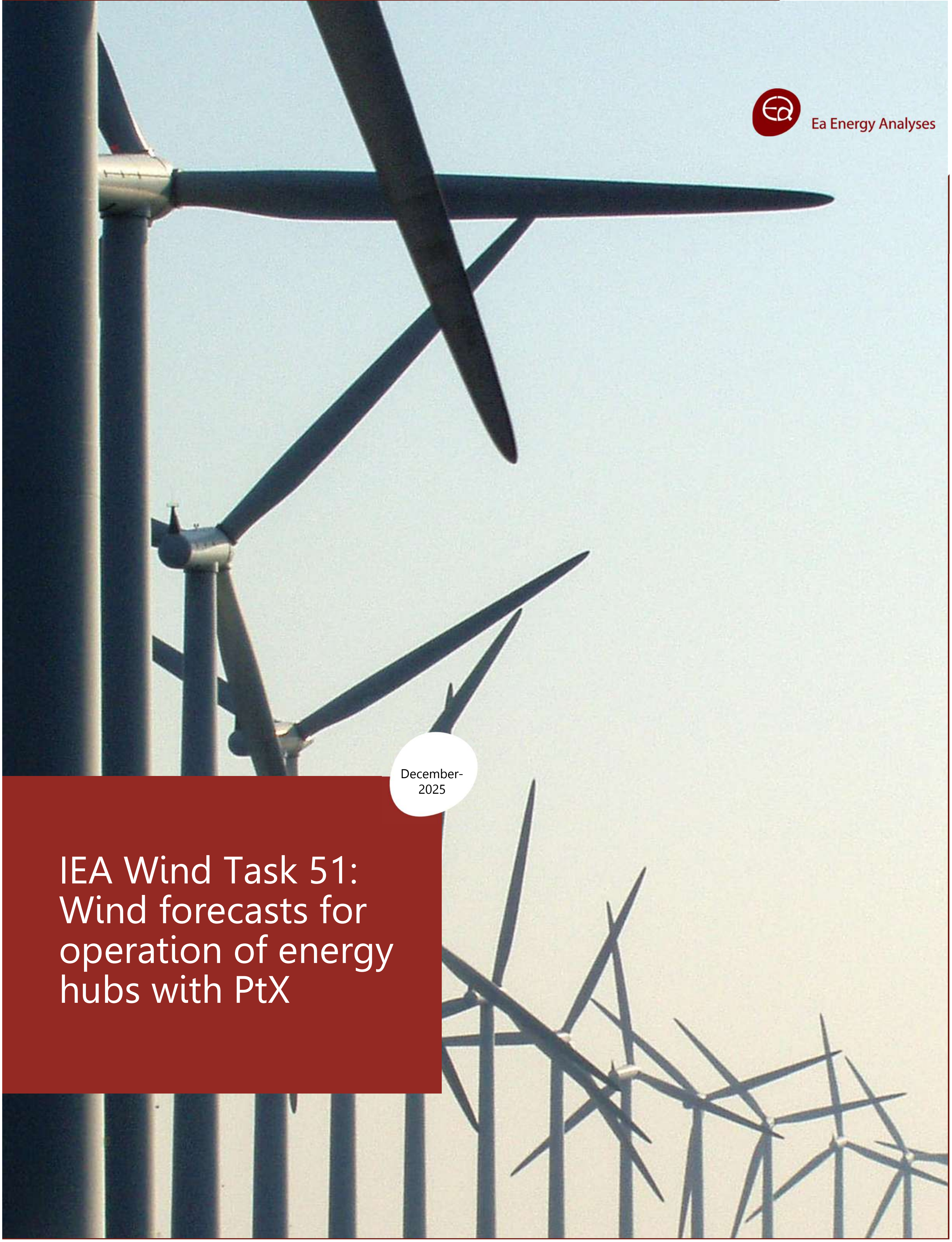

Ea Energy Analyses

December-
2025

# IEA Wind Task 51: Wind forecasts for operation of energy hubs with PtX

Acknowledgement:
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# Contents

# Executive Summary

### General

The present report is part of Ea Energy Analyses' (Ea's) contribution to *IEA Wind Task 51: Value of Forecasting.* The work has received financial support from EUDP (the Danish Energy Technology Development and Demonstration Programme).

A stochastic two-stage optimisation model with rolling horizon has been developed. The model is suited for simulating the operation of a multi-carrier energy hub consisting of wind power, electrolyser ($H_2$ generation) and $H_2$ storage. It is assumed that the hub is operating in the electricity market framework (day-ahead spot market and balancing market) and must deliver a certain amount of $H_2$ on a daily basis. Wind forecasts form part of the uncertainty on an operational basis.

Coupling wind turbines with flexible demand entities, such as electrolysers, create opportunities of behind the meter balancing. i.e. adjusting the operation of the flexible asset to its optimal value and thereby achieve economic benefits. Additionally, new revenue streams can also emerge, such as the participation of the demand units in the TSO managed regulating power markets. Also, the use of probabilistic forecasts is described for a specific case study.

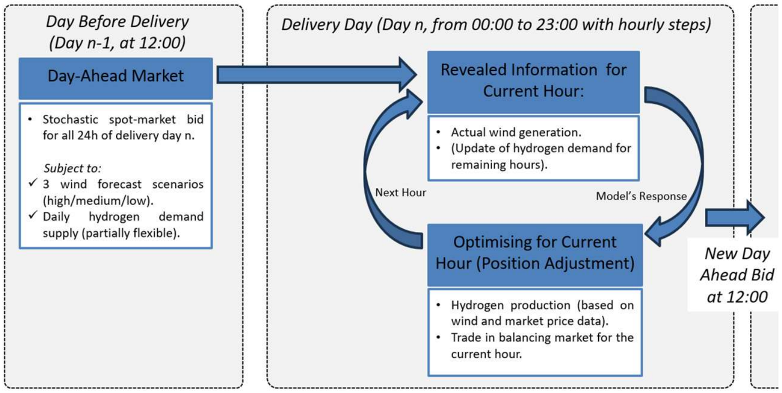
### Methodology

The general logic of the *Rolling Horizon* control scheme for the energy hub involves sequential stepping through each of the decision points of the energy markets (day-ahead and balancing market) and based on the known data and previous decisions at each of these steps solving a two-stage or multi-stage stochastic program, depending on the targeted model complexity level. Each of the optimisation problems are solved for a predefined foresight duration.

In the context of an energy hub participating in electricity markets but also aiming to satisfy a hydrogen demand at the least costly way, the demand for hydrogen is actively updated along the model's progress, based on the amount that was produced so far while updating the residual demand for the upcoming hours.

### Case study

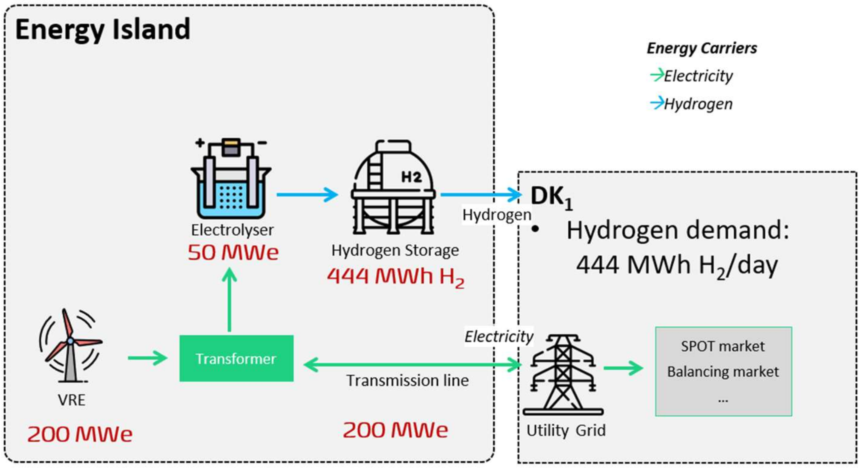
The illustration of the model with a rolling horizon technique in our case study is shown in the following figure:



*Operational example of a combined stochastic model with a rolling horizon method*

The day before delivery, the stochastic spot market bids for the next day are calculated based on three wind forecasts (high, medium, low) and the daily demand for hydrogen delivery. The next stage is the real time adjustments when the wind realisation is being revealed together with balancing prices.

The energy hub in the case study and the analyzed scenarios are described in the following figure:



*Technical setup of the analysed multi-carrier energy hub*

The hub consists of a 200 MW onshore wind farm, a 50 MWe alkaline electrolyser (efficiency 67%) and a compressed hydrogen storage tank with a capacity of 444 MWh $H_2$, equal to the daily targeted hydrogen supply volume.

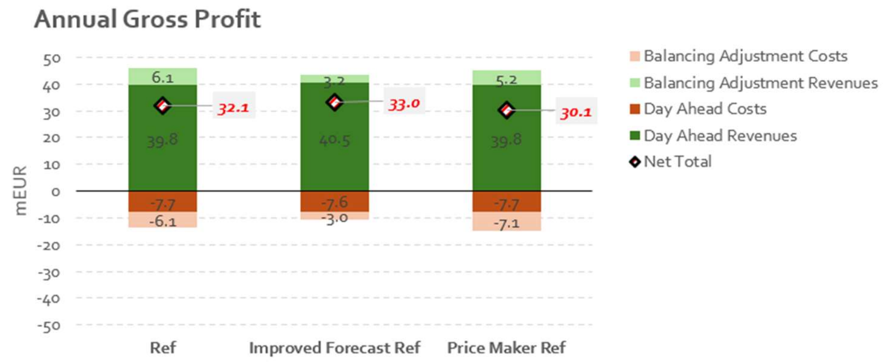
An overview of the 5 analysed scenarios in the present study can be found below.

*Analysed scenarios in the present study*

| Case | Scenario Name | Description | Evaluation |
|---|---|---|---|
| 1 | ***Ref*** | Obligation to an $H_2$ offtake agreement of 444MWh $H_2$ per day at a maximum 10% hourly deviation. | Evaluation of the annual gross profit of a base case scenario. |
| 2 | ***Improved Forecast Ref*** | Case 1 with improvement of the forecast scenarios by a factor of 50%, bringing them closer to the realised scenario. Scenarios remain equiprobable. | Impact of improved wind forecasts on the gross profit levels of case 1. |
| 3 | ***Price Maker Ref*** | Case 1 with original wind forecast scenarios, but with endogenously defined balancing market prices for the wind farm (price maker considerations). The new prices are a function of the hub's imbalances, on the basis of whether they hinder or benefit the broader balance of the system. | Due to the limited volume of balancing needs in the system in the evaluated bidding zone, the impact of the hub's imbalances on the system's balance and therefore balancing prices is being evaluated against the deterministic price taker conditions of case 1. |
| | | | |
| 4 | ***Price Maker + Improved Forecast*** | Monetary effects of combining cases 2 and 3. To be compared against case 3. | Combined monetary evaluation of cases 2 and 3. |
| 5 | ***Price Maker + Improved Forecast + Flex*** | Monetary effects of combining cases 2 and 3, while allowing for more flexibility on the hour-to-hour deviation of hydrogen sales. The 10% condition of case 1 is being eliminated. | Assessment of the benefits that flexible offtake contracts can enable. |

## Results

The figure below illustrates the annual gross profit for the hub in case 1 (reference), 2 (improved forecast) and 3 (price maker reference). The cashflows stem from trading in the day-ahead and balancing markets. The optimisation of the hub's operation is done subject to 3 probabilistic wind forecasts and daily delivery of a certain amount of hydrogen (444 MWh $H_2$/day). As expected, the largest benefit comes from day-ahead market trading. Balancing adjustment costs and benefits have smaller values and approximately cancel each other out.



*Annual gross profit in cases 1, 2 and 3 (see description of cases in table above)*

## Value of wind forecast

Utilising a more accurate wind forecast *(Improved Forecast Ref)* impacts the hub's economy by approximately halving both balancing costs and benefits compared to the reference (*Ref)*. Besides, it provides in our case an overall better Gross Profit at 33.0 m€, 0.9 m€ higher than without an improved by 50% wind forecast.

Intuitively, this can be expected. More precise forecasts will reduce trading in the balancing market and expectedly yield better overall economic results. However, when trading in the balancing market, both gain and loss of money can be expected. This fact is due to the single imbalance pricing design of the balancing market. If the hub realises an opposite balance compared to the system's balance, additional revenues will be accrued:

- it will sell the over-supply (hub must downregulate) compared to the day ahead- bid at the up-regulating price, which normally is higher than the day-ahead price or

- it will purchase under-supply (hub must upregulate) compared to the day-ahead bid at the down-regulation price, which normally is lower than the day-ahead price.

In analogy the hub will lose by trading in the balancing market (compared to trading solely in the day-ahead market) if the hub has the same direction of balancing as the system.

This rationale explains that an improvement of the hub's economy cannot be guaranteed when solely improving the hub's wind forecast. Even in the extreme case of a perfect forecast (forecast equal to realisation), an overall poorer hub economy can emerge, than in a normal case with hourly imbalances.

Switching from price taker (*Ref)* to price maker (*Price Maker Ref)* conditions in the balancing market reduces the overall gross profit with about 2.0 m€ (from 32.1 to 30.1 m€) per year, via increasing the balancing costs and reducing the balancing revenues for the hub with approximately 1.0 m€ each way. This is to be expected as the hub's imbalance in the price maker case impacts the imbalance price unfavourably for the hub's trading activities in the balancing market (the hub's imbalance is in some hours significant compared to the total system imbalance, which impacts the resulting balancing prices compared to the price taker case).

# 1. Introduction

The present report is part of Ea Energy Analyses' (Ea's) contribution to *IEA Wind Task 51: Value of Forecasting (WP3)*[1].

A large part of Ea's efforts and hours have been used to develop a stochastic two-stage optimisation model with rolling horizon for operation of a multi carrier energy hub consisting of wind power (subject to forecast), electrolyser ($H_2$ generation) and $H_2$ storage ($H_2$ flexibility). The hub is operating in the electricity market framework (day-ahead spot market and balancing market) and must deliver a certain amount of $H_2$ on a daily basis.

After the model's has been developed and tested, the present case study has been evaluated.

The work aims to show the use of probabilistic forecasts in selected markets, with an emphasis on wind energy in combination with PtX facilities. Documentation and communication of the assessment will be brought forward, considering various metrics and evaluations, aiming to show how forecasting is used in the overall operation on such setups. The overarching goal of the analysis is generating foreground knowledge for future developers and analysts by demonstrating optimised operations for PtX activities.

[1] This report has received financial support from EUDP, as part of the IEA Wind Task 51 Forecasting, Danish Consortium, EUDP project number 134-22015

## 1.1. Background

Hybrid power plants are becoming an increasingly important unit of the modern energy systems. They combine both demand and supply units, benefitting from synergies between different processes via producing and trading multiple energy carriers. Therefore, the decision-making process inevitably becomes more complex, but also opens up a series of opportunities for the optimisation of this type of asset layouts. One of these opportunities is related to optimisation of energy market participation.

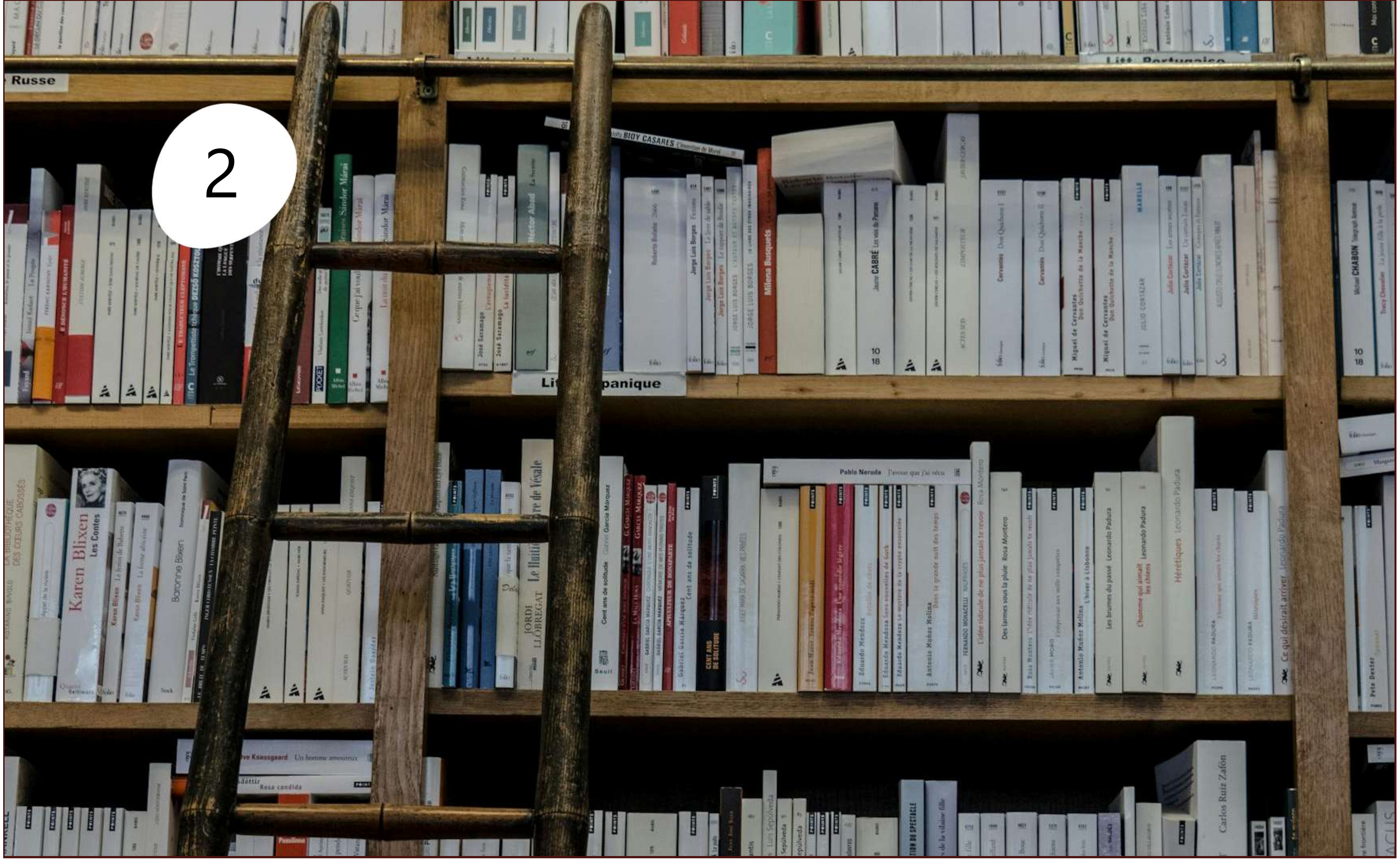
Parallel participation to markets such as the liberalised electricity markets in Denmark and other bilateral product agreements (e.g. purchase agreement of PtX fuels) adds layers of complexity on the decision making during the design or scheduling of energy hubs. On the flipside, interlinked "*behind-the-meter*" assets can provide a hedge against the various risks that revolve around the activities of these establishments.

Those risks could be linked to aspects like the mismatch of forecasts versus the realisation of variable renewable energy (VRE) powered operations, where utilising the implicit flexibility of behind-the-meter assets upon real time operations can provide the means for the reduction of balancing costs. Additionally, on the broader horizon, assessment of the returns in multi-carrier commodity setup can be the proof of concept and thereby breeding ground for the formation of such multi-carrier setups, which can ensure a high product value for the involved asset owner(s) across all stages of the project's lifecycle and a minimum level of returns even in the worst-case scenarios of the key market conditions.

## 1.2. Balancing of hubs by using flexible demand of PtX (electrolysers)

With the bulk of VRE power generation sales in Denmark being traded over the Day-Ahead market, and a gate closure for the bidders at 12:00 (midday) during the day before physical delivery, decisions for the scheduling of power trading assets have to be made 12-36 hours in advance of real-time operations. Due to the intermittent nature of VRE units, deviations from the accepted bids necessitate the settlement of imbalances recognised before or during the delivery hour.

Imbalances can be reduced in the Intraday market and finally settled in the TSO's balancing market. However, coupling VRE units with flexible demand entities, such as electrolysers, create opportunities of behind the meter balancing. i.e. adjusting the operation of the flexible asset to its optimal value and thereby achieve economic benefits. Additionally, new revenue streams can also emerge, such as the participation of demand units in the TSO managed regulating power markets.



# 2. Methodology

## 2.1. Theoretical Optimisation Backgrounds

With multiple opportunities for resource allocation present at any given moment in parallel to uncertain realisations of power generation or/and electricity prices during the operation of multi-carrier energy hubs, the decision-making process towards the best economic output requires the deployment of a series of optimisation techniques.

Therefore, there is a need for a framework that would allow actors to evaluate the potential uncertainty and use this information for taking well informed decisions. This need becomes even more apparent when maximizing the profit for the complex setups such as hybrid power plants. *Stochastic Optimisation* provides a framework for complex decision making under uncertainty over a set of probability weighted parametric scenarios.

In the core of *Stochastic Optimisation* (Figure 1) is the idea that the overall best decision can be found by quantifying the uncertainty into set of probability weighted scenarios and optimizing the decisions across all the scenarios. Later, the recourse action can be taken to account for the realisation of this uncertainty. According to the stochastic programming method, there are two types of decision variables namely: *Here-and-Now* and *Wait-and-See* decision variables. “Here and now” is decision that market participant must take “now” under some kind of uncertainty and “wait and see” is decision that market participant will take when the uncertainty is revealed. This type of program is called multi-stage stochastic program with recourse decisions.

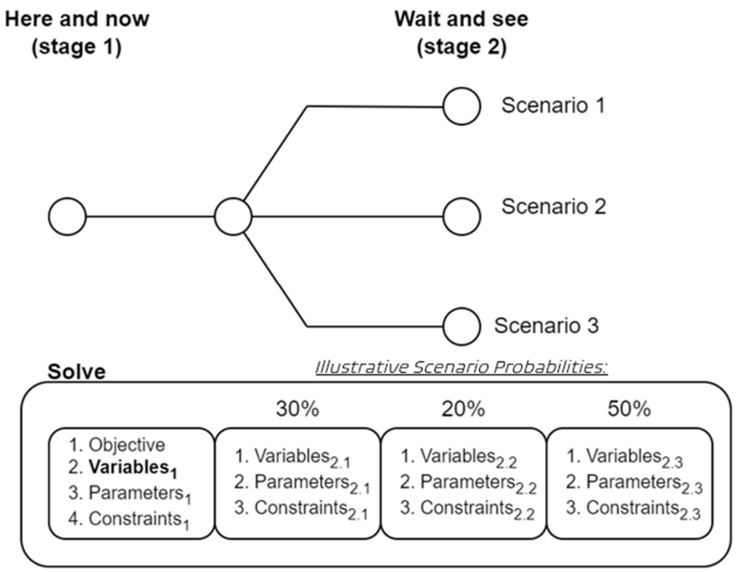


***Figure 1****. illustration of the rationale of a stochastic optimisation*

*Stochastic Optimisation* is ultimately a *proactive approach* that attempts to take all possible sources of uncertainty into consideration, in an attempt to tame the impacts of uncertainty in specific scenarios that may get realised. The best modelling result can be achieved when combining two types of approaches, *Proactive and Reactive*. The reactive approach is built upon forecast updates which reveal how the uncertainty unfolds, in order for corrective measures to be taken (e.g. adjustment of energy hub scheduling).

It becomes evident that there is an imminent need for updating the data with the best available knowledge of uncertainty estimations between simulation runs, especially in models of longer horizon (e.g. annual evaluations with hourly timesteps). For that reason, instead of running one uninterrupted multi-stage stochastic program, the option with repetitive solutions of smaller size stochastic programs and realistically achievable foresights, with the possibility of updating data between runs and market bids was chosen. This approach extends the decision-making process from a single decision to multiple sequential decisions, bound to previous choices and other constraints, accounting for unforeseen system changes upon forecast updates.

The developed *Rolling Horizon* approach was introduced alongside the implemented stochastic model, aiming to constantly update market and system states, allowing therefore for corrective actions across the optimisation horizon in order to dynamically optimise the dispatch of the energy hub to the best possible extent, while respecting the technical characteristics of all involved assets and all related market constraints.

The flow chart explaining the application of the *Rolling Horizon* planning technique for market bidding process can be seen in Figure 2.

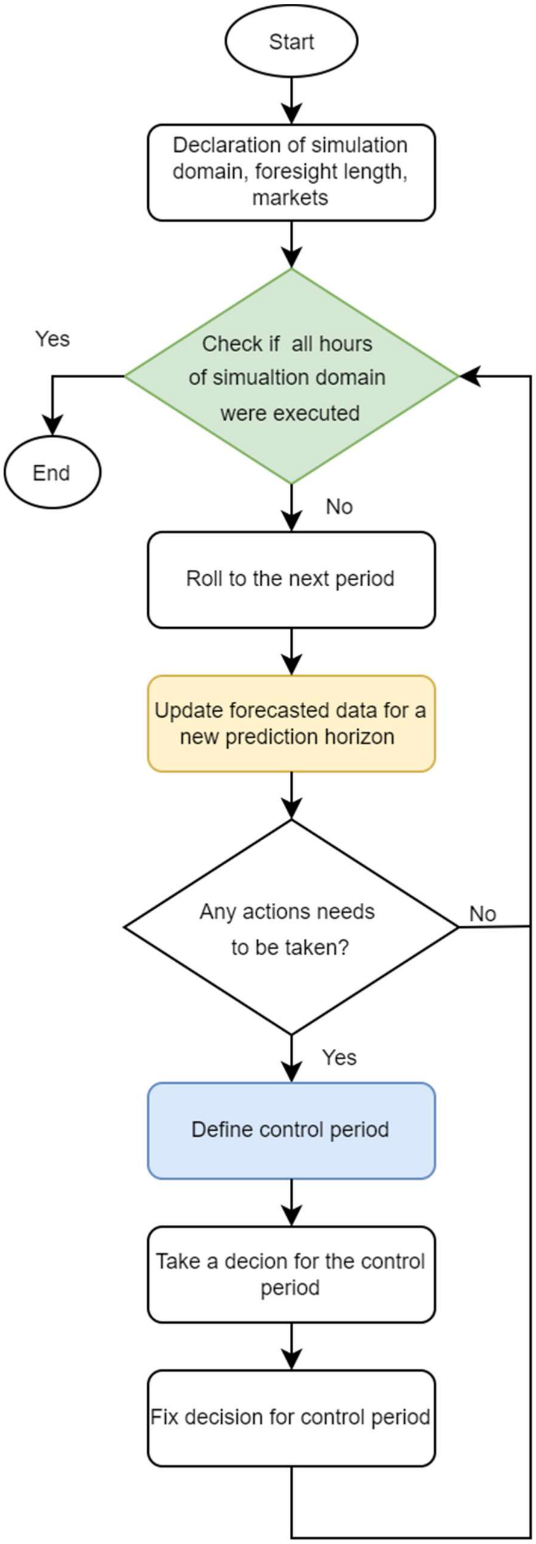


***Figure 2****. Illustration of the rationale of a rolling horizon technique*

## 2.2. Real-life Application

The general logic of the *Rolling Horizon* control scheme involves sequential stepping through each of the decisions points (energy markets) and based on the data available at each of these steps solving a two-stage or multi-stage stochastic program depending on model complexity level. Each of the optimisation problems are solved for a predefined foresight duration. When the optimal bid size is calculated, the model would fix the value corresponding to the specific market and time and continue going through the rest of the decision points (markets) until all the decision steps within the scope of the analysis have been taken.

In the context of an energy hub participating in electricity markets but also aiming to satisfy a flexible hydrogen demand at the least costly way, the demand for hydrogen is actively updated along the model's progress, based on the amount that was produced so far while updating the residual demand for the upcoming hours.

A narrowed example of the combined application of a stochastic model with a rolling horizon technique, as will be applied in the case study in chapter 3, can be found in Figure 3.

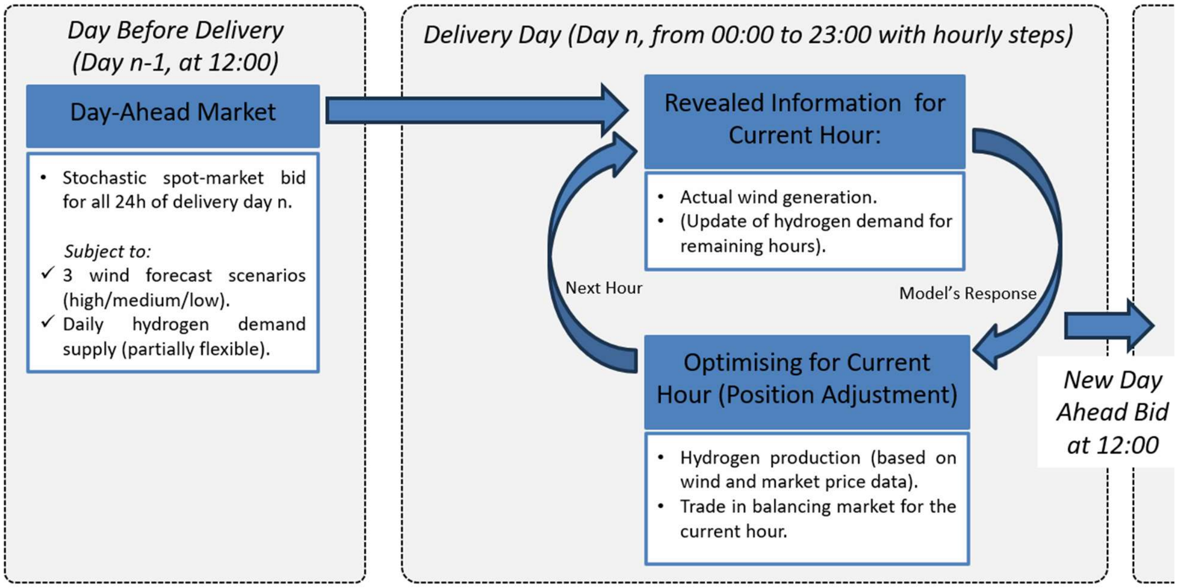


***Figure 3**. Operational example of a combined stochastic model with a rolling horizon method*

In case that the electricity market prices for day-ahead products are to be considered as a stochastic parameter, a slightly more complicated form of the control scheme must be implemented to account for the additional layer of uncertainty. However, further evaluation of multiple stochastic aspects is out of the scope of the present analysis.

# 3. Case Study

A local multi carrier energy system will be set under the microscope, providing the ground as proof of concept of the developed methodology. The energy hub will comprise of an on-site wind farm, alongside an electrolysis and a hydrogen storage tank. The layout and numerical characteristics of the system are illustrated in Figure 4.

The analysis targets the optimal economic performance of the multi-carrier energy hub across the selected rolling year, while supplying the agreed upon hydrogen offtake, as well as all applicable technical and market constraints. That is, the objective value of the model is the minimisation of the annual operational costs for the hub, while accounting for revenues via power exchanges. Price taker conditions (historically deterministic power market prices) are adopted in the reference case of the model, while price maker assessments are further examined during the evaluation of the *Value of Forecasting*. The source of uncertainty revolves around the forecasting of wind conditions in the area, and thereby the power generation of the wind turbine.

The examined system is situated in the western Danish bidding zone (DK1). For the sake of computational ease, only Day-Ahead and Balancing electricity market participations are considered for the hub, alongside the flexible, to an extent, daily hydrogen demand.

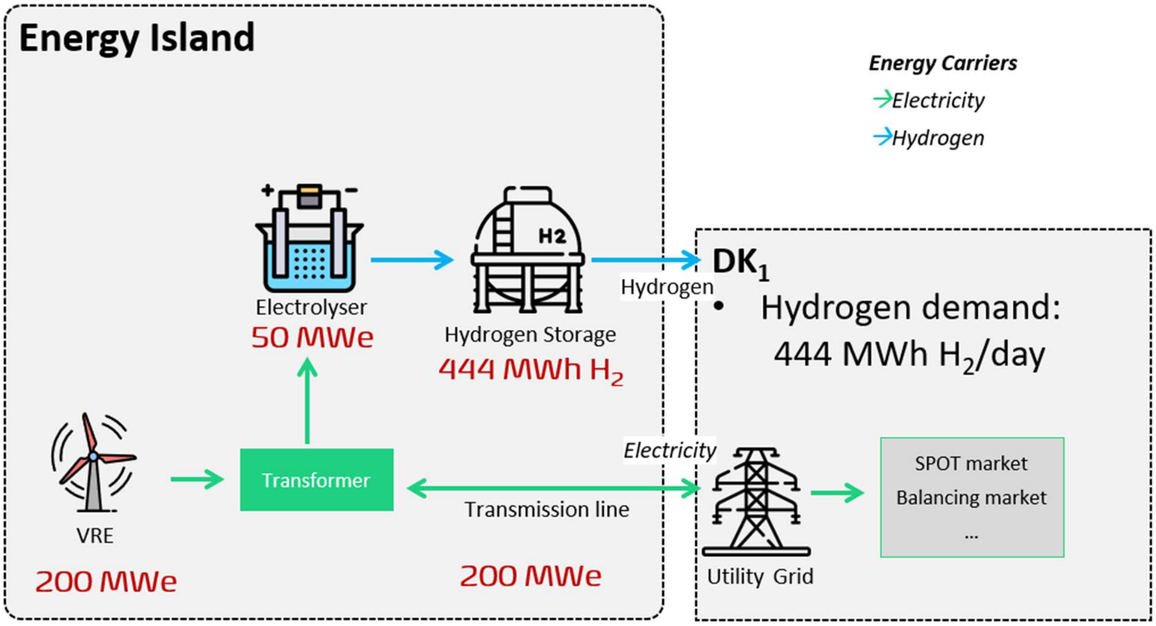


***Figure 4***. *Technical setup of the analysed multi-carrier energy hub*

## 3.1. Input Data and Optimisation Horizon

Naturally, deriving the value of good wind forecast requires an extended evaluation, that is, including multiple markets and timesteps. An annual evaluation was selected for the present analysis, based on the provision of wind forecasting scenario data by ENFOR[2].

Based on this data availability, the analysis span ranged from the beginning of August 2021 to the end of July 2022 (rolling year), with an hourly temporal resolution. The historical power market prices for DK1 were accessed via Nordpool and Energinet. Grid tariffs, reflecting transmission payments, are also accounted for in the model. For the sake of better representation, a restructuring (shuffling) of these datasets was undertaken, forming a calendar year (1st of January to 31st of December), while preserving the correlation between power generation forecasts/realisation and historical electricity market prices.

A summary of the adopted wind generation scenarios (forecasted and realised), as well as the accounted for electricity prices (day ahead and balancing) can be seen in Figure 5 in the form of descending duration curves. The realised FLHs (Full Load Hours) for the assessed wind farm reach slightly under 2,500 hours per year, while the average day ahead electricity price amounts to 163 €/MWh, which is of course a high value compared to other years. The high power prices and the related volatility are caused by the extreme market conditions of the evaluated period as a result of the European gas crisis at that time. The standard deviation of the hourly spot price is approximately 96 €/MWh. The Balancing market curve reflects a single imbalance price. The Day Ahead and Balancing market curves are illustrated together in an attempt to depict the magnitude of the experienced prices. With the focus of the study being on the value yielded by good wind forecasting across relative scenarios, the abnormally high prices do not impose a direct problem.

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[2] The company ENFOR (www.enfor.dk) is also s participant of the *IEA Wind Task 51*

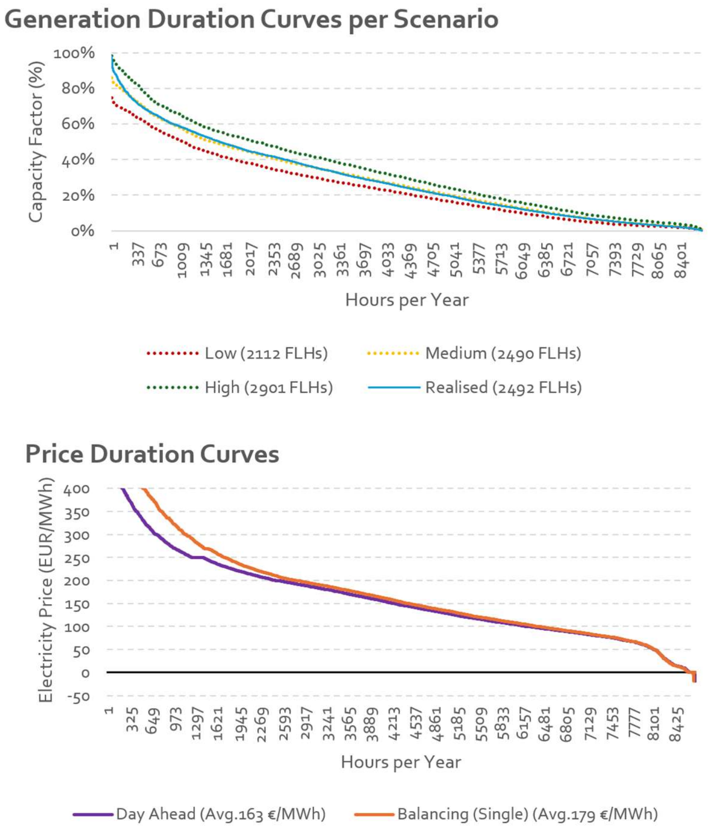

***Figure 5**. Summary of wind generation and power price datasets*

***Note:** For visualisation purposes, the scale of the y-axis is limited to 400 €/MWh, while the maximum values rise to 700 €/MWh for the Day Ahead curve and 1344 €/MWh for the Balancing price curve. In respect to data availability, the wind generation forecasts are updated daily with predictions for the next 373 hours. Nevertheless, the utilised foresight during the day ahead stage is limited to the end of the next delivery day (12 to 36 hours ahead of the gate closure).*

The technical characteristics of the installed assets are reflecting the specifications described by the Danish Energy Agency (DEA) and the Danish Technology Catalogues, for the projected technological maturity of the evaluated horizon (Table 1).

**Table 1.** Technical characteristics of installed assets[3]

| Technology | Capex | Fixed O&M | Variable O&M | Efficiency |
|---|---|---|---|---|
| **Onshore Wind Turbines** | 1.34 m€/MWe | 16.6 k€/MWe/y | 1.8 €/MWh(e) | - |
| **AEC Electrolysis[4]** | 0.71 m€/MWe | 25.8 k€/MWe/y | - | 67% |
| **$H_2$ Storage (Steel Tank)** | 0.07 m€/MWhH$_2$ | 0.7 k€/MW H$_2$/y | - | 88% (roundtrip) |

***Note:** The capex and O&M data for $H_2$ equipment is used in chapter 3.4, table 3.*

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[3] Data from the DEA: Danish Technology Catalogues: https://ens.dk/en/our-services/technology-catalogues

[4] Alkaline electrolysis cells

## 3.2. Proof of Concept

An illustration of the daily optimisation's behaviour across its decision-making stages is presented in Figure 6, representing the day with the **median** wind generation forecast across the utilised dataset (272nd bidding day of the year, i.e. 29th of September).

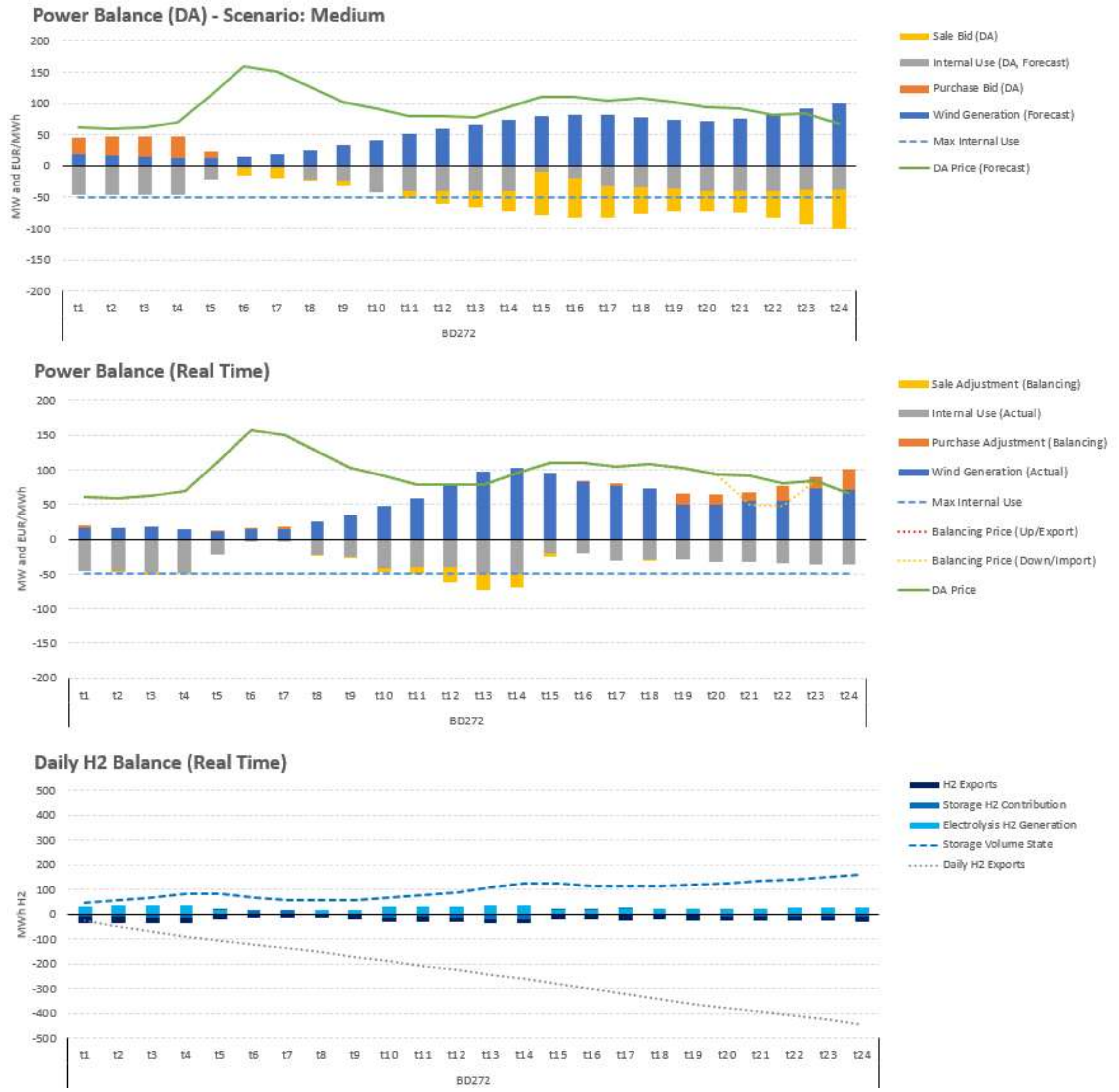

***Figure 6**. Evaluation of the model's behavior in the median wind production calendar day*

***Note:** For visualisation purposes, the forecasts of wind generation and internal electricity use in the top graph reflect the expectation of the medium wind production scenario.*

A series of distinctive decision-making patterns can be observed within the given day, summarised as follows:

- **t3:** *Low Prices with Low Wind Production* -> Purchase bid during the Day-Ahead (DA) stage, aimed to high $H_2$ generation. If during real time operations a surplus of wind generation emerges, then additional power sales in the balancing market take place, in case that the electrolyser's capacity has been already exhausted.

- **$t_7$**: *High Prices with Low Wind Production* -> Devoted power sale bid during the Day-Ahead (DA) stage, leading to no $H_2$ generation. If during real time operations a deficit of wind generation emerges, discharging of the $H_2$ storage is following alongside the necessary levels of purchases from the balancing market, aiming to settle the mismatch of the DA bid against the real time wind generation.
- **$t_{11}$ & $t_{14}$**: *Mid-Low Prices with High Wind Production* -> High $H_2$ generation without market purchases but with occasional power sales. If during real time operations a surplus of wind generation emerges, then additional power sales in the balancing market take place, in case that the electrolyser's capacity has been already exhausted.
  - $t_{14}$ reflects the more complicated effects that the model has to address, spanning longer than the specific targeted hour of the DA bid. Such dynamics drive partial electrolysis operation in hour $t_{14}$, even if the hourly-specific cost benefits would lean towards a market participation (73% of the wind generation forecast is aimed towards a sale bid, while 27% towards internal use by the electrolyser). These model dynamics involve forward looking actions based on the available foresight (e.g. charging of the hydrogen storage at the best possible price conditions), but also the fulfilment of the imposed condition that $H_2$ sales cannot deviate more than 10% from hour to hour (a condition which was set in an attempt to approximate a relatively stable offtake obligation).

## 3.3. Balancing Mechanisms

At the absence of perfect forecasts, the need for adjustments of the hub's planned operations frequently occurs. While the balancing power market offers an alternative for addressing DA bid mismatches, multi-carrier energy setups can also benefit from the possibilities of internal balancing. In the examined case, this can take the form of up or down ramping of the electrolysis facility operations with implications for charging or discharging of the onsite hydrogen storage.

An illustration of the "activated" balancing actions by the hub for the examined bidding day (BD272) is presented in Figure 7. The hub's reactions to forecast errors can be summarised below:

- *Power excess realisations:*
  - **$t_{10}$**: Sale of wind generation surplus to the balancing market.
  - **$t_{14}$ & $t_{15}$**: Rise of internal power consumption from the electrolyser, leading to higher $H_2$ sales. Residual wind generation surplus is sold to the balancing market.
- *Power deficit realisations:*
  - **$t_{18}$**: Decrease of internal power consumption from the electrolyser, accompanied by lower $H_2$ storage charge, leading to some higher $H_2$ sales. Residual wind generation deficit is purchased by the balancing market.
  - **$t_{22}$**: Decrease of internal power consumption from the electrolyser, accompanied by higher $H_2$ storage charge, leading to lower $H_2$ sales. Residual wind generation deficit is purchased by the balancing market.

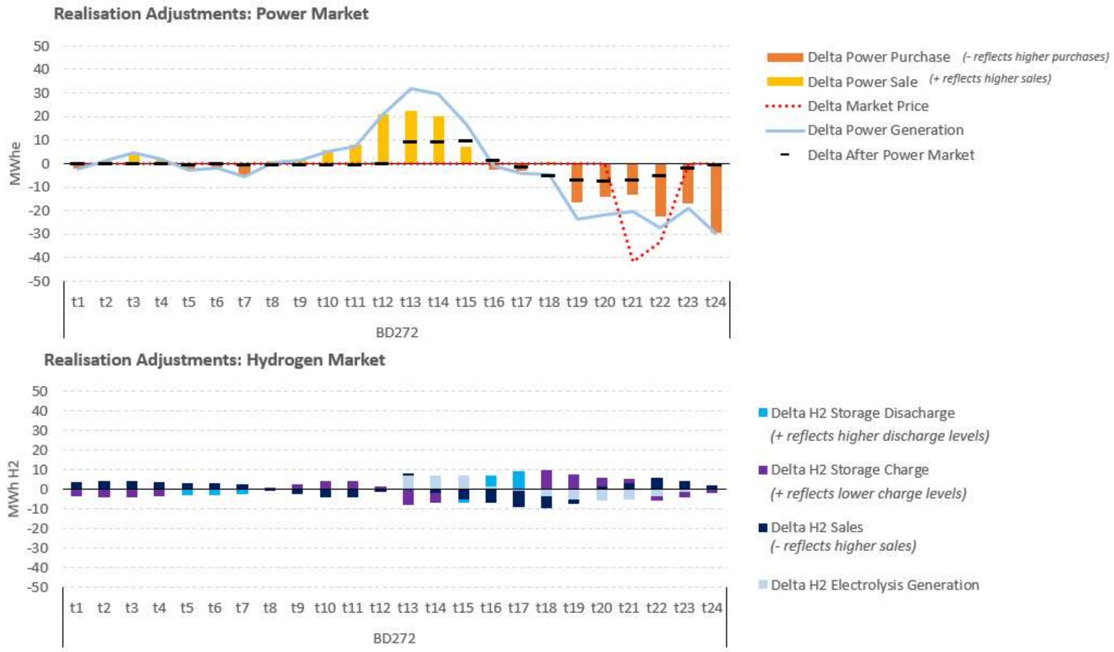

***Figure 7**. Balancing reactions to forecast realisations by the system*

***Note:** Top graph: The category "Delta After Power Market" in the top graph represents the imbalance quantities that are handled internally within the hub. The horizontal black marker overlaps the graph and is not stacked, while residual categories are visualized by stacked bars. Also note that delta power generation doesn't necessarily correspond to an adjustment of the DA bid (e.g. in case where the whole forecasted generation was not bid in the market). Delta market price corresponds to the balancing electricity price minus the day ahead market price (difference).*

The top part of Figure 7 stresses out the theoretical conflicts that deterministic price taking assumptions can create when linked with forecasts and realisations of wind power generation. The majority of hours of BD272 historically led to a balanced power system (the delta of the market price against a single balancing price was 0 (red dotted line). Such price occasions don't necessarily correspond to bid mismatches in the system, but they could also emerge due to overall system balancing via the unilateral bid mismatches across actors. However, with the forecast error rising to an absolute of 30 MWh for some hours of the analysed day (light blue line), a negative influence on the balancing price (according to direction) can be expected, due to the considerable imbalance size against the usual market depth in $DK_1$ (~75 MWh past 2021). An evaluation of the impacts of price maker considerations will be analysed in section 3.4.

## 3.4. Annual power balances and economics

Taking as point of departure the outcomes of the already presented model (Figure 4 and Paragraph 3.1), hereafter referred to as "Reference" case, the power balance expectation during the day ahead bidding stage (for the three wind forecasts) as well as the ultimate realisation can be seen in Figure 8.

It becomes evident that the realisation of wind generation (bottom graph) roughly in total matches the annual generation of the medium scenario (top graph). Nevertheless, the hourly realisation patterns reveal higher deviations from what the medium forecast expected ahead (reflected in the DA adjustments). This is stressed by the larger electricity amounts being traded and purchased for the hub over the balancing market, than expected during the DA bidding stage. While in the day ahead stage the model is prevented from relying on balancing market price expectations, unless absolutely necessary for satisfying the power balances across all possible scenario realisations (ensuring the avoidance of infeasibilities in cases of extreme wind generation differences between scenarios), the balancing stage reveals balancing needs of approximately ~45 GWh in each direction (up and down), beyond the internal self-balancing capabilities of the hub via utilising the storage asset and the electrolyser's ramping abilities.

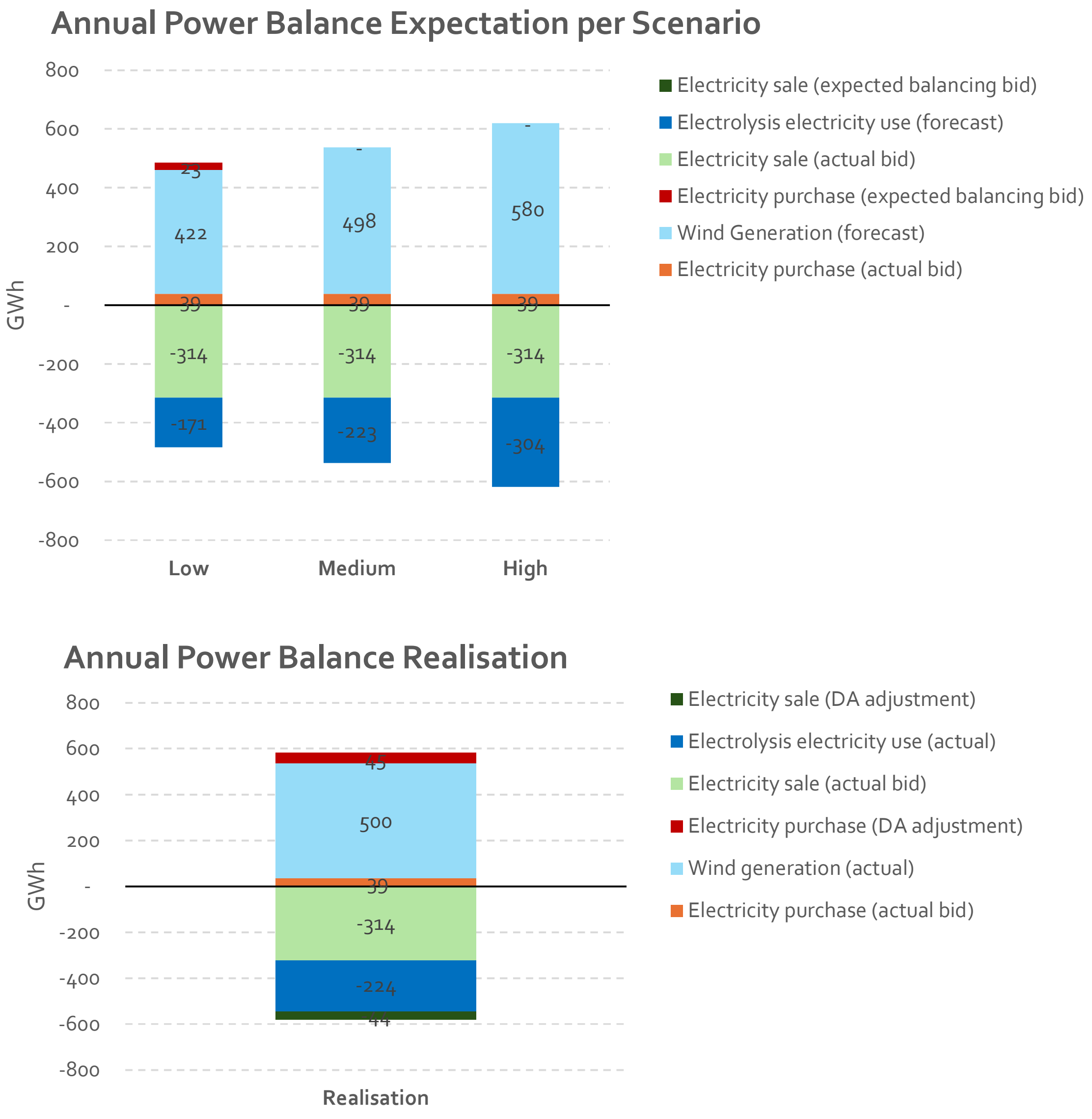

***Figure 8**. Energy Hub's annual power balances*

****Note:** Upper figure – expectation per scenario. Lower figure - actual realisation*

The value of good wind forecasting can be directly reflected in the economic flows that the energy hub encounters via electricity market trading. It is to be expected that better wind forecasting will correspond to more accurate asset scheduling and therefore longer technical lifetimes with lower ramping changes, but farther insights on the technical utilisation of the assets considered is out of the scope of the present analysis.

A series of scenarios will be brought forward to evaluate the value that improved wind forecasts can have on the annual gross profit of the energy hub. These can be seen in Table 2.

***Table 2.** Analysed scenarios in the present study*

| Case | Scenario Name | Description | Evaluation |
|---|---|---|---|
| 1 | ***Ref*** | Obligation to an $H_2$ offtake agreement of 444MWh $H_2$ per day at a maximum 10% hourly deviation. | Evaluation of the annual gross profit of a base case scenario. |
| 2 | ***Improved Forecast Ref*** | Case 1 with improvement of the forecast scenarios by a factor of 50%, bringing them closer to the realised scenario. Scenarios remain equiprobable. | Impact of improved wind forecasts on the gross profit levels of case 1. |
| 3 | ***Price Maker Ref*** | Case 1 with original wind forecast scenarios, but with endogenously defined balancing market prices for the wind farm (price maker considerations). The new prices are a function of the hub's imbalances, on the basis of whether they hinder or benefit the broader balance of the system. | Due to the limited volume of balancing needs in the system in the evaluated bidding zone, the impact of the hub's imbalances on the system's balance and therefore balancing prices is being evaluated against the deterministic price taker conditions of case 1. |
| | | | |
| 4 | ***Price Maker + Improved Forecast*** | Monetary effects of combining cases 2 and 3. To be compared against case 3. | Combined monetary evaluation of cases 2 and 3. |
| 5 | ***Price Maker + Improved Forecast + Flex*** | Monetary effects of combining cases 2 and 3, while allowing for more flexibility on the hour-to-hour deviation of hydrogen sales. The 10% condition of case 1 is being eliminated. | Assessment of the benefits that flexible offtake contracts can enable. |

The annual gross profit of the energy hub (Figure 9) under the reference case scenario ("*Ref*") for the evaluated period (as described in Section 3.1) rises to 32.1 m€ via its electricity trading with the day ahead market and the consequent balancing actions, while in parallel supplying a revenue-less (for the context of the present analysis) hydrogen generation obligation of ~162 GWh $H_2$.

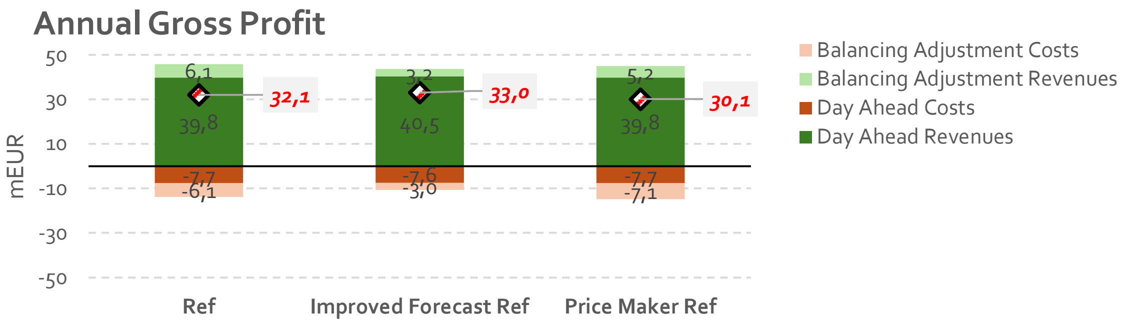

***Figure 9**. Gross profit perturbations of the Reference case*

As already seen in Figure , the overall electricity sale and purchase volumes during the balancing stage roughly match each other, and the balance of revenues and costs through the balancing market cancel each other out, when considering the market price and transmission tariffs.

Overall, by utilising a more accurate wind forecast ("*Improved Forecast Ref"),* the hub's economy is impacted by approximately halving both balancing costs and benefits. Nevertheless, the forecast provides a better day ahead trading ground, therefore rising the overall Gross Profit to 33.0 m€, 0.9 m€ higher than the reference case.

Intuitively, this can be expected. More precise forecasts will reduce trading in the balancing market and expectedly yield better overall economic results. However, when trading in the balancing market, both gain and loss of money can occur. This fact is due to the single imbalance pricing design of the balancing market. If the hub realises an opposite balance compared to the system's balance, additional revenues will be accrued:

- it will sell the over-supply (hub must downregulate) compared to the day ahead- bid at the up-regulating price, which normally is higher than the day-ahead price or
- it will purchase under-supply (hub must upregulate) compared to the day-ahead bid at the down-regulation price, which normally is lower than the day-ahead price.

In analogy the hub will lose by trading in the balancing market (compared to trading solely in the day-ahead market) if the hub has the same direction of balancing as the system. For further discussion of this important issue, reference is made to ref: "Value of Forecast for a wind power plant Owner, IEA Wind task 36, Ea, Dec. 2021"[5].

This rationale explains that an improvement of the hub's economy cannot be guaranteed when solely improving the hub's wind forecast. Even in the extreme case of a perfect forecast (forecast equal to realisation), an overall poorer hub economy can emerge, than in a normal case with hourly imbalances.

In the analysed cases, switching from price taker (*Ref*) to price maker (*Price Maker Ref*) conditions in the balancing market reduces the overall gross profit with about 2.0 m€ (from 32.1 to 30.1 m€) per year, via increasing the balancing costs and reducing the balancing revenues for the hub with approximately 1.0 m€ each way. This is to be expected as the hub's imbalance in the price maker case impacts the imbalance price unfavourably for the hub's trading activities in the balancing market (the hub's imbalance is in some hours significant compared to the total system imbalance, which impacts the resulting balancing prices compared to the price taker case). (See reference in footnote 5 for more details.)

The *Price Maker Ref* scenario constitutes a more dynamic case for the reaction of balancing prices to the hub's own imbalances and will therefore be utilised as a base Case for the presented results from this point and onwards. The relative benefits of combining such considerations with improved operational conditions (improved wind forecast and flexibility regarding $H_2$ delivery) of the hub can be found in Figure 10.

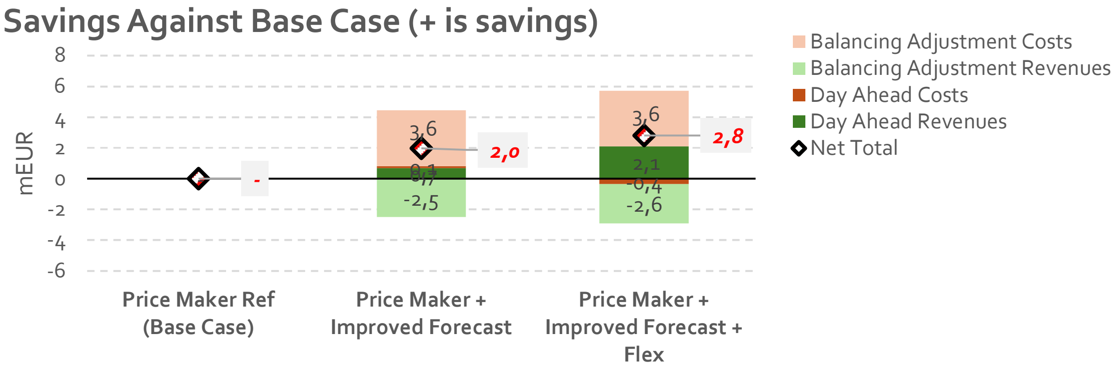

***Figure 10***. *Annual monetary savings enabled by improved operational conditions*

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[5] https://www.ea-energianalyse.dk/en/publications/value-of-forecast-for-a-wind-power-plant-owner/).

In the present case study, the value of the generated hydrogen is equal to the difference in net total costs between the case without $H_2$ and the cases with $H_2$ generation, as seen in **Table 3**.

The opportunity cost of supplying $H_2$ via the hub is evaluated against a run where no $H_2$ offtake obligation is in place. The overall incurred costs between scenarios and against the reference case at the absence of $H_2$ generation define the average economically acceptable lower value of the generated $H_2$.

All listed runs in Figure  are compared against a reference run without $H_2$ offtake obligations, under the initial 3 wind forecasts (unimproved). The average annual cost of the generated $H_2$ and the subsequent savings achieved via improved wind forecasting and a more flexible offtake obligation are listed below in **Table 3**. The figures reveal a yielded value of 0.4 to 0.6 €/kg H2 during improved dispatch conditions, and an overall value of $H_2$ between 6.8 and 7.4 €/kg H2, given the high electricity market price scenery.

***Table 3.*** *Overview of hydrogen generation costs between scenarios*

| **Element** | **Price Maker Ref (No H2)** | **Price Maker Ref** | **Price Maker + Improved Forecast** | **Price Maker + Improved Forecast + Flex** |
|---|---|---|---|---|
| **Day Ahead Revenues (m€)** | *54.4* | 39.8 | 40.5 | 41.9 |
| **Day Ahead Costs (m€)** | - | -7.7 | -7.6 | -8.1 |
| **Balancing Revenues (m€)** | *9.5* | 5.2 | 2.7 | 2.6 |
| **Balancing Costs (m€)** | *-3.4* | -7.1 | -3.5 | -3.5 |
| **Net Total** | ***60.5*** | **30.1** | **32.1** | **32.9** |
| **Opportunity Cost for $H_2$ Generation (m€)** | | **-30.4** | **-28.5** | **-27.6** |
| | | | | |
| **Annualised $H_2$ Related Capex (m€)** | *4.7* | 4.7 | 4.7 | 4.7 |
| **Annualised $H_2$ Related Fixed O&M (m€)** | *1.0* | 1.0 | 1.0 | 1.0 |
| | | | | |
| **Opportunity Cost for $H_2$ Generation incl. Annualised Capex (m€)** | | -36.1 | -34.1 | -33.2 |
| **Annual $H_2$ Generation (GWh $H_2$)** | | 162 | 162 | 162 |
| | | | | |
| **Value of $H_2$ (€/MWh $H_2$)** | | **222** | **210** | **205** |
| **Value of $H_2$ (€/kg $H_2$)** | | **7.4** | **7.0** | **6.8** |
| **Savings vs Ref (€/kg $H_2$)** | | | *-0.4* | *-0.6* |

***Note:*** *$H_2$ LHV: 33.33 kWh/kg. Annuity factor for $H_2$ related investments 0.082 (6.5% WACC over 25 years)*

# 4. Conclusion

The present report is part of Ea Energy Analyses' (Ea's) contribution to *IEA Wind Task 51: Value of Forecasting.* The work has received financial support from EUDP (the Danish Energy Technology Development and Demonstration Programme).

A large part of Ea's efforts and hours have been used to develop a stochastic two-stage optimisation model with rolling horizon for operation of a multi carrier energy hub consisting of wind power, electrolysis ($H_2$ generation) and $H_2$ storage units. The hub is operating in the electricity market framework (day-ahead spot market and balancing market) and is liable to a certain amount of $H_2$ on a daily basis.

Following the model's development, the present case study has been analysed in order to validate its robustness, simulating the bidding behaviour of an energy hub under different wind expectations. The case reflects a setup of an energy hub with 200 MW wind power, a 50 MWe electrolyser, a 444 MWh$_{H_2}$ $H_2$ storage unit and a daily $H_2$ demand of 444 MWh $H_2$.

Different scenario cases have been analysed involving different operational conditions for the hub, namely: improved wind forecasts, price taker and price maker conditions, as well as more flexible $H_2$ offtake conditions.

A more accurate wind forecast provides a better day ahead trading ground and approximately halving both balancing costs and benefits, therefore rising the overall gross profit for the year by 0.9 m€ compared to the reference case (+3%).

Switching from price taker to price maker conditions in the balancing market reduces the overall gross profit for the hub by about 2.0 m€ for the year (-6%), via increasing the balancing costs and reducing the balancing revenues for the hub with approximately 1.0 m€ each way. This is to be expected as the hub's imbalance in the price maker case impacts the imbalance price unfavourably for the hub's trading in the balancing stage. The hub's imbalance, due to the wind forecast and realisation mismatches in the present case study, is in some hours significant compared to the total system imbalance traded in the price area. Therefore, price impacts can be expected in the balancing market.

On the basis of price maker conditions, improved wind forecasting proved to provide 2.0 m€ benefits for the year (+7%), stretching to 2.8 m€ for the year (+9%) when a more flexible $H_2$ offtake agreement is being followed.

In the absence of an $H_2$ selling price, the hub's opportunity cost for supplying the imposed hydrogen schedule can approximate the value of the generated hydrogen. The resulting opportunity cost is consequently decreased by 0.4 €/kg (-5%) and 0.6 €/kg (-8%) respectively for the aforementioned cases. Of course, it has to be stressed that the operational conditions for the hub reflected increased electricity prices on the backdrop of the gas crisis and the post COVID-19 period, therefore resulting in high opportunity costs and therefore value of generated $H_2$.