For each use case, a given improvement on a specific Key Performance Indicator (KPI) is prescribed with respect to the *baseline wind farm* case, and the ESS sizing that enables that improvement for the minimum ESS Capital Expenditure (CAPEX) is identified. This study therefore establishes correlations between system-level performance improvement and minimum capital cost of ESS.

D. System value assumption

Even though the present study purposely stays away from revenue maximization to focus on system-level KPIs, day-ahead (DA) electricity prices were chosen to represent the system value of electricity at each time step (1 hour in the present case). Therefore, the contribution of a wind farm to system flexibility at time t is obtained by weighting its power output by the DA price. That contribution is higher when demand exceeds renewable generation, which is associated with high prices, and lower when renewable production can meet demand.

E. Definitions

1. Wind farm

We introduce here the terms used in the remainder of this document to identify various wind farms.

Reference wind farm: conventional wind farm, completely described in section II.B, used as a reference case for OESTER.

Baseline wind farm: conventional wind farm without energy storage, with a specific overplanting level that can be different from the *Reference wind farm*, but with the same export capacity. It serves as a non-storage benchmark for the *hybrid wind farm*.

Hybrid wind farm: wind farm integrated with co-located energy storage, treated as a single entity behind the transmission meter. It shares all characteristics with its corresponding *Baseline wind farm*, except for the addition of energy storage.

2. System-level KPIs

Below are defined various KPIs used through that document. The time step dt is one hour.

Annual Energy Exported $$AEE = \sum_t p_{net}(t).dt$$ [MWh]

The **Annual Energy Exported** (AEE) is the sum of all energy exports over a given year, where the net power p_{net} at the substation is assumed to be constant over a time step dt.

Day-Ahead Revenue $$Rev = \sum_t DA_{€}(t).p_{net}(t).dt$$ [€]

The Day-Ahead Revenue is the sum of all hourly revenues over a given year, where it is assumed that all hourly energy exports can be sold at the day-ahead price. Day-ahead prices are used in the present study as a proxy for marginal system demand and scarcity.

Capture Rate $$CR = \frac{Rev/AEE}{\overline{DA_{€}}}$$ [-]

The Capture Rate (CR) is the ratio of the average electricity price Rev/AEE received by the farm to the average price over the same period. As day-ahead prices are used as a proxy for marginal system value and scarcity of electricity, the Capture Rate quantifies how well the timing of an asset's energy delivery aligns with periods of high system value.

A CR above unity indicates that energy is preferentially delivered during periods of above-average system scarcity (above mean day-ahead price), thereby supporting system balance. Conversely, a CR below unity indicates that energy is primarily delivered when its value is relatively lower, contributing less system flexibility. **The CR therefore captures the quality of temporal alignment between farm supply and system-value, independent of the total volume of energy delivered.**

Value-Weighted Energy $$VWE = CR.AEE = \sum_t \frac{DA_{€}(t)}{\overline{DA_{€}}}.p_{net}(t).dt$$ [MWh]

The **Value-Weighted Energy** (VWE) is the product of the Capture Rate by the Annual Energy Exported. The VWE measures the system-relevant contribution of the wind farm by weighting its energy delivery at each time step by the corresponding normalized day-ahead price.

By incorporating both the volume (AEE) and the alignment with system value (CR), the VWE captures how much energy is supplied and how valuable that energy is from a system perspective. In other terms, it conveys both the quality and quantity of energy supplied from the system viewpoint. Therefore, the VWE is interpreted here as an energy-based indicator of system contribution.

3. Curtailment

A dedicated section in the Methodology, section II.D, details the way curtailment is accounted for as well as the approach undertaken for their estimation.

Curtailment involves intentionally reducing power output to accommodate different operational limitations. For a conventional wind farm, production and export are correlated, so the farm manages these constraints by adjusting its power generation at the rotor, which is the only control mechanism available.

In contrast, for a *hybrid wind farm*, the addition of an integrated ESS de-correlates production and export. This means that operating limitations must be distinguished based on whether they relate to production (upstream of the ESS) or export (downstream of the ESS), as those would not entail an identical response from the *hybrid wind farm*. The nomenclature that we adopt distinguishes curtailment based on the source of the constraint that causes it.

- Production Curtailment: the deliberate reduction of a *hybrid wind farm* power production to comply with internal constraints.
- Export Curtailment: the deliberate reduction of the power export of a *hybrid wind farm*, regardless of its technical capacity to export more, to comply with external constraints.

Based on that definition, it should be noted cause and consequences differ, such that an “export curtailment” can relate to a reduction in power production. For instance, for a *hybrid wind farm*, if wind production exceeds the available export capacity, the ESS can capture a fraction of the power production that would otherwise be curtailed. However, a reduction in wind production must occur to bring the remaining difference to zero, even though that curtailment would be accounted for as an export curtailment.

Production Curtailment

As it concerns constraints upstream of the ESS, that curtailment cannot be captured and is therefore not a specific focus of the present study, albeit accounted for. The following components of production curtailment are accounted for.

1. Operations and maintenance (O&M). It is a production curtailment that applies to the raw wind production timeseries and applies before any other. We assumed that a given un-availability level is distributed randomly throughout the year in such a way that it remains constant for all cases studied here. See section
2. Avian. Similar in approach to the above O&M curtailment, albeit with different statistical inputs. O&M and avian curtailment are not related to any ESS sizing and dispatch strategy and as such are accounted for before performing the study cases and then not reported as the results

Export Curtailment

In contrast with a conventional wind farm, the ESS can reduce overall export curtailment by capturing power that otherwise would need to be curtailed. That reduction is therefore a key result of the present study s is reported for along the various components below.

1. Economic. It is assumed that the wind farm, either conventional or hybrid, has an incentive to stop its export during negative price hours. This is in line with the latest rules in Europe [2], which stipulate that EU members should not encourage renewable generation during negative prices. Some room for interpretation is left to implementing countries, we apply it

strictly by assuming that no export happens during negative price hours, and that any power curtailed during such episodes are accounted for as economic curtailment.

2. **Overplanting.** During episodes when production, eventually adding the battery discharge, exceeds the nominal export power capacity, all curtailed power is accounted for as overplanting curtailment.
3. **Congestion.** During episodes when production, eventually adding the battery discharge, exceeds the derated export power capacity, which is a function of inland grid congestion, all curtailed power is accounted for as congestion curtailment.

The above constraints and related curtailment are not mutually exclusive, as all three can happen simultaneously. To avoid double accounting, curtailed power components are computed following the approach detailed in section II.D.5.

F. Storage sizing cases

In collaboration with OESTER partners, the two following use cases have been identified as being particularly relevant regarding the eventual system-value benefit that storage can bring.

The first, called ***Time Shifting,*** aims to enable a better alignment between wind farm exports and system-demand, such that storage can increase the flexibility that wind brings to the system. For that use case, the *Value Weighted Energy* (see section KPI) is used as the primary requirement metric for sizing. To get a grasp of what a given increase in VWE entails, it should be noted that it scales proportionally to the day-ahead revenues.

Increases in VWE relative to a *baseline wind farm* are prescribed for the *hybrid wind farm*, and the storage system is sized to achieve the minimum CAPEX while meeting that requirement. In other words, for a given VWE increase, the sizing process determines the minimum-CAPEX storage capacity that enables it, for each of the three technologies considered in this project.

The second use case, called ***Increase Export***, aims to increase the Annual Energy Exported (see section KPI) compared to a *baseline wind farm*, which is equivalent to capturing the energy that is otherwise curtailed. This occurs in moments where the farm could technically produce power, but production is reduced or stopped, either due to overplanting or grid congestion (see section I.E.3). Identical to the above use case, the AEE is used here as the primary requirement metric for sizing.

Increases in AEE relative to a *baseline wind farm* are prescribed for the *hybrid wind farm*, and the storage system is sized to achieve the minimum CAPEX while meeting that requirement. In other words, for a given AEE increase, the sizing process determines the minimum-CAPEX storage capacity that enables it, for each of the three technologies considered in this project.

II. METHODOLOGY

A. Reference wind farm

The *reference wind farm* used in the present study is summarised in the Table 1 below. Values have been selected with the consortium to be representative of a bottom-fixed wind farm in the North Sea.

Parameters that are accounted for in result 1.1, are highlighted in colour.

Table 1.Summary of high-level parameters used to identify the reference wind farm used in this study.

Parameters	Value	Unit
Substation	HVDC	-
Cable overloading allowance	none	-
Export Cable Capacity	1000	MW
Planted Capacity	1050	MW
Distance to shore	100	km
Average water depth	30	m
WTG type	IEA 15MW - Reference	-
WTG power rating	15	MW
WTG hub height	150	m
WTG rotor diameter	240	m
Number of WTGs	70	-
Commissioning date	1-1-2035	-
Wind farm lifetime	30	years
CAPEX per MW	2,500,000	$€_{2025}$/MW
OPEX per MW	62,500	$€_{2025}$/MW/year

B. Input Data

The present study simulates the operation of a *hybrid wind farm* and compares it to its corresponding *baseline wind farm* for the reference year 2035, using weather data from 2019. The wind farm is simulated based on data for a site in the Dutch North Sea. Similarly, the price data describes prices on the Dutch Day-Ahead market.

1. Price and load data

Price and load data are sourced from Montel, a provider of energy market intelligence, offering price forecasting tools for European energy markets, with dedicated analytics and market oversight [3].

which, under a given deployment scenario for renewables and storage and assumptions about future demand evolution, simulates day-ahead (DA) electricity prices. For this analysis, DA prices are obtained for 2035, corresponding to the 2019 weather year.

Montel data (day-ahead price and residual load) are provided at 15-minute intervals. However, for the present sizing exercise, an hourly time resolution was adopted, consistent with the resolution of the wind production dataset (see below). Accordingly, the four quarter-hourly values were averaged to obtain hourly day-ahead (DA) prices. For the remainder of the study, this averaging approach was adopted, yielding 767 hours of negative prices (8.8 % of yearly hours). This is considered conservative in the sense that averaging smooths out short-lived negative price spikes, thereby underestimating the number of hours with negative prices compared to point-reading the hh:00 timestamp (1091 hours, 12.5 % of yearly hours).

2. Wind production data

In alignment with the underlying demand data, wind production time series are also used for 2019. The data is provided by project partner Vattenfall for the *reference wind farm* described previously. Vattenfall's simulations account for internal wake losses as well as individual turbine and park-level control behaviour. Consequently, the study emulates what the wind farm production and system demand would look like in 2035 under Montel's assumed development scenario, assuming the weather year is identical to 2019. That weather year 2019 was selected as it was representative of average wind and solar production.

3. Energy Storage System

Each of the three storage system developers have provided the same high-level parameters for their system.

The high-level parameters of ESS listed below were obtained respectively from *FLASC* for their HPES system, *Verlume* for their battery system and the *University of Groningen* for the UPHS system.

- The charging efficiency, in %
- The discharging efficiency, in %
- The specific CAPEX per unit energy capacity installed, in €/MWh
- The specific CAPEX per unit system power, in €/MW
- The minimum and maximum state of charge of the system, in %

C. System Power Flow

For the present study, the modelling concentrates on high-level power flows and assumes the following simplified representation for the *hybrid wind farm*. All power flows are defined on the same hourly time discretization.

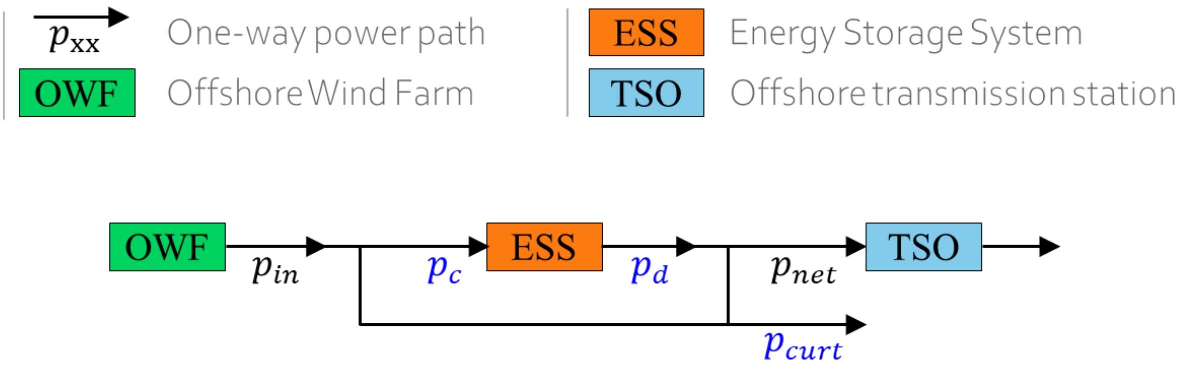

Figure 1. Simplified power flow diagram. In blue, power flows that are optimization variable, determined by the optimal dispatch strategy. p_{in} is the wind production after any production curtailment has been subtracted. p_{net} is the resulting net power, at the meter of the offshore transmission station.

The *hybrid wind farm* adds an Energy Storage System (ESS) to the Offshore Wind Farm (OWF). The OWP outputs p_{in} , which already accounts for production curtailment (due to O&M and avian migration). The ESS charges with p_c and discharges p_d.

An originality of the present approach is to include the export curtailment power p_{curt} as a design variable. It is therefore left to the optimization to establish if some power should be curtailed, based on the export constraints listed above in section I.E.3. The curtailed power p_{curt} is therefore an output of the optimization.

The resulting net power at the meter of the offshore transmission station, p_{net}, is obtained by summing all power flow components with their respective signs, where in Figure 1 all powers are assumed unidirectional and positive. The net power should not exceed a variable export capacity, with grid congestion episodes lowering that available capacity by 25 % during congestion episodes.

D. Production & Export Constraints

1. Production Constraints

We assume that two events can result in a deliberate reduction in wind production: maintenance operations (referred to as O&M curtailment) and bird migration (referred to as avian curtailment). Both are modelled following a statistical approach, albeit with variations in the associated parameters. What that means is that we inherently set-up a given randomness in how such respective events occur, that is supposed to reflect a corresponding randomness in how those events unfold in real-life. Those events are spread sporadically along a calendar year by following the statistical parameters listed in the table below. Those are representative of current industry values and are applied once, to the wind production timeseries to create a subsequent production-curtailed timeseries used identically for all cases in the present study.

Table 2. Statistical parameters accounted for the two types of production curtailment accounted for. Bold lines correspond to resulting values of the statistical approach.

	Avian curtailment	O&M curtailment
Derating intensity	50 %	20 %
Occurrence	45 h /year	98 % availability
Season/hour rules	March - Oct, 6 am – 9 pm	all year, any hour
Event duration [h]	Random(1h-4h)	Random(4h-12h)
Yearly un-availability	**0.26 %**	**2 %** (by definition)
Production Curtailment	**0.11 %**	**1.72 %**

In the table above, the derating intensity corresponds to the sudden deficit in production capacity due to the disturbing event, relatively to the total unabated capacity.

The yearly un-availability is the result of the statistical approach conducted with the parameters above. It is defined as the cumulative farm availability deficit, due to the disturbing event, relative to the total production capacity. The definition is given below, where $p_{in\_raw}(t)$ is the raw wind production at time t and $\gamma_{curt}(t)$ the derating intensity.

Un-availability
$$UnAvail = \frac{\sum[1-\gamma_{curt}(t)].dt}{\sum dt} \quad [\text{-}]$$

The production curtailment represents the actual production deficit, due to the disturbing event, relative to the total production unabated production.

Production Curtailment
$$Curt = \frac{\sum p_{in\_raw}(t).[1-\gamma_{curt}(t)].dt}{\sum p_{in\_raw}(t).dt} \quad [\text{-}]$$

As avian and O&M are two independent events, each affecting random turbines of the farm. In case those happen simultaneously, it is assumed that they do not impact the wind park cumulatively. For hours of simultaneous O&M and bird migration, the production capacity is not reduced by 70 % but is rather equal to (1-20 %).(1-50 %) = 40 %, which corresponds to a 60 % cumulative derating intensity.

For avian curtailment, 45 hours are randomly distributed in bins between 1 hour and 4 hours from March to October, between 6 am and 9 pm. For impacted hours, the wind planted capacity is assumed halved. It corresponds overall to a 0.26 % yearly un-availability and in the present simulation case to a production curtailment of 0.11 %.

For O&M curtailment, the total un-availability is set at 2 %, distributed in randomly assigned durations between 4h to 12h all year around, which leads, in the present simulation case, to a production curtailment of 1.72 %.

2. Export constraints - Economic

Under the modelling framework used, the *hybrid wind farm* has the possibility to optimally curtail power, along with the charge/discharge of the ESS, to provide the required system-level improvement in KPI with the lowest ESS CAPEX. There is therefore no strict minimum price level constraint imposed for exports, but the optimization would anyway avoid negative price episodes which will decrease the overall VWE.

For the *baseline wind farm*, it is assumed that no exports occur during adverse economic episodes, which are strictly defined by negative price hours. The reality of wind farm operations during negative electricity prices is more complex, even if revenues are fully merchant as stopping and restarting a farm comes at a cost.

However, this assumption is in line with a general behaviour observed with offshore wind during recent negative price episodes and as such is taken for the sake of simplicity, after discussion with our OESTER partners.

All power that is curtailed in relation to that constraint is accounted for as *economic curtailment*.

3. Export constraints - Overplanting

Overplanting is common industry practice in offshore wind. In such cases, the planted wind capacity is higher than the nominal cable export capacity P_{cable_max}, so the wind production can at times exceed the exporting capability under nominal grid access conditions. The case of a reduced available export capacity is treated in the following section. We assume that this constraint is implemented strictly, such that the nominal cable capacity can not be exceeded at any time.

All power that is curtailed in relation to that constraint is accounted for as *overplanting curtailment*.

4. Export constraints - Grid congestion

The grid availability is anticipated by adapting a grid curtailment model developed by TNO [4] to the present study case. It is based on the non-firm access introduced by the *IJmuiden Ver Gamma* offshore wind tender, where temporary curtailment is allowed to manage grid congestion and balancing. It should be noted that this tender was not procured and that a new tender is expected later in 2026.

Under the original tender, wind developers must account for reduced output, with maximum points awarded for a 25 % curtailment contract for up to 15 % of annual hours. The grid curtailment model provides a method to identify these hours, to anticipate their occurrence in future years.

The curtailment profile is constructed as per the following logic.

- It only concerns the highest wind speed hours that would entail a wind production above 75 % of the export capacity.
- Among the above hours, it only concerns the subset of 1315 hours (15 % of annual hours) of lowest residual load.

The corresponding hours are associated with a reduction in available export capacity, or export capacity derating factor, of $\delta_{export} = 25\ \%$. In the figure below, each blue dot represents an hour, grid congestion limitation happens in the top left corner of the chart.

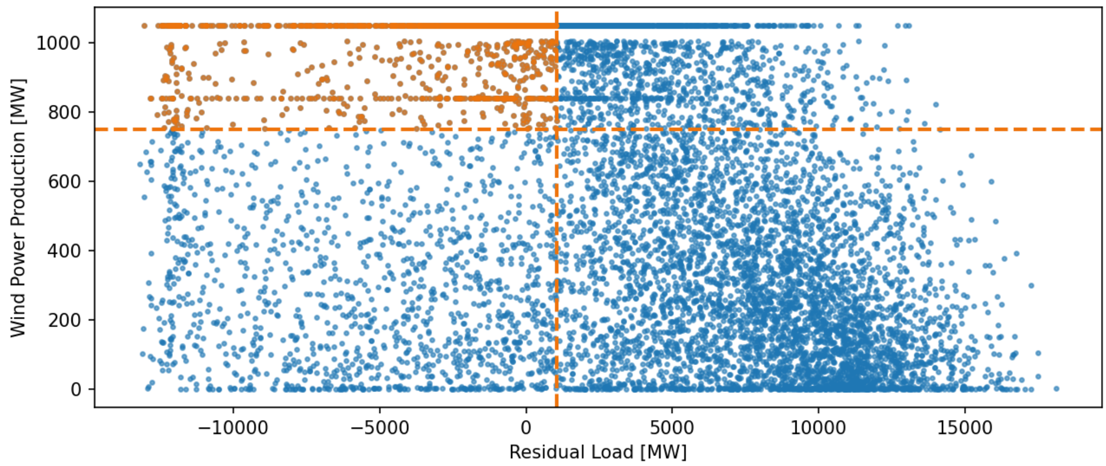

Figure 2. Display of each hour of the study year considered in residual load vs wind production coordinates, for the reference wind farm. The hours for which the grid availability is reduced are plotted in orange.

For a wind farm with low overplanting level, which is the case of our *reference wind farm*, and also the case of the farm assumed by TNO in their study [4], the above approach leads in identifying the combination of high wind production and low residual load. However, for a wind farm with a higher overplanting level, more hours will see the condition of a production exceeding 75 % of the export capacity, such that the corresponding residual load threshold (vertical dashed line) will be altered. Yet it does not seem realistic that the overplanting level of a single wind farm would affect the system-level residual load threshold that triggers grid congestion episodes.

As the present study investigates the impact of large overplanting levels, it was assumed that grid congestion would occur over the same hours identified for the *reference wind farm*, plotted in Figure 2. Those hours are therefore used to anticipate on grid curtailment episodes, with the same 25 % intensity, for each *baseline wind farm*, regardless of their overplanting level.

All power that is curtailed in relation to that constraint is accounted for as *congestion curtailment*.

5. Export curtailment accounting

For the ***baseline wind farm***, the curtailed power can be broken down into various components stemming from the production-curtailed $p_{in}(t)$. In the following equations, for the sake of clarity, all power components at time step t are noted without the time argument: $p_{xx} \Leftrightarrow p_{xx}(t)$. All power components below are expressed in MW.

Wind production	p_{in}, which already account for power reduction related to "production curtailment", see II.D.1.
Economic curtailment	$p_{curt\_e}(t) = p_{in}(t) - p_{in\_curt\_e}(t)$ with:

$$p_{in\_curt\_e}(t) = p_{in}(t) \quad if \quad DA_{€}(t) > 0$$
$$p_{in\_curt\_e}(t) = 0 \qquad if \quad DA_{€}(t) \leq 0$$

Overplanting curtailment	$p_{curt\_o}(t) = p_{in\_curt\_e}(t) - p_{in\_curt\_e/o}(t)$ with: $p_{in\_curt\_e/o}(t) = p_{in\_curt\_e}(t)$ if $p_{in\_curt\_e}(t) \leq P_{cable\_max}$ $p_{in\_curt\_e/o}(t) = P_{cable\_max}$ if $p_{in\_curt\_e}(t) > P_{cable\_max}$ where P_{cable_max} is the nominal export capacity of the HVDC cable, that we assume cannot be exceeded at any time.
Congestion curtailment	$p_{curt\_c}(t) = p_{in\_curt\_e/o}(t) - p_{in\_curt\_e/o/c}(t)$ with: $p_{in\_curt\_e/o/c}(t) = p_{in\_curt\_e/o}(t) \quad if \quad p_{in\_curt\_e/o}(t) \leq p_{cable\_max}(t)$ $p_{in\_curt\_e/o/c}(t) = p_{cable\_max}(t) \quad if \quad p_{in\_curt\_e/o}(t) > p_{cable\_max}(t)$ where: $p_{cable\_max}(t) = P_{cable\_max}. [1 - \delta_{export}(t)]$ $\delta_{export}(t)$ being the export capacity derating factor

Curtailment is attributed following a TSO-aligned hierarchy: reductions due to low or negative day-ahead prices are classified as economic curtailment, and any remaining reductions caused by physical grid constraints are classified as overplanting or congestion curtailment, ensuring that no curtailment is double-counted.

For the ***hybrid wind farm***, the determination of various curtailed components stems from p^*_{curt}, the optimal curtailed power, an output of the optimization. In the following equations, for the sake of clarity, all power components at time step t are noted without t as an argument: $p_{xx} \approx p_{xx}(t)$. All power components below are expressed in MW.

Overall curtailed power	p^*_{curt}, the optimal curtailed power.
Economic curtailment	$p_{curt\_e} = p^*_{in\_hybrid} - p^*_{in\_hybrid\_curt\_e}$ with: $p^*_{in\_hybrid} = p_{in} + p^*_d - p^*_c$ with: p^*_d and p^*_c the optimal discharge and charge power of the ESS

and:

$$p^*_{in\_hybrid\_curt\_e} = p^*_{in\_hybrid} \qquad if\ \ DA_€(t) > 0$$

$$p^*_{in\_hybrid\_curt\_e} = p^*_{in\_hybrid} - p^*_{curt} \qquad if\ \ DA_€(t) \leq 0$$

Overplanting curtailment

$$p_{curt\_o} = p^*_{in\_hybrid\_curt\_e} - p^*_{in\_hybrid\_curt\_e/o}$$

with:

$$p^*_{in\_hybrid\_curt\_e/o} = p^*_{in\_hybrid\_curt\_e} \quad \text{if } p^*_{in\_hybrid\_curt\_e} \leq P_{cable\_max}$$

$$p^*_{in\_hybrid\_curt\_e/o} = P_{cable\_max} \qquad \text{if } p^*_{in\_hybrid\_curt\_e} > P_{cable\_max}$$

where P_{cable_max} is the nominal export capacity of the HVDC cable, that we assume cannot be exceeded at any time.

Congestion curtailment

$$p_{curt\_c} = p^*_{in\_hybrid\_curt\_e/o} - p^*_{in\_hybrid\_curt\_e/o/c}$$

with:

if $p^*_{in\_hybrid\_curt\_e/o} \leq p_{cable\_max}(t)$:

$$p^*_{in\_hybrid\_curt\_e/o/c} = p^*_{in\_hybrid\_curt\_e/o}$$

else:

$$p^*_{in\_hybrid\_curt\_e/o/c} = p_{cable\_max}(t)$$

where:

$$p_{cable\_max}(t) = P_{cable\_max}. [1 - \delta_{export}(t)]$$

$\delta_{export}(t)$ being the export capacity derating factor.

For any export curtailment type, the curtailment level is defined below, based on the curtailed power p_{curt} and relatively to the production-curtailed wind production p_{in}.

Export Curtailment

$$Curt = \sum_t p_{curt}(t).dt \Big/ \sum_t p_{in}(t).dt \qquad [\text{-}]$$

E. Optimal Problem Formulation

An optimal problem is formulated for the two use-cases described previously, that differ only by the nature of the operational requirement, implemented as a constraint in the formulation. The *Time Shifting* requires a given increase in VWE, while the *Increase Export* requires a given increase in AEE. Problem formulations are otherwise similar, except that for the *Increase Export* use case, it was decided to only allow exports during positive price episodes, for both the baseline and the *hybrid wind farm*. For the *Time Shifting* use case that is only implemented for the baseline wind farm, see section curtailment above.

The parametrization is set such that the optimal ESS dispatch - the optimal charging and discharging power flows at each time step - and the ESS sizing - the rated power and the energy capacity - are optimization variables. In a nutshell, our approach optimizes the dispatch and the ESS size at once. Over a whole year with a time discretization of one hour, the problem amounts to {2 x 24 x 365 + 2 = 17,522} optimization variables. All results are produced over a single year and not over the lifetime of the farm.

The code can also suppress one degree of freedom of the problem by linking ESS power rating and energy capacity, thereby freezing the storage duration. However, results that follow have been established without that constraint. Therefore, the solver finds for each sizing use-case the optimal storage duration and the optimal energy storage capacity.

III. ANALYSIS OF OPERATING CONDITIONS

A. Wind production

For the *reference wind farm*, the heatmap of wind production, after production curtailment is applied, is outlined below. Such episodes are of low intensity and are randomly distributed along the year such that the impact on the optimal sizing of the ESS is negligible.

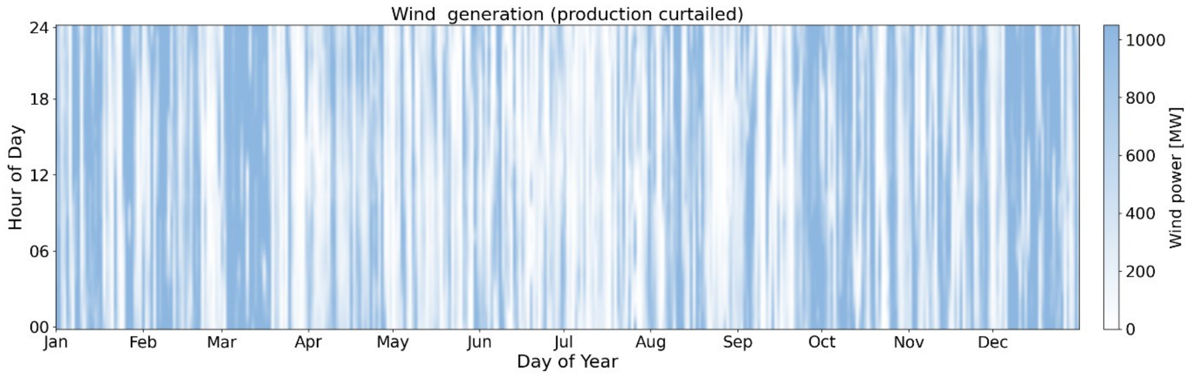

Figure 3. Heatmap of power production for the reference wind farm, for the year 2019, as provided by Vattenfall.

An overall seasonality of wind production can be observed, with production being overall quite high from October to March. Late spring and summer are exhibiting a lower intensity, more scarce production pattern, with that trend being quite pronounced from late June until the end of July. Inversely, an intense and almost uninterrupted production period can be observed over the first half of March, for this 2019 dataset. Another point is that multi-day periods of near-zero wind production occur regularly, while periods of high wind production can also persist over several consecutive days. In comparison to solar energy production, no clear indications to an hourly pattern through the day are visible.

B. Day-ahead prices

Day-ahead prices are used in the present study as a proxy for system demand and scarcity.

In the heatmap shown in Figure 4, prices close to zero are dark, while positive prices are green and negative prices red. A first striking observation concerns the occurrence and distribution of negative price episodes, which can be seen to cover multiple consecutive hours for several days in a row. A significant fraction of the heatmap is red, which illustrates the adverse economic conditions simulated for the year 2035.

A general trend concerns a bandwidth of high prices that spans, for most days, over morning hours 7 am - 9.30 am and over evening hours 5.30 pm – 9 pm. That is related to the high system demand associated with daily routine.

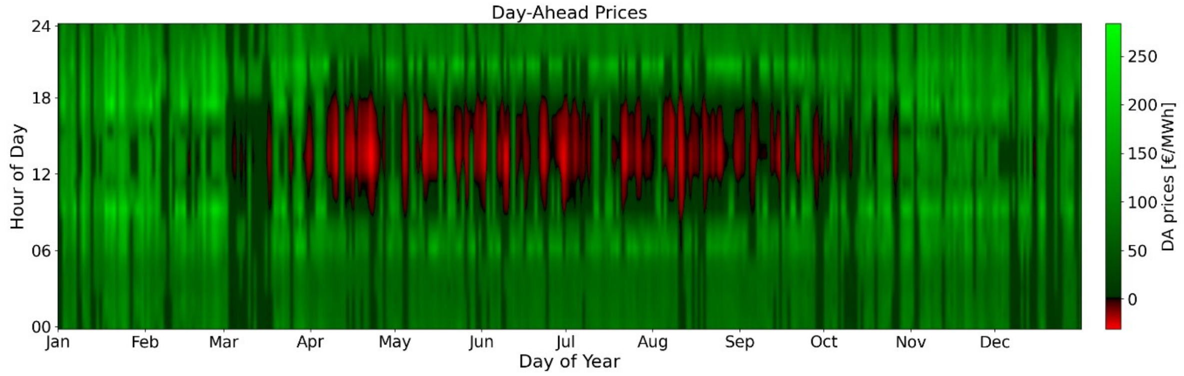

Figure 4. Heatmap of day-ahead prices, for the study year 2035, as provided by Montel.

Negative price episodes can be seen rarely from November until February but can be seen to cover an increasing bandwidth of hours from April until October, which can be explained by the high seasonality of solar energy in the Netherlands. A significant low-price region can be observed outside of that solar-dominated patch, over the first half of March, which corresponds distinctively with the episode of high wind production noted above. In that region, negative minima can be observed in the prolongation of the solar patch.

This high-level price overview outlines that price cannibalization is severe. Overproduction in wind and solar exacerbates each-other but is overall driven by the conjunction of high solar production with low system demand during mid-day hours. The temporal mismatch between supply and demand is largely occurring daily and it typically corresponds to a 3 to 5 hours period.

C. Curtailment of Reference Wind Farm

The heatmap below illustrates both economic and grid-congestion curtailments, with the colour scale reflecting the amount of power curtailed each hour due to these factors.

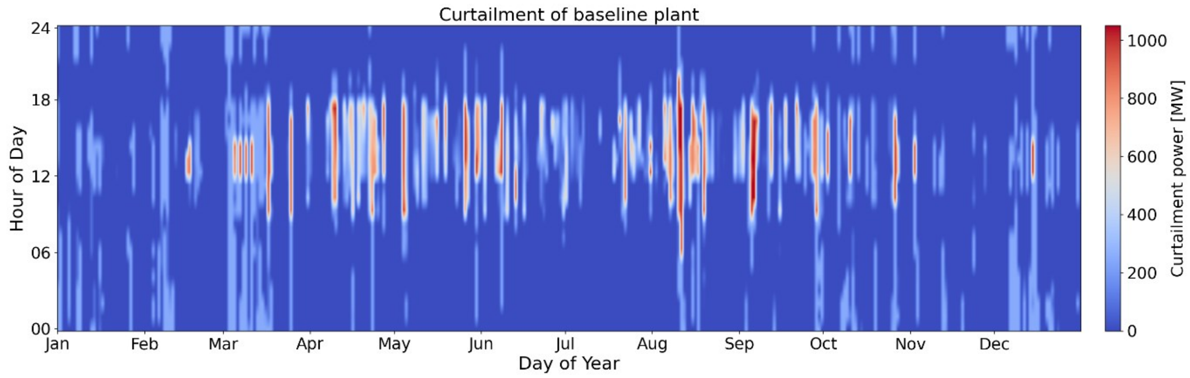

Figure 5. Heatmap of curtailed power for the reference wind farm, accounting for all export curtailment components combined: economic, overplanting and congestion.

Overall curtailment for the simulated year amounts to 15.6 % (economic 8.7 %, overplanting 1.7 % and congestion 5.3 %, as per the accounting detailed in II.D.5)

Economic curtailment is the most intense, as up to 100 % of the farm production at full rate can be curtailed, which can be seen in the upper value of the colour scale. Congestion curtailment, under the model adopted, can represent a maximum of 25 % of the farm production at full rate and as such will be marked only by shades of light blue. Therefore, red spots in the above figure are the result of economic curtailment only.

A similar shape pattern as seen in the negative day-ahead price heatmap is present here by definition, weighted here however by the wind production intensity during those negative price episodes. Unsurprisingly, the episode of strong wind production in the first half of March is associated with a pronounced curtailment episode: wind is strong and prices are low. However, day-ahead prices are still mostly positive during that episode, such that grid curtailment is also intensely occurring in that period.

D. Analysis of capture rates

Cannibalization in renewables refers to the phenomenon where the growing deployment of a renewable technology progressively erodes its own economic value by systematically depressing electricity prices during the hours it generates most. It creates favourable conditions for energy storage by widening the spread between low-value generation hours and high-value delivery hours, increasing the potential system value that storage can capture.

The most useful metric to capture cannibalization in renewables is the Capture Rate (CR). A CR below 100 % indicates cannibalization, the technology is producing more when prices are low, dragging down its revenue relative to the market average. Table 3 below outlines the CR for various renewable production, in two specific cases. The first considering directly the un-curtailed renewable production that is assumed to be sold at day-ahead prices at any time (Gross Capture Rate). The second that assumes that the renewable are steerable and responsive to price signals, where production during negative price hours is curtailed (Net economic Capture Rate)

Table 3. Capture rates computed for the various renewable sources based on 2019 production, computed with day-ahead prices forecasted for the year 2035

	Gross Capture Rate	Net economic Capture Rate
Montel Offshore wind	80.6 %	89.8 %
Montel Solar	38.4 %	70.3 %
Vattenfall wind farm	83.3 %	92.5 %

Both capture rates are computed for the national load forecasted by *Montel* for the year 2035 in the Netherlands, which is based on 2035 deployment scenario and an assumed 2019 weather year. In the last row, both values are also provided for the wind farm production that is the focus of the present study, where wind production timeseries are provided by *Vattenfall*.

Cannibalization is prevalent for solar, with a large impact of negative price, as curtailing production during associated hours nearly doubles the CR from 38.4 % to 70.3 %. Wind overall is also affected, albeit relatively less, and negative prices have also a lower relative impact, as those bring the CR from ~ 90 % down to 81 %. This outlines that cannibalization is driven by solar, which is further detailed in the following section III.E.

Finally, the specific wind farm modelled by *Vattenfall* follows the same trend in capture rates as the overall offshore wind production accounted for by *Montel*, but with a CR increase of 2.7 % shift towards higher values.

E. Reference Wind Farm behaviour

To better understand and portray how the ESS would operate in the *hybrid wind farm*, a snapshot of the behaviour of the *reference wind farm* is displayed in Figure 6 for a week in April. This week is of special interest as it combines episodes of negative price and of grid congestion.

The figure illustrates, on a shorter time scale, the curtailment behaviour described above. When day-ahead prices (bottom, green) are negative, the wind farm is curtailing any wind production (above, in purple). Grid congestion episodes are marked by 25 % drops in available export capacity (dotted red). When negative price and grid congestion occur simultaneously, seen here on the 15 April at 6 pm, curtailment is solely accounted for as economic curtailment (purple). A few hours later, another grid congestion episode occurs, while prices remain positive this time, entailing power curtailment accounted as export curtailment (in red).

Overall, Figure 6 displays how the raw wind production is affected by these export constraints. Areas in purple and red correspond to the wind production that must be curtailed, leaving a power exported marked by the orange area. The total curtailment represents 26.8 % of the wind production over that week and 15.6 % over the whole year 2035.

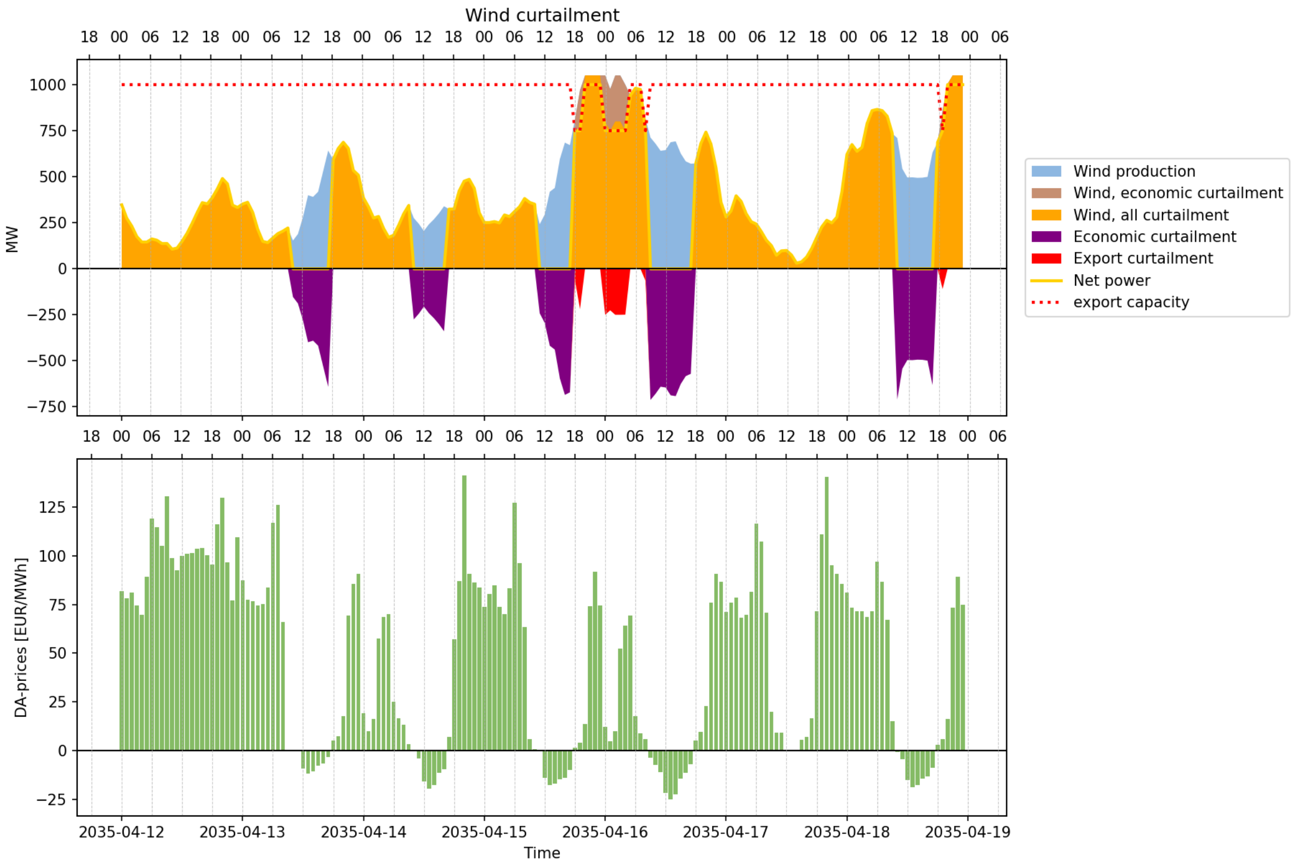

Figure 6. Time evolution in power flows for the reference wind farm (top) and in day-ahead prices (bottom), for the second week of April 2035.

IV. SIZING OF ENERGY STORAGE SYSTEM

All results of the present section are produced for the hybridization of the *reference wind farm*. Increase of 10 % in the VWE and in the AEE are respectively prescribed in the following two subsections. For both, the sizing routine finds the ESS of minimum CAPEX that enables such an increase. The value of 10 % was chosen as an illustrative target, being high enough to represent a significant increase, yet not too large to keep the storage system sizing within typical utility-scale ESS power ratings.

A. Time Shifting

Table 4. Summary of parameters used through section IV.A

Parameters	hybrid wind farm
Export Cable Capacity	1000 MW
Planted Capacity	1050 MW
VWE prescribed increase over the *baseline wind farm*	10 %

Figure 7 outlines the optimal control of the *hybrid wind farm* over the same timeline as displayed in Figure 6 for the *reference wind farm*, in the case of a FLASC ESS.

The raw wind production (light blue area), export availability (dotted red curve) and day-ahead prices (bottom, green) represent the external operating conditions and as such are identical to the figure above. The ESS operation is illustrated on the chart through the charging (orange area) and discharging (purple area) power profiles. Charging reduces the net exported power (yellow curve) relative to the wind generation, whereas discharging leads to a net power output greater than the instantaneous wind production.

For the sake of plotting clarity, all curtailment sources have been combined into one overall curtailment (red area). That later is far from being entirely captured by the ESS, illustrating how the solver only sizes the ESS suitable to provide an increase in VWE of 10 % over the baseline. Capturing more curtailment would require more power and energy capacity at a cost penalty compared to the optimal case.

The main trend of the optimal dispatch strategy can also be seen in Figure 7. The ESS shifts a fraction of wind production that is otherwise curtailed to hours when system demand is high. It can also be seen, on the 17 April between 9 am and 5 pm that the ESS charges during hours that are not exposed to any curtailment but to low prices. The optimal *FLASC* ESS size is 184 MW, 1530 MWh, and the rated power limit can be clearly visualized during several charging cycles.

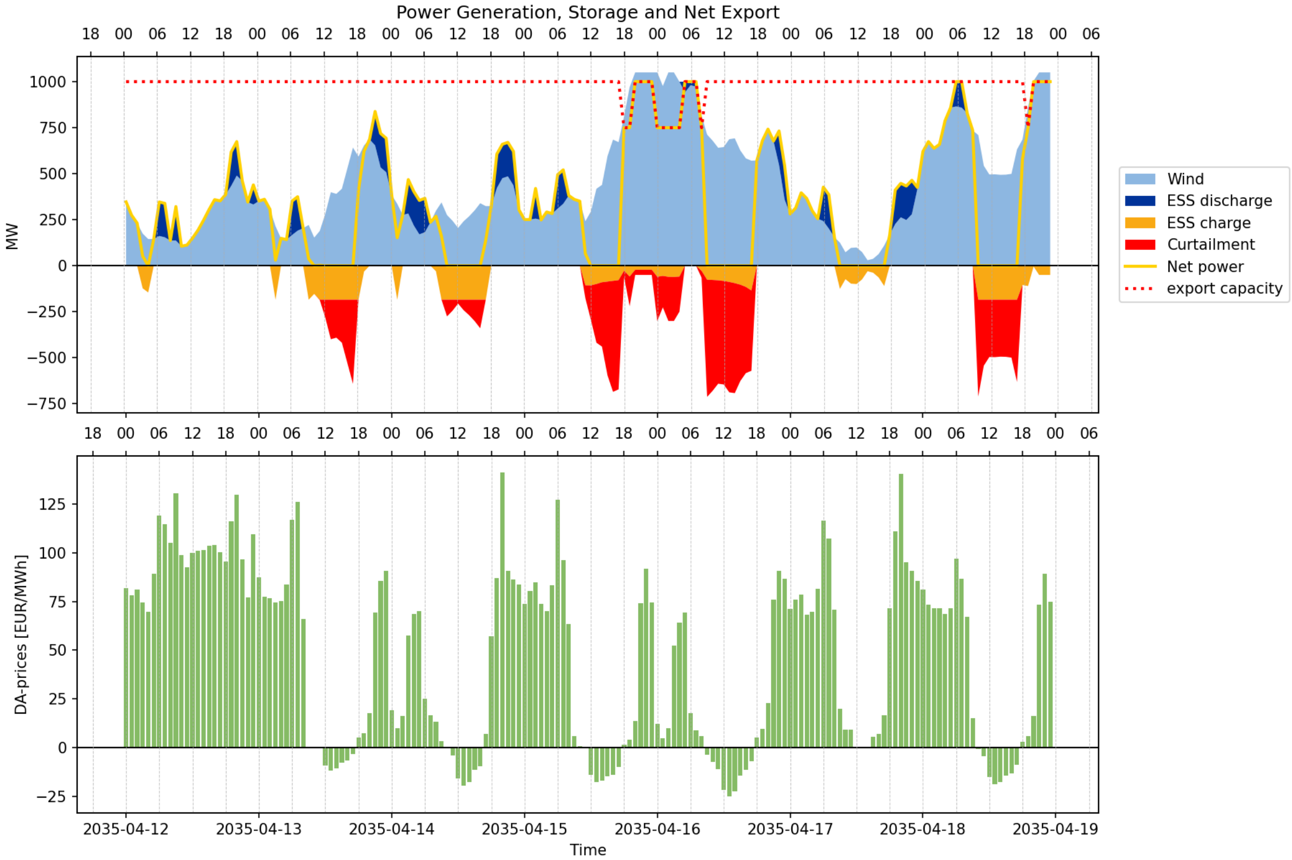

Figure 7. Time evolution in power flows for the hybrid wind farm with FLASC ESS (top) and in day-ahead prices (bottom), for the second week of April 2035. The hybrid wind farm enables a 10 % increase in VWE over the baseline wind farm.

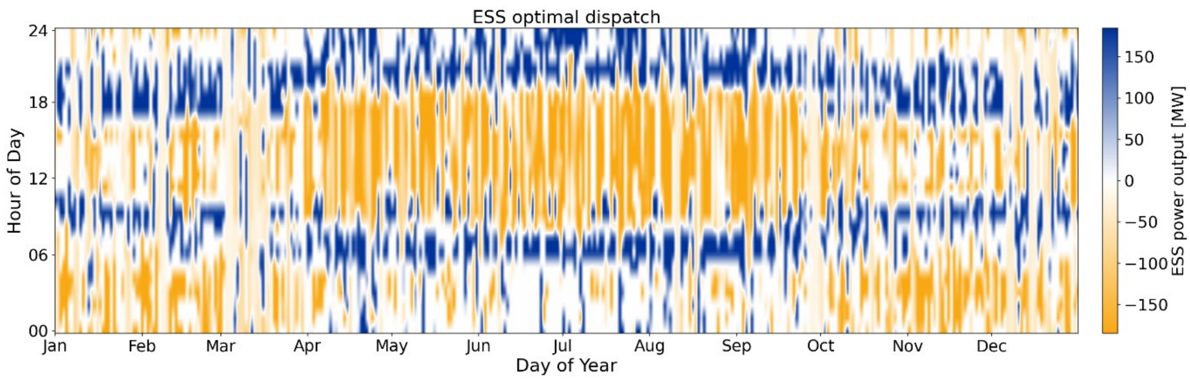

Figure 8. Heatmap of optimal dispatch for the FLASC ESS. Blue and orange respectively represent system discharge and charge.

The optimal operation of the *FLASC* ESS exhibits charging episodes that occur on a quasi-daily basis, typically over extended and continuous periods ranging from 9 am to 5 pm (see Figure 8). Discharging episodes are more frequent and shorter. That dissymmetric behaviour can be related to the day-ahead price evolution: negative price episodes span over multiple hours, while local maximum form sharp hourly peaks. In Figure 8 , the colour scale spans over the rated power (assumed identical for charge and discharge) of the ESS. The sharp colour outlines that for the *FLASC* ESS, the system often makes full use of its power range available.

Table 5 below summarizes how ESS technologies compare for the identical *Time Shifting* use case. The ESS generate the same VWE increase with different configurations: the *Verlume* system, which has the highest specific CAPEX per unit energy capacity, minimizes its overall CAPEX by installing significantly less energy capacity than *FLASC* solution (-45 %), but combines it with a much larger installed power (+73 %).

Although the systems differ substantially in size, a remarkable outcome is that all three ESS reach the prescribed VWE by an identical increase in AEE and Capture Rate (CR) respectively. This indicates that each configuration enhances the Value-Weighted Energy through the same balance between increase in exported energy and increase in demand alignment.

Table 5. Result at both farm level and ESS level for the sizing use case Time Shifting, where a 10 % increase in VWE is prescribed over the reference wind farm.

Yearly farm-level KPIs		***Reference wind farm***	***Hybrid wind farm*** FLASC	**Verlume**	**UPHS**
VWE	[MWh]	3.63×10^6	*Prescribed 10% increase in VWE:* **3.99×10^6**		
AEE	[MWh]	3.73×10^6	3.81×10^6	3.82×10^6	3.83×10^6
CR	[-]	0.97	1.05	1.04	1.04
Economic curt.	[%]	8.7	6.5	7.3	6.7
Overplanting curt.	[%]	1.7	0.4	0.8	0.5
Congestion curt.	[%]	5.3	4.0	4.8	4.3
Total curt.	[%]	15.6	10.9	12.9	11.5
DA capture price	[€/MWh]	69.4	74.7	74.6	74.5
ESS-sizing KPI			**FLASC**	**Verlume**	**UPHS**
Energy capacity		[MWh]	1530	843	1357
Rated power		[MW]	184	320	167
Storage duration		[h]	8.3	2.6	8.1
CAPEX of ESS		[m€]	791	2010	1190

However, the curtailment of the *reference wind farm*, 15.6 % over the year, is not identically captured by the various ESS. *FLASC* captures 30 % of it to bring its yearly value down to 10.9 %, while *Verlume* captures 17 % of it and leaves an overall curtailment of 12.9 % over the year. Besides all sources of curtailment are not captured in the same proportions: *FLASC* captures 25 % of *economic curtailment*, 76 % of *overplanting curtailment* and 25 % of *congestion curtailment*. In comparison, *Verlume* captures 16 % of *economic curtailment*, 53 % of *overplanting curtailment* and 9 % of *congestion curtailment*.

The specificities of each technology, in terms of round-trip efficiency and costs (see section II.B.3) determine how well-suited they are for capturing curtailment of different types.

Overall, the total curtailment achieved by the *hybrid wind farm* is 10.9 % with *FLASC* system (from 15.6 % for the *reference wind farm*) and 12.9 % with the *Verlume* system. The difference in round-trip efficiency explains why the two systems enable the same annual energy exported with different levels of curtailment. *Verlume* ESS has a higher efficiency such that a lower fraction of the energy captured is lost, it can capture less curtailment to reach the same increase in AEE.

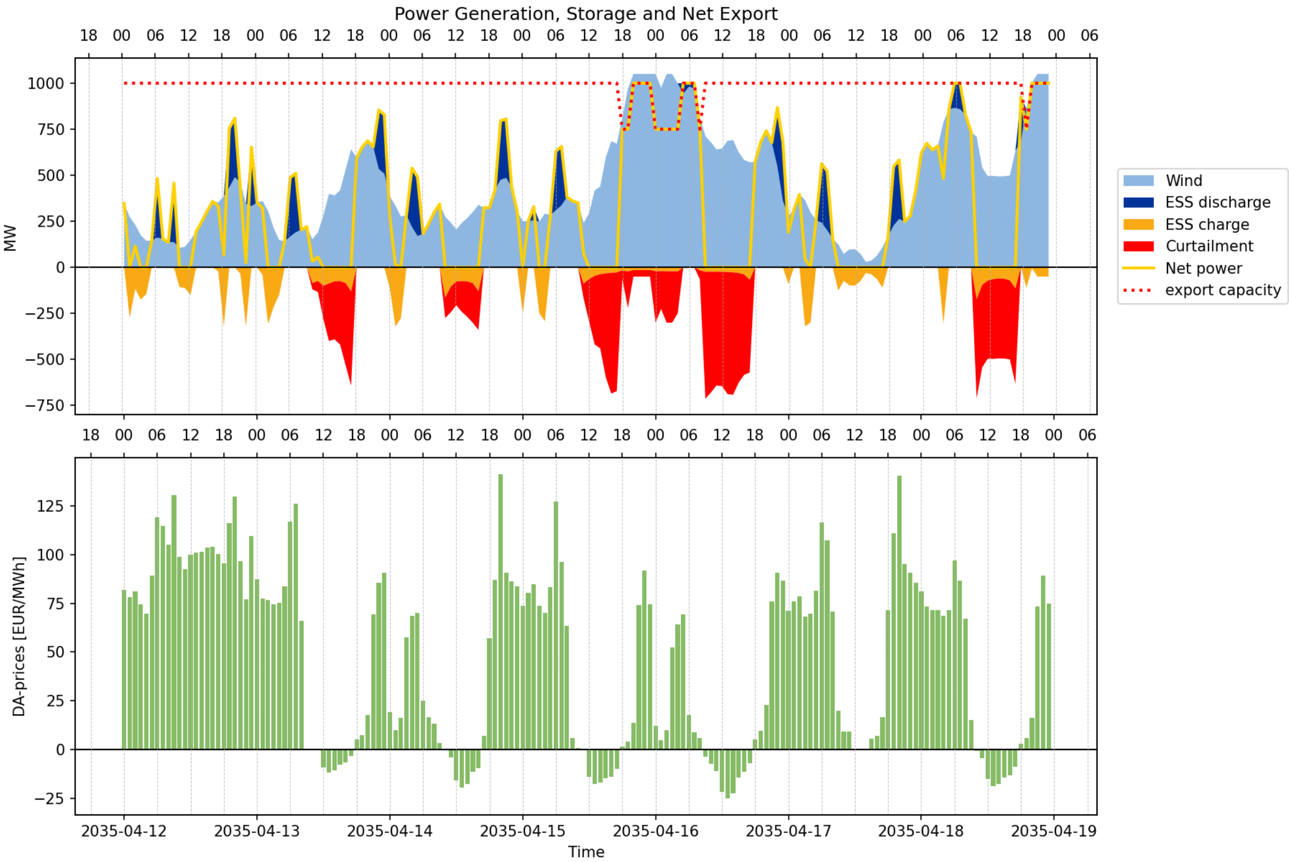

Figure 9. Time evolution in power flows for the hybrid wind farm with Verlume ESS (top) and in day-ahead prices (bottom), for the second week of April 2035. The hybrid wind farm enables a 10 % increase in VWE over the baseline wind farm.

Figure 9 displays the optimal dispatch of the *Verlume* system over the same week as shown previously for *FLASC*. It can be seen the dispatch is more dynamic than the *FLASC* ESS, characterized by:

- **more frequent cycles** - over the year the *Verlume* ESS ran 876 charging episodes and 839 discharging ones, in comparison to 637 and 735 for *FLASC*
- **shorter episodes** - over the year the average durations per charge and discharge event are 5h and 1h47 respectively, in comparison to 6h22 and 2h25 for *FLASC*

- **smaller price differences** - over the year the average DA price spread between charge and discharge (regardless of the order) is 60.6 €/MWh, in comparison to 73.2 €/MWh for *FLASC*
- **higher charging and discharging power rating** - over the year the average power per charge and discharge event are 139 MW and 236 MW respectively, in comparison to 111.5 MW and 152 MW for *FLASC*

Finally, the total energy discharged over a year by the *Verlume* ESS (337× 103 MWh) significantly exceeds that of *FLASC* (277× 103 MWh). The costlier energy capacity of *Verlume* ESS requires it to feed from more frequent and smaller price difference. It can then only match the required VWE energy by displacing more energy. Its higher round-trip efficiency enables it to do so by capturing overall less energy over a year (373× 103 MWh) than the *FLASC* ESS (403× 103 MWh).

Figure 10 shows that the *Verlume* ESS often operates far from its maximum power rating of 320 MW, illustrated by the faded colours of charge and discharge power, which are on average of 84 MW (26 % of the rated power) and 225 MW (70 % of the rated power). This suggests that the system rarely operates at rated power, pointing to operating conditions that are not conducive to cost-efficient utilisation.

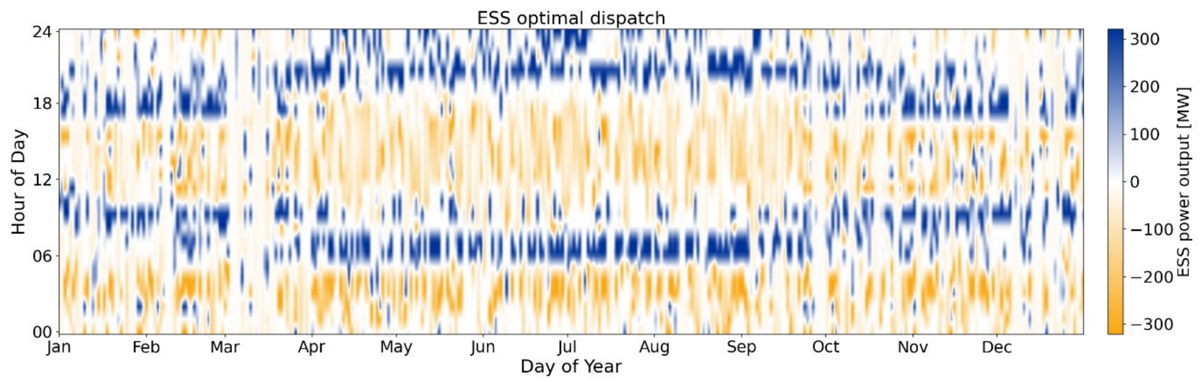

Figure 10. Heatmap of optimal dispatch for the Verlume ESS. Blue and orange respectively represent system discharge and charge

The optimal storage durations for *FLASC* ESS and the UPHS ESS are nearly comparable (see Table 5) and above 8 hours, while *Verlume* reaches its lowest CAPEX for a duration below 3 hours. Overall, the *FLASC* system achieves the lowest CAPEX for that use-case by a 34 % margin over the closest one.

B. Increase Export

Table 6. Summary of parameters used through section IV.B

Parameters	hybrid wind farm
Export Cable Capacity	1000 MW
Planted Capacity	1050 MW
AEE prescribed increase over the *baseline wind farm*	10 %

The *Increase Export* use case requires a given increase in annual exported energy (10 % here) over the *reference wind farm*. It reflects a wind farm that maximizes exports irrespective of market prices, consistent with the behaviour of a farm under a Contract for Difference (CfD). However, an important assumption made concerns the conditions of exports: no exports are permitted during negative price episodes, for either the *reference* or the *hybrid wind farm*.

The optimal dispatch, for *FLASC* ESS, can be observed in Figure 11 to be very different than for the *Time Shifting* use case. Charging periods still correspond to hours of negative prices, as exports are artificially blocked during such hours, albeit at much higher charging power rating: the average charging power per event is 190 MW (vs 111.5 MW for the *Time Shifting* use case) but can reach 715 MW (vs 184 MW maximum for the *Time Shifting* use case). Exports are distributed over much longer periods (the average duration per discharge event is 20h30, vs 2h25 for the *Time Shifting* use case), at a much lower discharge rate (on average at 80 MW compared to 152 MW) during positive day-ahead price periods, regardless of price level.

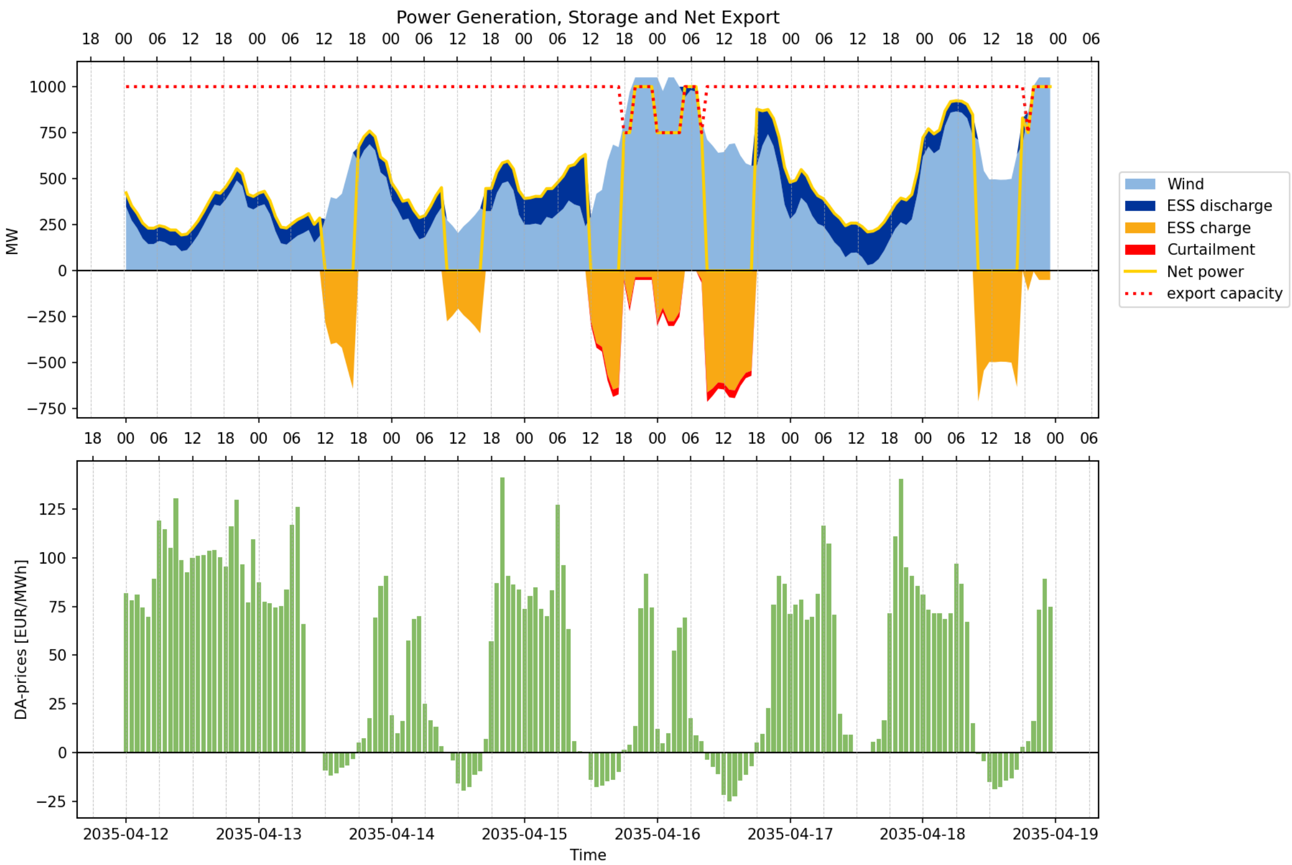

Figure 11. Time evolution in power flows for the hybrid wind farm with FLASC ESS (top) and in day-ahead prices (bottom), for the second week of April 2035. The hybrid wind farm enables a 10 % increase in AEE over the baseline wind farm.

Overall, achieving the same relative increase (+10 %) in AEE as in VWE requires much larger ESS. In the case of *FLASC*, a fivefold increase in energy capacity (8287 MWh) and a fourfold increase in rated power (714 MW) are required. Such an increase in ESS size, compared to the previous *Time Shifting* use case, highlights that achieving a 10 % increase in AEE is substantially more demanding in terms of storage than achieving an equivalent relative increase in VWE.

To achieve a 10 % increase in AEE in the present study case, where the total curtailment of the *reference wind farm* is less than 16 %, a large fraction of that curtailment must be captured, especially as a fraction of it is lost through ESS cycling, (31.1% in the case of *FLASC*).

The largest share of curtailment for the *reference wind farm* is related to negative prices and ESS must scale-up their energy capacity and power rating to capture energy during such events. That sizing logic leads to very large ESS, where for instance *FLASC* system could absorb the full farm production for nearly 8 hours straight. Figure 11 illustrates that, during the week plotted, the charging power never seems to level at a maximum value, in contrast to the *Time Shifting* use case, illustrated in Figure 7. This suggests that the ESS power rating is sized to capture energy during rare events, yet necessary to reach a 10 % increase in VWE. The discharge rate in Figure 11 reaches much lower values, as the discharge is spread over multi days. Overall, maximizing AEE under the condition of no export during negative price conditions opens the possibility for the ESS to capture economic curtailment. That requires sizing rated power and energy capacity adequately and yields to large and largely under-used power systems, suggesting that ESS may not be very cost-effective at increasing the AEE.

Table 7. Result at both farm level and ESS level for the sizing use case Increase Export, where a 10 % increase in AEE is prescribed over the reference wind farm.

Yearly farm-level KPIs		*Reference wind farm*	*Hybrid wind farm* FLASC	Verlume	UPHS
VWE	[MWh]	3.63×10^6	4.05×10^6	4.03×10^6	4.05×10^6
AEE	[MWh]	3.73×10^6	*Prescribed 10 % increase in AEE:* $\mathbf{4.11 \times 10^6}$		
CR	[-]	0.97	0.99	0.98	0.99
Economic curt.	[%]	8.7	2.0	3.4	2.8
Overplanting curt.	[%]	1.7	0.1	0.2	0.1
Congestion curt.	[%]	5.3	1.3	2.6	1.8
Total curt.	[%]	15.6	3.4	6.3	4.7
DA capture price	[€/MWh]	69.4	70.5	70.1	70.4
ESS-level KPI			**FLASC**	**Verlume**	**UPHS**
Energy capacity		[MWh]	8287	5436	6629
Rated power		[MW]	715	738	603
Storage duration		[h]	11.6	7.4	11
CAPEX of ESS		[m€]	3626	10570	5052

V. SENSITIVITY STUDY

In the present section, previous results are repeated for various overplanting levels of the *reference wind plant*, creating multiple *baseline wind plants*. Various steps in VWE and AEE are prescribed for the sizing of the installed ESS in each of the *baseline wind plants,* for the *Time Shifting* and *Increase Export* use case respectively. The export capacity remains fixed in those study cases.

A. Time Shifting

1. Storage System Sizing for the Baseline Overplanting Level

The effect of the prescribed increase in VWE on storage system sizing is explored for the 5 % overplanting level of the *reference wind farm* and displayed in Figure 12 below.

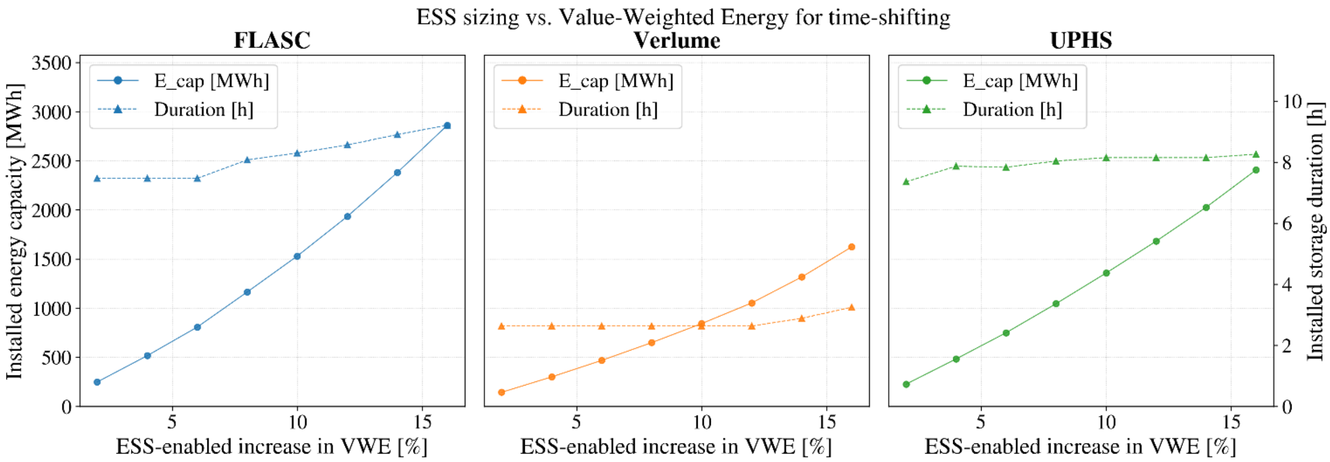

Figure 12. Evolution in energy capacity and installed storage duration as a function of the prescribed relative increase in VWE over the reference wind farm (overplanting level of 5 %), for the Time Shifting use case.

For all technologies, the installed energy capacity follows a polynomial growth with the prescribed VWE increase, albeit at different rates for each technology. To enable a VWE increase from +2 % to +4 %, *FLASC* energy capacity increases by 268 MWh, UPHS by 256 MWh and *Verlume* by 157 MWh. To enable the same increase from +14 % to +16 %, the *FLASC* energy capacity increases by 481 MWh, UPHS by 380 MWh and *Verlume* by 306 MWh. Overall, over the VWE range explored from +2 % to +16, *FLASC* energy capacity increases by 11.5 fold, 10.6 fold for UPHS and 11.3 fold for *Verlume*.

In contrast, the installed storage durations remain largely unchanged with the prescribed VWE increase. Over the whole VWE range, *FLASC* duration increases from 7.5 to 9.2 hours, UPHS from 7.4 to 8.3 hours and *Verlume* from 2.6 to 3.2 hours. Therefore, the installed power capacity increase at a slightly lower rate with the prescribed VWE than the energy capacity.

As the ESS capital expenditure is assumed to scale linearly with both the installed capacity and the rated power, the capital cost will follow the same polynomial growth with the prescribed VWE increase. In other words, enabling a higher VWE becomes increasingly capital-intensive on the storage side. This reflects a diminishing returns effect: each successive increment in VWE demands progressively greater capital investment, suggesting that an upper bound on the VWE increase should be defined. In this regard, it should be noted that the GWh mark is exceeded by all technologies across the range of VWE increase investigated.

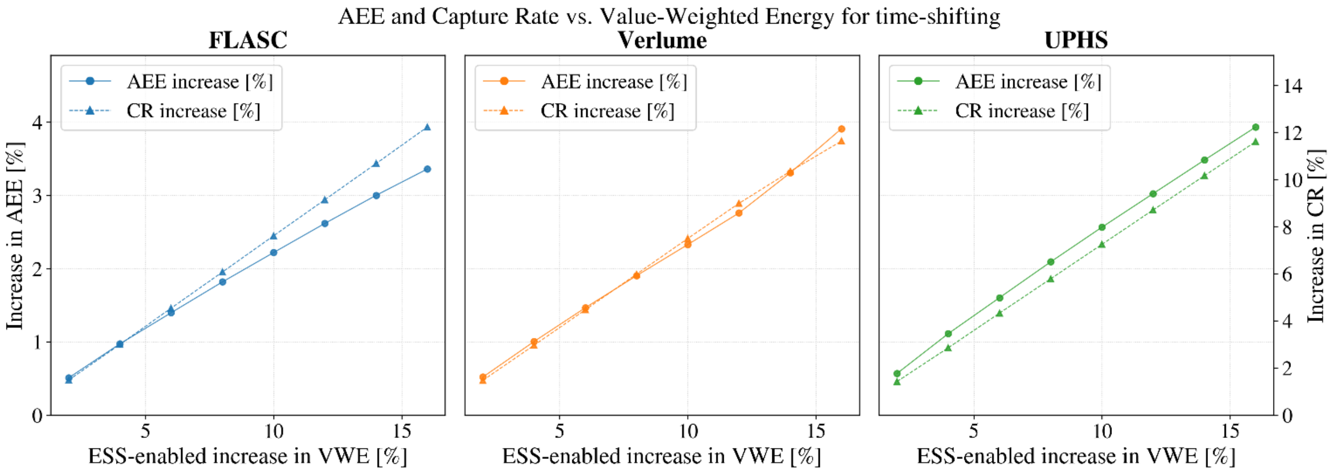

Figure 13. Increase in AEE and in Capture Rate (CR) as a function of the prescribed relative increase in VWE over the reference wind farm (overplanting level of 5 %), for the Time Shifting use case.

The increase in VWE has two components, an increase in the volume of energy exported and an increase in the value of energy exported. Figure 13 illustrates how the three storage technologies navigate this decomposition across the prescribed range of VWE increases. For all technologies, any relative increase in VWE involves a higher relative increase in capture rate than in AEE, and this trend becomes more pronounced at higher VWE increases. For instance, for *FLASC*, a 2 % prescribed VWE increase sees CR accounting for 74 % of the total gain and AEE for 26 %, while for a 16 % increase, CR accounts for 78 % and AEE for 22 %. In other words, increasing the volume of energy exported becomes relatively harder than increasing its value.

2. Capital cost-effectiveness

The variable sweep is enlarged to various overplanting levels between [0–25 %] for the same target VWE increases between [0–16 %]. For instance, one sizing case among that sweep requires the *hybrid wind farm* to deliver an 8 % increase in VWE over the *baseline wind farm*, for an identical overplanting level of 15 %.

The capital cost-effectiveness of the *hybrid wind farm* at delivering system value-weighted energy (VWE-to-CAPEX) ratio is analysed in the following section.

The CAPEX is the total CAPEX of the {wind farm + ESS}, excluding the cost of the transmission infrastructure. We assume that the CAPEX of the wind farm scales linearly, at a rate that corresponds to the CAPEX per MW value from Table 1.

It is assumed that the entire wind production time series is scaled by the overplanting factor, which implicitly assumes that wake losses remain constant and control behaviour stays unchanged.

Figure 14 below displays the variation in the VWE-to-CAPEX ratio for all ESS technologies considered in this study.

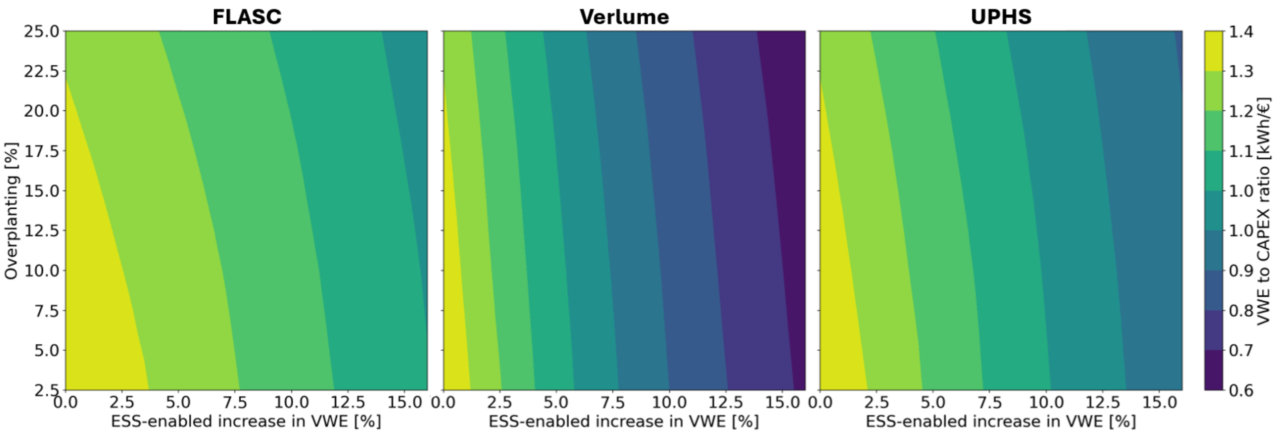

Figure 14.Colored contour plots of VWE to CAPEX ratio for the three ESS technologies.

Overall, for all three ESS technologies, the *reference wind farm* achieves the highest ratio over the entire hybridization and overplanting domain, at 1.4 kWh/€. It means that overplanting or energy storage do not yield a higher cost effectiveness at delivering VWE; under the assumptions taken here. The case of overplanting could reside in diluting a fixed transmission CAPEX, not accounted for here, such that our conclusion should not focus on the relevance of overplanting as such.

However, even if not accounted for, the cost of transmission infrastructure is unchanged over the whole domain of Figure 14, as the export capacity is fixed. Therefore, the above study enables to establish how cost-effective overplanting is with respect to farm hybridization. In that regard, for all three technologies, overplanting enables to increase the VWE at a lower cost than storage. For the case of *FLASC*, the most cost-effective technology studied here, providing a 6 % increase in VWE over the *reference wind farm* , for a *hybrid wind farm* that has the same 5 % overplanting, requires a CAPEX for the ESS alone of 442 m$€_{2025}$, which represents an overall CAPEX increase of 17 % from 2.625 b$€_{2025}$ to 3.067 b$€_{2025}$. This should be compared with the *baseline wind farm* that enables an identical increase in VWE by increasing overplanting alone. This is achieved for 15 % of overplanting (VWE increase of 6.28 % over the *reference wind farm*), at the expense of an additional 250 m$€_{2025}$ which represents an overall CAPEX increase of 9.5 %. Therefore, under the assumptions taken, overplanting is more CAPEX-effective at increasing the value-weighted energy of the farm than the addition of storage.

If the above conclusion can largely be related to the respective CAPEX of overplanting and storage, a more counter-intuitive result can however be observed: overplanting does not create favourable conditions for storage. In other words, it is harder and more CAPEX-intensive for the ESS to provide added-value to a *baseline wind farm* with a higher overplanting. For instance, a minimum of 461 m€$_{2025}$ CAPEX is required, with *FLASC* ESS, to provide a 6 % increase in VWE over the *baseline wind farm* with 15 % of overplanting. That is 4.3 % more than the 442 m€$_{2025}$ CAPEX required for the same 6 % increase in VWE over the *reference wind farm* described in the above paragraph.

B. Increase Export

For the *Increase Export* sizing use case, the effect of the prescribed increase in AEE on storage system sizing is explored for the 5 % overplanting level of the *reference wind farm* and displayed in Figure 15 below.

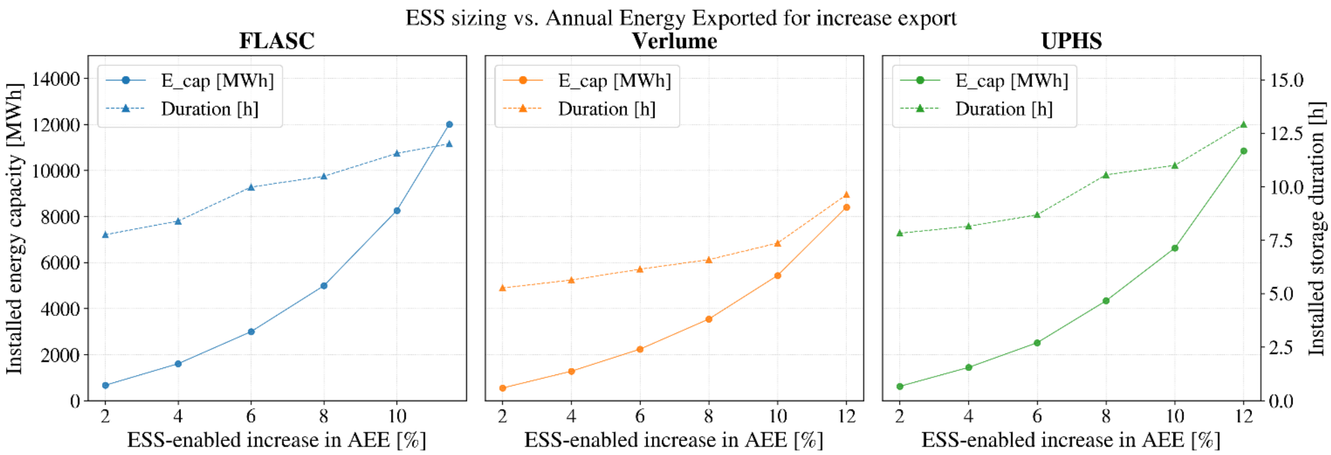

Figure 15. Evolution in energy capacity and installed storage duration as a function of the prescribed relative increase in AEE over the reference wind farm, for the Increase Export use case.

For all technologies, the installed energy capacity follows a polynomial growth of high rate with the prescribed AEE increase. For *FLASC* for instance, the energy capacity increases by 2.4-fold to enable an AEE increase from +2 % to +4 %, and then by another 1.87-fold for the next step to 6 %, etc...The rate of growth is therefore much higher than for the *Time Shifting* use case, underlining how much more demanding increasing AEE is, in comparison to increasing the VWE. To enable a 12 % increase in exported energy, the required installed storage capacity is close to or exceeds the 10 GWh mark for all technologies, which is an order of magnitude beyond the capacity of the largest energy storage park currently developed. Besides, for all technologies and across all relative increases in AEE, installed storage durations are higher than for the same relative increases in VWE, with this being more pronounced for *Verlume*. At 2 % increase in AEE, the storage duration of *FLASC* is 3.4 % higher than for the *Time Shifting* use case, while *Verlume*'s is more than double (+104 %).

VI. CONCLUSIONS

This study explores the optimal sizing of energy storage systems assets of various technologies that could provide a system-value benefit for the wind farm, for two different use cases, one that increase the value-weighted energy of the farm (*Time Shifting*), the other that increase its annual exported energy (*Increase Export*). The *Time Shifting* use case is representative of a *hybrid wind farm* fully merchant on the day-ahead wholesale electricity market and that increases revenues by combining a bigger export volume and a higher strike price. For the *Increase Export* use case, the constraint prohibiting export during negative price episodes is representative of current Contract for Difference (CfD) schemes. Under such schemes, wind farms receive no compensation during negative price hours but are guaranteed a fixed strike price for all energy exported outside those periods. As a result, increasing annual exported energy is the only lever available to improve revenues, making export maximization the natural objective for storage deployment under CfD.

For both *Time Shifting* and *Increase Export* use cases, an optimization routine sizes the energy capacity and the rated power of an energy storage system that minimize its overall capex for a prescribed increase in either value weight energy (*Time Shifting*) or annual energy exported (*Increase Export*) over a *baseline wind farm*. It accounts for high-level specifications of each storage technology investigated: *FLASC*, Underwater Pumped Hydro Energy Storage and *Verlume*. The three technologies can therefore be compared based on the same system-level improvement they provide since identical increases in value-weighted energy and annual energy output are set as requirements of the sizing routine.

Although sizing objectives, wind production profiles, and day-ahead prices are identical, the resulting energy system sizing as well as the dispatch strategy vary significantly from one technology to another. For the *Time Shifting* use case, with a prescribed increase of 10 % in value-weighted energy, *Verlume* ESS has 45 % less energy capacity but 73 % higher rated power compared to *FLASC* system. The corresponding optimal dispatch of *Verlume* ESS involves charge and discharge events that are 20 to 30 % shorter than those of *FLASC* and cover price spreads averaging 17 % lower. The optimal storage system configuration and related dispatch is therefore not solely governed by wind and price variability, but largely by the techno-economic parameters of the technology in question.

A distinctive feature of the present approach is that curtailed power is a design variable of the optimisation, subject to export constraints such as non-firm grid access and negative electricity prices. For both sizing use cases, the curtailment captured by storage differs across the three technologies. In all cases, storage reduces curtailment relative to the *reference wind farm*, though a residual curtailment remains. The techno-economic characteristics of each technology determine how well-suited it is for capturing curtailment events of varying intensity and duration.

A remarkable result is that, for the *Time Shifting* use case, all three technologies achieve, relatively to the *reference wind farm*, the prescribed increase in value-weighted energy through the same balance between a higher volume of energy export (+2.4 % ± 0.3 %) and a higher value of energy exported (capture rate +7.7 % ± 0.5 %).

All three technologies also share a pronounced charge/discharge asymmetry, though its direction reverses across the two use cases. For *Time Shifting*, charging episodes are longer but at lower power than discharging episodes. For *FLASC*, charging averages 6h22 at 111 MW against 2h25 at 152 MW for discharging. This reflects the underlying strategy of the use case: the storage captures wind production that would otherwise be curtailed or exported at low prices, then discharges around local price peaks, naturally producing shorter, higher-power discharge episodes. For *Increase Export*, the asymmetry reverses: charging episodes are shorter but at higher power. For *FLASC*, charging averages 8h40 at 190 MW, against 20h30 at 80 MW for discharging. For that use case, discharge price is irrelevant. Instead, absorbing curtailment matters, which occurs in multi-hour episodes for the *reference wind farm*: on average 5h10, 7h20, and 4h50 for economic, overplanting, and congestion curtailment respectively. The storage must therefore discharge slowly over extended periods to make room for the next curtailment event, resulting in comparatively brief charging episodes.

Across all technologies, the energy storage sizing, in terms of both energy capacity and rated power, required to achieve a given increase in annual exported energy is considerably higher than that needed to deliver the same relative increase in value-weighted energy. This disparity is reflected in the capital cost of the energy storage system, which increases by a factor of 4.3 to 5.3 depending on the technology. Curtailment capture therefore emerges as an economically challenging use case for energy storage, with storage costs that are several times higher than for equivalent value-based improvement. This raises serious questions about the viability of storage deployment under CfD schemes, where the incremental revenue from additional energy exports may be insufficient to offset the disproportionate capital investment required.

A parametric sweep over overplanting levels and prescribed value-weighted energy increases was conducted to assess the cost-effectiveness of storage and identify conditions that favour its deployment. Under the assumptions of this study, that overplanting does not alter farm-level wake losses and that wind farm capital expenditure scales linearly with installed capacity, energy storage is, in the best case, 46 % less cost-effective than overplanting as a means of increasing value-weighted energy. A counter-intuitive result is the adverse interaction between overplanting and ESS. To deliver the same 6 % increase in value-weighted energy, a *FLASC* system requires 4.3 % higher capital cost when paired with a 15 % overplanted farm than with the reference 5 % overplanted farm. Higher overplanting generates more related curtailment, rising from 1.7 % to 5.1 % in this case, which would intuitively seem to create more opportunity for storage to add value. However, the results show that higher overplanting consistently requires more storage to achieve the same relative increase in value-weighted energy, regardless of technology or overplanting level. Under the current conditions, overplanting does not create favourable conditions for storage.

This can be partly attributed to the high capture rate (97 %) of the *reference wind farm* for the study year 2035. In that case, overplanting saturates the most favorable export windows (i.e. high-price periods) and therefore limit the increase in revenues that ESS can bring. In other words, when the average selling price of wind energy (69.4 €/MWh in the case of the *reference wind farm*) is close to the mean market price (71.4 €/MWh), the cost advantage of generating over storing energy becomes the dominant economic driver. In the current price database, negative price episodes are primarily driven by solar cannibalization and the 97 % capture rate of the *reference wind farm* implies that no significant wind-driven price cannibalization is taking place. Overall, our results are largely dependent on the day-ahead price timeseries that are used as inputs, as the shape of the system's energy value profile is the key factor in evaluating the benefits of storage. In that regard, the absence of pronounced wind cannibalization does not provide strong incentives for storage deployment.

Finally, no cost-effectiveness optimum exists across the sizing range: for all technologies investigated, cost-effectiveness decreases monotonically with installed capacity. The relationship between storage system size and system-level KPI improvement, whether in value-weighted energy or annual exported energy, follows a polynomial growth, reflecting a diminishing returns effect: each successive increment of improvement requires a disproportionately larger storage system. This effect is particularly pronounced for the *Increase Export* use case, where obtained sizes exceed by a multi-fold factor the size of the largest storage system currently being developed. The *Time Shifting* use case therefore provides the more relevant reference for defining the storage size ranges of practical relevance for subsequent study.

The analysis presented here does not aim to determine a single storage system size per technology but to sketch a meaningful design envelope within which further study should be focused. The lower bound of this envelope should be defined by a minimum performance threshold: storage capacities that deliver less than a 5 % increase in value-weighted energy contribute negligibly to enhancing the system-value of the offshore wind asset. The upper bound should be defined pragmatically by reference to commercially deployed storage capacities in comparable wind co-located case. In that regard, the *Ørsted Boudica battery ESS* (300 MW / 600 MWh) in the UK, collocated with the *Hornsea* 3 offshore wind farm, can be used as a reference. Our results show that, in the comparable 500 to 650 MWh range, the battery-based system of *Verlume*, in our case the closest technology to the one used by the *Boudica ESS*, enables an increase in value-weighted energy between +6 % and +8 % over the *reference wind farm*.

For the OESTER project, this preliminary sizing study suggests that further work should target a value-weight energy increase of at least 5 %, relative to the *reference wind farm*, and focus on the the lower-to-mid range of the design envelope, where incremental gains in value-weighted energy of +6 % to +8 % remain achievable at moderate storage costs. The three technologies, *FLASC*, *Verlume*, and Underwater Pumped Hydro Storage exhibit different system sizes across that envelope, based on high-level techno-economic parameters such as efficiency and capital cost structure. However, deployment-specific constraints have not been accounted for in the present study and should be considered before the size envelope is refined for each technology individually.

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