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From Bird Migration to Market Prices: How Will Offshore Wind Curtailment affect Future Electricity Markets?

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Abstract

Bird-related offshore wind curtailment is increasingly used to reduce collision risk during periods of intense bird migration, but its energy and electricity-market consequences depend strongly on when curtailment occurs. This study combines a historical analysis of Dutch Start/Stop events with a forward-looking electricity-market assessment. First, Start/Stop notifications between 2023 and 2026 are analysed using observed offshore wind conditions and aggregated offshore wind production to characterise the meteorological and generation conditions associated with individual events. The selected events occurred under markedly different wind conditions, with mean wind speeds during the notified periods ranging from approximately 5.0 to 12 m/s, indicating substantial variation in the wind-generation potential available during curtailment periods. Second, the EYE electricity-market model is used to assess the potential future electricity-system consequences of bird-related offshore wind curtailment under the National Drivers 2030 scenario. Sensitivity cases with offshore wind availability reduced by 40%, 60%, and 90% are compared with a reference case with full offshore wind availability. In the 2030 simulations, reduced offshore wind generation is compensated through changes in imports, dispatchable generation, storage, and other flexibility options. Daily-average market-clearing prices increase by approximately 2.0–5.0%, while larger price deviations are concentrated within the actual curtailment hours. The results demonstrate that the consequences of Start/Stop operation are both time-specific and resource-dependent, reflecting not only curtailment duration but also wind availability and electricity-system conditions during the affected hours.

Keywords: offshore wind; bird migration; wind curtailment; energy-system modelling

1. Introduction

Offshore wind is becoming a central component of Europe's transition towards a decarbonized electricity system. The European Commission's offshore renewable energy strategy set an initial target of at least 60 GW of offshore wind capacity by 2030 and 300 GW by 2050. More recently, the 2023 Ostend Declaration raised the regional ambition for the North Seas, with participating countries committing to pursue at least 120 GW by 2030 and 300 GW by 2050 [1,2]. The North Sea is therefore expected to develop into one of Europe's principal renewable-energy regions. As offshore wind deployment expands, projects are increasingly assessed not only in terms of installed capacity and electricity cost, but also with respect to tender design, electricity-system integration, environmental performance, and compatibility with other uses of the marine environment [3].

This broader perspective is reflected in the growing use of non-price criteria in offshore wind tenders. In the Netherlands, recent tender procedures have explicitly rewarded

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contributions to the ecology of the Dutch North Sea. These criteria have included measures aimed at reducing habitat loss, improving knowledge of bird behaviour, strengthening underwater nature, and testing ecological mitigation measures [4]. Environmental considerations can therefore influence not only project permitting, but also developer selection, wind-farm design, and operational requirements.

Bird protection is an important component of these ecological considerations. At the European level, the Birds Directive provides the legal basis for protecting naturally occurring wild bird species, including migratory species, and for limiting habitat deterioration and significant disturbance [5]. Offshore wind farms may affect marine and migratory birds through collision risk, displacement from feeding or resting areas, barrier effects, and changes in habitat use. The magnitude of these effects varies between species, locations, seasons, and turbine configurations, making monitoring and mitigation strongly dependent on local conditions [6]. These considerations are particularly relevant for offshore wind development in and around major migration corridors.

A range of monitoring and mitigation approaches is currently being investigated or applied to address bird migration around offshore wind farms. Weather-surveillance radar, dedicated offshore bird radar, and meteorological information can be combined to identify migration activity and forecast periods of elevated bird movement. Recent research has shown that such information can support short-term forecasts of nocturnal migration intensity with sufficient accuracy to inform operational measures [7]. In parallel, studies have investigated how turbine operation can be adapted according to migration intensity, wind conditions, and expected electricity production. Curtailment at relatively low wind speeds can reduce collision exposure while causing comparatively limited production losses because turbine output remains below rated power. At higher wind speeds, however, the same duration of curtailment can correspond to a substantially larger loss of available electricity generation as turbine output approaches rated power [8].

One operational measure receiving increasing attention is *bird-related offshore wind curtailment*: the temporary reduction of turbine rotor speed, or near-shutdown of turbines, during periods in which high bird-migration intensity is forecast. In contrast to fixed seasonal shutdown rules, dynamic curtailment concentrates the intervention within selected periods of elevated migration activity. Its practical implementation therefore depends on the accuracy of migration forecasts, the notice available to wind-farm operators, and the operating conditions of the affected turbines.

The Netherlands has taken a prominent role in translating this concept into offshore wind operation. The Dutch offshore *Start/Stop* procedure entered into force on 1 July 2023 and allows predicted peaks in bird migration to result in instructions to reduce turbine rotational speed to fewer than two revolutions per minute [9]. The procedure combines migration forecasting, expert assessment, a ministerial decision, and advance communication with wind-farm operators and the transmission system operator. In 2026, the Dutch framework was amended by replacing the original fixed migration threshold with a flexible threshold and introducing a maximum of 60 curtailment hours per year, calculated from one autumn migration period to the next [10]. Several other North Sea countries are also investigating or applying combinations of turbine shutdown, rotor-speed reduction, radar monitoring, and migration-triggered mitigation, although the procedures, thresholds, and legal responsibilities differ between jurisdictions [11].

From an electricity-system perspective, bird-related curtailment temporarily reduces the availability of offshore wind generation. Although the *trigger* for this form of curtailment is ecological rather than a grid or market constraint, its consequences propagate through the electricity system in a similar way to other temporary reductions in generation availability. The resulting effect depends not only on the quantity of offshore wind generation removed,

but also on the time at which the reduction occurs. One megawatt-hour of foregone generation during a period of low or negative electricity prices has a different economic value from the same quantity curtailed during a high-price period. Wind availability, electricity demand, interconnection, system flexibility, and the generation mix therefore influence the economic significance of an individual curtailment event. This timing effect is particularly relevant in electricity systems with a high share of variable renewable generation, where simultaneous wind production can reduce the market value, or capture price, of wind electricity relative to the average wholesale electricity price [12].

These effects may become more important as the contribution of offshore wind to the electricity system increases. Recent assessments of the Dutch offshore wind market indicate that project revenues are becoming increasingly sensitive to project costs, wholesale-price exposure, supply-chain conditions, and the balance between renewable generation and flexible electricity demand [13]. Scenario studies similarly show that the future financial performance of offshore wind depends strongly on electrification, market prices, interconnection, and the availability of flexible demand [14]. Bird-related curtailment introduces an additional form of time-dependent generation unavailability. Its economic consequences may therefore differ between present and future electricity systems even when the number of unavailable turbine hours remains unchanged.

Existing research on bird-related curtailment has primarily focused on migration forecasting, collision-risk reduction, ecological effectiveness, and the relationship between avoided collisions and lost power production [6–8]. Comparatively less attention has been given to the time-specific interaction between individual curtailment events, prevailing wind availability, and electricity-market conditions, or to how these effects may change as offshore wind becomes a larger component of the electricity system. Assessments based solely on annual energy losses, total unavailable hours, or historical electricity prices may therefore not fully represent the system and market consequences of curtailed generation under future configurations of electricity supply, demand, interconnection, and flexibility.

This paper addresses this gap by combining a historical analysis of Dutch Start/Stop events with forward-looking electricity-market modelling. The historical analysis characterises when Start/Stop events occur, how long they last, and the offshore wind and generation conditions prevailing during the affected periods. Because the available generation data are aggregated at national level and the meteorological observations represent regional offshore conditions, the historical analysis is not used to derive a direct counterfactual estimate of the electricity lost solely because of Start/Stop operation. Instead, it is used to demonstrate that the significance of bird-related curtailment is both *time-specific* and *resource-dependent*, and to motivate its representation as a time-specific reduction in offshore wind availability.

The electricity-system consequences are subsequently assessed using the EYE model [14], a merit-order-based electricity-market simulator that represents hourly electricity supply, demand, generation dispatch, and market-price formation. The analysis uses the National Drivers 2030 scenario, which provides a near-term future electricity-system configuration with a substantially increased contribution from offshore wind. A reference case with full offshore wind availability is compared with sensitivity cases in which offshore wind availability is reduced during prescribed curtailment periods. This approach makes it possible to examine how temporary reductions in offshore wind generation affect generation dispatch, system flexibility, and hourly market-clearing prices while keeping the remaining electricity-system assumptions unchanged.

The study therefore distinguishes between two related dimensions of bird-related offshore wind curtailment. First, the historical analysis examines the relationship between Start/Stop timing, wind availability, and observed offshore wind production. Second, the

modelling analysis evaluates how time-specific reductions in offshore wind availability propagate through a future electricity system. The central research question is therefore not only how much offshore wind generation is unavailable, but also *when* that unavailability occurs and under which wind and electricity-system conditions. The analysis further considers the implications for relevant stakeholders, including offshore wind operators, transmission system operators, electricity consumers, public authorities, investors, and insurers.

The remainder of the paper is organised as follows. Section 2 reviews historical Dutch Start/Stop events and examines their timing, duration, prevailing offshore wind conditions, and observed offshore wind production. Section 3 introduces the EYE model and the modelling framework used to represent time-specific reductions in offshore wind availability under the National Drivers 2030 electricity-system scenario. Section 4 presents and discusses the electricity-system and market responses to a set of offshore wind curtailment sensitivity cases, including changes in generation dispatch, flexibility use, and market-clearing prices, together with their implications for relevant stakeholders. Finally, Section 5 summarises the principal findings, limitations, and directions for future work.

2. Historical Wind Farm Curtailments

The Dutch *Start/Stop* procedure provides a practical basis for examining how bird-related offshore wind curtailment has been implemented under real operating conditions. The historical record captures the timing and duration of individual events, together with the prevailing offshore wind conditions and the offshore wind generation observed during the corresponding periods. These observations are used to characterise the operational context of Start/Stop events and their dependence on prevailing conditions, rather than to derive a direct counterfactual estimate of the electricity lost solely because of curtailment.

The Netherlands introduced the *Start/Stop* procedure to reduce the collision risk faced by migratory birds at offshore wind farms. During predicted periods of intense bird migration, affected offshore wind turbines may be recommended or required to reduce their rotational speed to fewer than 2 rpm. The procedure combines bird-migration forecasts based on offshore radar measurements and meteorological conditions with expert assessment and an evaluation of electricity-system security by the transmission system operator TenneT [15,17]. The forecasting framework is designed to provide approximately 48 h of advance information, allowing wind-farm operators and the electricity system to prepare for a temporary reduction in offshore wind availability [17].

An important distinction in interpreting the historical record is that between a *recommendation* and a formal *decision*. Under the framework initially applied, mass bird migration was associated with a migration-intensity threshold of at least 500 birds km^{-1} h^{-1}. When the relevant conditions were met, the competent authority could issue a formal decision requiring the applicable wind-farm operators to reduce turbine rotational speed to fewer than 2 rpm. Recommendations could also be issued under less stringent conditions, but these were non-binding and individual operators retained discretion over whether to implement the requested reduction [15]. Consequently, the existence of a Start/Stop notification does not necessarily imply that all wind farms affected by the notification reduced their production. Several notifications in 2024, for example, explicitly indicated that some operators intended to follow the recommendation whereas others did not [15].

The Start/Stop procedure was formally introduced in 2023 following an earlier test during the spring migration season. During autumn 2023, three recommendations were issued, on 8, 16, and 31 October, each covering a three-hour evening period [15,16]. The subsequent record shows that bird-related curtailment is episodic rather than continuously distributed throughout the year. Events are concentrated around the principal spring and

Table 1. Selected Start/Stop notifications for offshore wind farms in the Dutch North Sea between 2023 and 2026. A recommendation is non-binding, whereas a formal decision requires the applicable wind-farm operators to reduce turbine rotational speed below 2 rpm [15].

Date	Time window	Duration	Type
8 Oct 2023	21:00–24:00	3 h	Recommendation
16 Oct 2023	19:00–22:00	3 h	Recommendation
31 Oct 2023	18:00–21:00	3 h	Recommendation
16 Mar 2024	21:00–24:00	3 h	Recommendation
13 Oct 2024	21:00–24:00	3 h	Recommendation
25 Oct 2024	20:00–23:00	3 h	Recommendation
30 Oct 2024	19:00–23:00	4 h	Recommendation
24 Sep 2025	20:00–23:00	3 h	Recommendation
25 Sep 2025	20:00–23:00	3 h	Recommendation
13 Oct 2025	00:00–06:00	6 h	Recommendation
13 Oct 2025	18:00–24:00	6 h	Recommendation
14 Oct 2025	18:00–24:00	6 h	Recommendation
8 Nov 2025	18:00–24:00	6 h	Recommendation
9 Nov 2025	00:00–06:00	6 h	Recommendation
17 Mar 2026	18:00–24:00	6 h	Decision
18 Mar 2026	00:00–06:00	6 h	Decision
23 Mar 2026	21:00–24:00	3 h	Decision
24 Mar 2026	00:00–06:00	6 h	Decision
27 Mar 2026	03:00–06:00	3 h	Decision

autumn migration periods and occur predominantly during evening, night, and early-morning hours, reflecting the temporal characteristics of large-scale bird migration over the North Sea.

Table 1 summarises the officially reported Start/Stop windows between autumn 2023 and spring 2026. Notifications in 2023 and 2024 generally covered periods of three to four hours. During autumn 2025, several recommendations extended to six hours and occurred across consecutive evening and overnight periods. A notable example occurred on 13 October 2025, when recommendations covered both 00:00–06:00 and 18:00–24:00. In March 2026, the published notifications included formal decisions rather than recommendations, with both three- and six-hour restriction windows [15]. The notification record therefore shows that bird-related curtailment may consist of a sequence of discrete operational restrictions across neighbouring nights rather than a single isolated event.

The available notification sources document this change in the duration of individual Start/Stop windows, but do not establish whether the longer periods resulted from changes in migration intensity, forecasting methodology, operational procedures, or other factors. The change in duration is therefore treated here as an observed characteristic of the historical record rather than being assigned a specific causal explanation.

The concentration of Start/Stop events within a limited number of migration periods is consistent with observations of nocturnal migration across the southern North Sea. Long-term offshore radar measurements indicate pronounced seasonal variability in migration intensity, with periods of very high bird flux occurring relatively infrequently [21]. This temporal concentration provides the rationale for an event-based mitigation strategy: turbine operation can be modified during selected high-risk periods rather than being restricted continuously throughout the migration season.

Previous studies have also demonstrated that the energetic cost of such an intervention depends strongly on the wind conditions prevailing during the curtailment period. Curtailment during relatively low wind speeds can reduce collision exposure while causing comparatively limited production losses, whereas the same duration of curtailment during

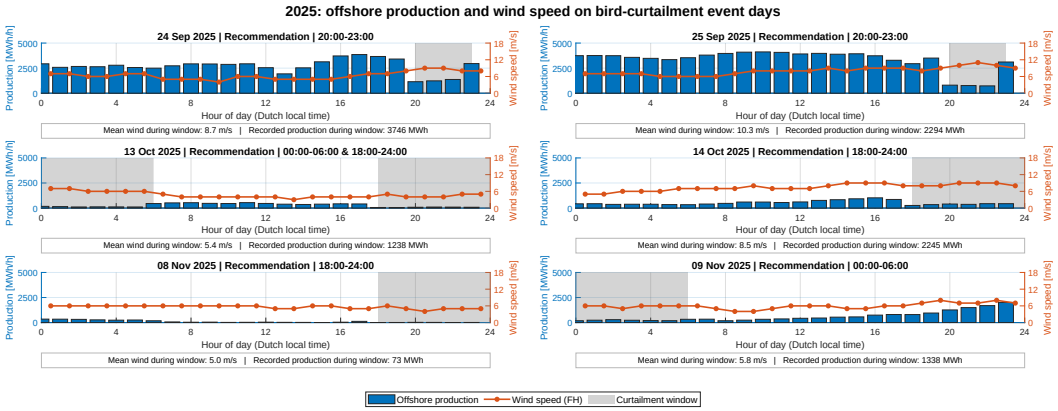


Figure 1. Hourly aggregated Dutch offshore wind generation and observed offshore wind speed on the selected Start/Stop event days in 2025. Bars show recorded offshore wind generation, the line shows hourly mean offshore wind speed, and shaded regions indicate the officially notified curtailment windows. Generation data are obtained from the Nationaal Energie Dashboard [19], and wind-speed observations are obtained from the KNMI North Sea station archive [20].

higher wind speeds can remove substantially more potential wind generation [18]. The energetic significance of a Start/Stop event therefore cannot be inferred from its duration alone.

To examine this relationship in the available Dutch record, the analysis focuses in greater detail on the events in 2025 and 2026. These two years provide contrasting operational cases. The selected 2025 events occurred during the autumn migration period and were issued as recommendations, meaning that implementation could differ between operators. By contrast, the selected March 2026 events were formal decisions requiring the applicable operators to reduce turbine rotational speed. The 2026 events therefore provide a stronger temporal basis for examining whether changes in offshore generation coincide with formal Start/Stop windows, although the nationally aggregated generation data still prevent direct attribution to individual wind farms.

Hourly aggregated Dutch offshore wind generation was obtained from the Nationaal Energie Dashboard (NED) [19]. Hourly offshore wind-speed observations were obtained from the Royal Netherlands Meteorological Institute (KNMI) North Sea station archive [20]. The wind-speed series represents hourly mean observed offshore wind speed and should therefore be interpreted as an indicator of regional meteorological conditions rather than as turbine-specific hub-height wind speed. For selected 2025 events, historical Dutch wholesale electricity prices were also examined to provide additional information on the market conditions prevailing during the Start/Stop periods. The corresponding historical price profiles for 13 and 14 October 2025 are presented in Appendix A.

Figure 1 shows that the 2025 Start/Stop recommendations occurred under markedly different wind conditions. The events on 13 October, 8 November, and 9 November were associated with comparatively low mean wind speeds during the notified windows, of approximately 5.4, 5.0, and 5.8 m/s, respectively. Offshore wind generation was also relatively low during these periods. The most pronounced low-resource case occurred on 8 November, when only approximately 73 MWh of offshore generation was recorded over the six-hour recommendation window. Under such conditions, the amount of wind energy available for generation is already limited, making it difficult to distinguish the effect of an operational restriction from naturally low production using aggregated data alone.

Different conditions were observed during the events of 24 and 25 September and 14 October 2025. Mean wind speeds during the corresponding notification windows were approximately 8.7, 10.3, and 8.5 m/s, respectively, indicating substantially greater wind-

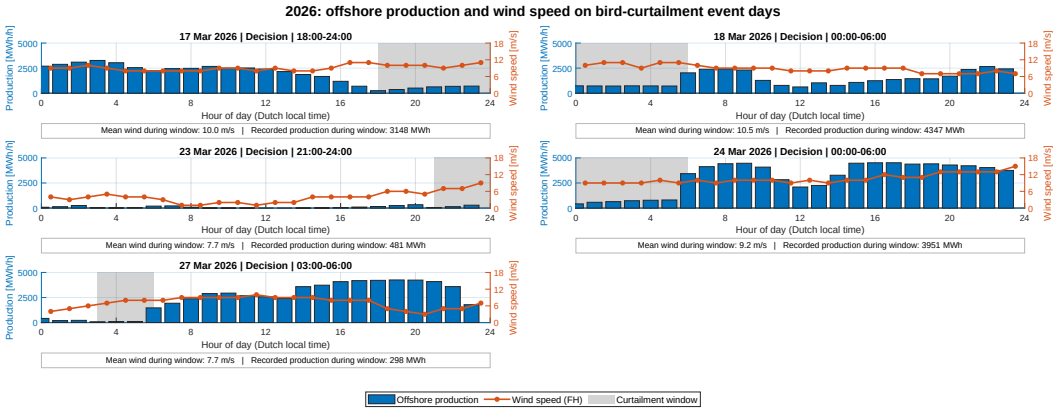


Figure 2. Hourly aggregated Dutch offshore wind generation and observed offshore wind speed on the selected Start/Stop event days in March 2026. Bars show recorded offshore wind generation, the line shows hourly mean offshore wind speed, and shaded regions indicate periods covered by formal Start/Stop decisions. Generation data are obtained from the Nationaal Energie Dashboard [19], and wind-speed observations are obtained from the KNMI North Sea station archive [20].

generation potential. The event on 25 September is particularly illustrative. Offshore generation was approximately 3500–4100 MW during much of the day but declined to approximately 700–800 MW during the 20:00–23:00 recommendation window while offshore wind speeds remained around 10–11 m/s. The generation level during the recommendation window was therefore approximately 80% lower than the 3500–4100 MW range observed during the higher-production part of the same day. A total of approximately 2294 MWh was recorded during the three-hour window. This comparison is descriptive rather than a direct estimate of the energy curtailed, because changes in turbine availability, operator participation, and other system conditions may also affect the aggregated generation profile.

A similar contrast is visible on 24 September, when offshore generation decreased substantially during the evening recommendation despite comparatively high wind speeds. On 14 October, the six-hour recommendation coincided with a mean wind speed of approximately 8.5 m/s, while approximately 2245 MWh of offshore generation was recorded over the complete window. These events show that Start/Stop recommendations can coincide with periods of substantially different underlying wind-generation potential. The historical electricity-price observations provide an additional temporal perspective. On 13 October 2025, two six-hour Start/Stop recommendation periods occurred on the same day but under markedly different market conditions: the daily minimum price occurred during the 00:00–06:00 recommendation, whereas the daily maximum occurred during the 18:00–24:00 recommendation. On 14 October, the evening recommendation similarly coincided with the highest-price interval of the day. The complete historical price profiles are provided in Appendix A.

The 2025 observations must nevertheless be interpreted with caution. All of the selected notifications in that year were recommendations rather than formal decisions. Operator participation could therefore differ between events, and some offshore wind farms, particularly older installations, were not participating in the Start/Stop measure. Changes in wind conditions, turbine availability, maintenance, grid restrictions, market-driven operation, and other factors can also influence nationally aggregated offshore generation. The observed reductions in 2025 therefore cannot be interpreted as direct measurements of generation curtailed specifically because of bird migration.

The formal decisions issued in March 2026 provide a clearer set of observations for examining the temporal relationship between Start/Stop operation, offshore wind condi-

tions, and recorded generation. Figure 2 shows that several of these decisions coincided with relatively strong offshore winds. Mean wind speeds during the notified periods were approximately 10.0 m/s on 17 March, 10.5 m/s on 18 March, and 9.2 m/s on 24 March. These values correspond to conditions under which modern offshore wind turbines would generally be expected to generate substantial power, although actual electrical output remains dependent on turbine-specific power curves and operating states [22].

On 17 March, offshore generation declined substantially during the 18:00–24:00 decision window. Generation exceeded approximately 2000 MW during much of the earlier part of the day but fell to only a few hundred MW during much of the Start/Stop period while observed wind speeds remained close to 10 m/s. Approximately 3148 MWh of offshore generation was recorded during the complete six-hour window. The persistence of relatively strong winds alongside substantially lower generation indicates that deterioration of the regional wind resource alone is insufficient to explain the observed profile.

An even clearer temporal contrast is observed on 18 March. During the 00:00–06:00 decision window, offshore generation remained at approximately 700 MW while observed wind speeds were generally around 10–11 m/s. Shortly after the decision window ended, generation increased to more than 2000 MW while the observed wind speed remained of a similar magnitude. The generation level during the decision window was therefore at least approximately 65% below the level observed shortly afterwards. The abrupt increase in generation around the end of the notified period, without an equivalent change in the measured wind resource, is consistent with the presence of a substantial operational restriction during the Start/Stop window.

A comparable pattern is visible on 24 March. The 00:00–06:00 decision occurred at a mean offshore wind speed of approximately 9.2 m/s. Offshore generation remained below approximately 800 MW during much of this period and increased rapidly to more than 3000 MW shortly after 06:00, while the wind-speed series did not display a corresponding step change. The level during the decision period was therefore more than approximately 70% below the post-event generation level. Again, this comparison describes the temporal pattern in the aggregated data rather than providing a direct estimate of curtailed energy.

The remaining March 2026 decisions occurred under somewhat lower, although still potentially productive, wind conditions. Both the 23 March and 27 March events were associated with a mean wind speed of approximately 7.7 m/s during their respective decision windows. Approximately 481 MWh was recorded during the three-hour decision on 23 March, while approximately 298 MWh was recorded during the 03:00–06:00 decision on 27 March. The latter event again exhibits a pronounced temporal pattern, with offshore generation remaining very low during the decision period and increasing rapidly after 06:00 while the observed wind speed remained sufficiently high for continued turbine operation.

Taken together, the historical observations show that the selected Start/Stop events occurred across a broad range of wind conditions. Mean wind speeds during the analysed notification windows ranged from approximately 5.0 to 10.5 m/s. Events at the lower end of this range occurred when the available wind-generation potential was already comparatively limited, whereas events at the upper end coincided with conditions associated with substantially greater potential production. Event duration alone is therefore insufficient to characterise the energetic significance of a Start/Stop restriction.

At the same time, the recorded generation shown in Figures 1 and 2 should not be interpreted as a direct measure of energy lost because of bird-related curtailment. The NED data represent aggregated Dutch offshore wind generation, whereas individual Start/Stop notifications may apply only to specific wind farms or may not be implemented uniformly across operators. Similarly, the KNMI observations describe regional offshore

meteorological conditions rather than wind-farm-specific hub-height wind speeds. Turbine availability, wake losses, maintenance, grid restrictions, market-driven operation, and other operational factors can also influence realised generation.

The historical analysis should therefore be interpreted as a descriptive assessment of the relationship between Start/Stop timing, offshore wind conditions, and observed generation rather than as a direct counterfactual estimate of curtailment losses. Its principal implication for the present study is that bird-related curtailment is both *time-specific* and *resource-dependent*. The same duration of operational restriction can have a limited energetic significance during periods of weak wind and a much larger potential effect when it coincides with high wind availability. Moreover, the economic significance of any reduction in offshore wind generation depends on the electricity-system and market conditions prevailing during the same hours. The historical price observations presented in Appendix A illustrate this temporal variation: Start/Stop periods of equal duration can coincide with substantially different wholesale-price conditions. Section 3 therefore introduces the EYE model and the framework used to evaluate these time-specific electricity-system and market consequences under a future electricity-system configuration.

3. Energy Transition Model: EYE Model

The historical analysis in Section 2 shows that the significance of bird-related offshore wind curtailment depends not only on the duration of a Start/Stop event, but also on the wind conditions prevailing during the affected hours. Its electricity-market consequence introduces an additional temporal dimension, because the effect of a temporary reduction in offshore wind availability depends on the state of the electricity system at the time of the event. Electricity demand, renewable generation, imports, available flexibility, and the marginal generating technology can therefore influence the system response to an otherwise similar curtailment event.

To evaluate this interaction, the present study uses the EYE model [14]. EYE is a scenario-based electricity-system simulation model that represents the interaction between electricity supply and demand through an hourly market-clearing mechanism. Different electricity-system configurations can be represented by varying assumptions regarding installed generation capacity, electricity demand, renewable-generation profiles, fuel and carbon prices, and available system flexibility.

In the present study, bird-related offshore wind curtailment is represented as a time-specific reduction in offshore wind availability. A reference simulation with normal offshore wind availability is compared with otherwise identical simulations in which offshore wind availability is modified during prescribed Start/Stop hours. The historical observations are therefore used to motivate the time-specific and resource-dependent representation of curtailment, rather than to derive a direct estimate of the fraction of generation lost solely because of historical Start/Stop operation.

The modelling framework adopted in this study is summarised in Figure 3. The input layer specifies the electricity-system configuration and hourly renewable-generation conditions. The model subsequently constructs the market representation, clears the electricity market, and determines generation dispatch and the marginal generating unit. The resulting hourly outputs are then compared between the reference and curtailment simulations to evaluate the electricity-system and market response to the imposed reduction in offshore wind availability.

3.1. Input–Model–Output Structure

The implementation of EYE in this study follows an input–model–output structure. The input layer defines the electricity-system configuration and the hourly availability of

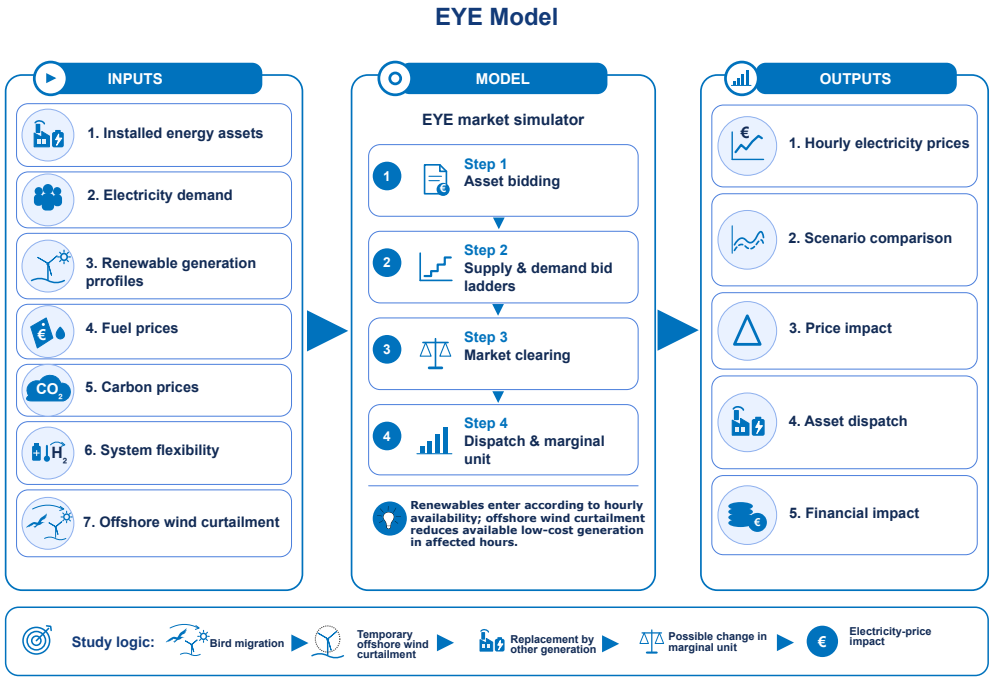


Figure 3. Input–model–output architecture of the EYE model as applied in this study. The scenario inputs define the electricity-system conditions and offshore wind availability. EYE subsequently constructs asset bids, forms the supply and demand bid ladders, clears the electricity market, and determines the resulting dispatch and marginal generating unit. The model outputs are used to compare reference and bird-related offshore wind curtailment simulations and to assess the resulting electricity-system and market-price response.

offshore wind generation. The model layer represents the market-clearing process through which available generation and flexibility resources are used to satisfy electricity demand. The output layer provides the resulting hourly generation dispatch and electricity-market outcomes.

This structure separates the imposed reduction in offshore wind availability from the electricity-system response to that reduction. The physical reduction is prescribed through the offshore wind availability profile, whereas the resulting market response depends on the generation technologies and flexibility options available during the affected hours.

3.1.1. Inputs

The principal inputs to EYE include installed generation capacities, hourly electricity demand, renewable-generation profiles, fuel prices, carbon prices, and available system-flexibility options. Conventional generation technologies are represented according to their available capacities and marginal generation costs, whereas variable renewable technologies such as wind and solar are represented through time-dependent generation profiles. Together, these inputs determine the quantity and cost of electricity available to the system during each simulation hour.

Bird-related offshore wind curtailment is introduced by modifying the offshore wind availability profile during prescribed Start/Stop periods. The offshore wind production remaining available during hour t is represented as

$$P_t^{\text{curt}} = \alpha_t P_t^{\text{base}}, \tag{1}$$

where P_t^{base} denotes the offshore wind production available under normal operation, P_t^{curt} denotes the offshore wind production remaining available after application of the

curtailment constraint, and α_t represents the fraction of normal offshore wind production remaining available during hour t. Under normal operation, $\alpha_t = 1$, whereas $0 \leq \alpha_t < 1$ represents partial or near-complete curtailment.

The corresponding quantity of curtailed offshore wind energy during each simulation hour is

$$E_t^{\text{curt}} = \left(P_t^{\text{base}} - P_t^{\text{curt}}\right)\Delta t, \tag{2}$$

where E_t^{curt} is the curtailed offshore wind energy and Δt is the duration of the simulation time step. Since the analysis is performed at hourly resolution,

$$\Delta t = 1\ \text{h}. \tag{3}$$

A Start/Stop period is therefore represented through the corresponding sequence of hourly simulation steps. For example, a three-hour restriction is represented by modifying offshore wind availability during three consecutive hours, while a six-hour restriction is represented over six consecutive simulation hours. Outside the prescribed event window, offshore wind availability returns to its reference value.

This formulation preserves the temporal characteristics identified in the historical analysis. Curtailment is therefore not represented as a fixed annual energy reduction. Instead, offshore wind availability is modified during specific hours, allowing the physical quantity of generation removed to depend on the offshore wind production that would otherwise have been available during those hours.

3.1.2. Market-Clearing Model

For each simulation hour, EYE determines how the available electricity supply is used to meet demand. Generation assets are represented according to their marginal generation costs, thereby forming a merit order from lower-cost to higher-cost generation. Renewable generation from technologies such as wind and solar enters the system according to the corresponding time-dependent generation profiles and is treated as must-run generation when available.

Generation is dispatched according to this ordering until electricity demand is satisfied. The generating unit required to supply the final increment of demand determines the marginal generating unit and, consequently, the market-clearing price for that hour. This procedure is repeated for each simulation hour, allowing changes in electricity demand, renewable generation, available generation capacity, and other scenario conditions to affect market outcomes over time.

Bird-related offshore wind curtailment affects this process by reducing the amount of low-marginal-cost offshore wind generation available during the affected hours. The missing production must then be compensated by the remaining generation and flexibility options represented in the model, including other generation technologies, imports, storage, and available demand-side flexibility.

The electricity-market response therefore depends on the system state at the time of the event. During periods with abundant low-cost generation or sufficient flexibility, the reduction in offshore wind availability may be accommodated without changing the marginal generating technology. During tighter system conditions, however, the same reduction may require a higher-cost technology or flexibility resource to become marginal, resulting in a larger market-clearing-price response. This mechanism provides the basis for examining why curtailment events of similar duration can produce different electricity-system and economic consequences.

3.1.3. Outputs

EYE provides hourly electricity-market outputs, including information on the dispatch of individual generation assets and the resulting market-clearing price. The principal market variable considered in this study is the hourly market-clearing price,

$$p_t, \tag{4}$$

where p_t denotes the electricity price during hour t, expressed in €/MWh.

The modelled effect of bird-related offshore wind curtailment is evaluated by comparing two otherwise identical simulations. The reference simulation represents normal offshore wind availability, whereas the curtailment simulation introduces a prescribed reduction in offshore wind availability during the selected event hours. All other electricity-system assumptions are kept unchanged.

This paired-simulation approach therefore isolates the electricity-system response to the *modelled curtailment assumption*. It should not be interpreted as implying that the reductions observed in the historical generation data can be causally attributed solely to Start/Stop operation.

The hourly change in market-clearing price is calculated as

$$\Delta p_t = p_t^{\text{curt}} - p_t^{\text{ref}}, \tag{5}$$

where p_t^{ref} is the hourly market-clearing price in the reference simulation and p_t^{curt} is the corresponding price when the prescribed offshore wind curtailment is imposed. A positive value of Δp_t indicates a higher market-clearing price in the curtailment simulation, whereas a negative value indicates a lower market-clearing price relative to the reference case.

The hourly comparison makes it possible to determine not only whether curtailment affects the electricity price, but also when the response occurs and how strongly it is concentrated within the affected period. The analysis therefore distinguishes between three related quantities: the duration of the operational restriction, the physical quantity of offshore wind generation removed, and the corresponding time-specific electricity-market response.

3.1.4. Energy-System Scenario

The future electricity-system conditions represented in this study are based on the *National Drivers (ND) 2030* scenario. The scenario provides a consistent representation of the development of the Dutch energy system towards 2030 and is used to define assumptions regarding installed generation capacity, electricity demand, renewable generation, and available system flexibility.

The National Drivers scenario represents an energy transition characterised by strong national coordination and a substantial contribution from domestic renewable-energy production. Offshore wind plays an increasingly important role in electricity supply, complemented by solar PV and onshore wind. At the same time, increasing electrification across demand sectors strengthens the role of electricity within the wider energy system. The larger contribution of weather-dependent renewable generation also increases the importance of flexible demand, storage, interconnection, and dispatchable generation for maintaining the balance between electricity supply and demand.

These characteristics make the ND 2030 scenario relevant for assessing bird-related offshore wind curtailment. With a larger contribution from offshore wind, a temporary reduction in its availability can represent a more substantial change in electricity supply than under present-day conditions. The resulting market effect, however, continues to

depend on the availability and marginal cost of alternative generation and flexibility during the affected hours.

The ND 2030 configuration is therefore used to define the generation mix, electricity demand, renewable-generation profiles, and flexibility options represented in EYE. These electricity-system assumptions are kept unchanged between the reference and curtailment simulations. Offshore wind availability is modified only during the prescribed event hours, allowing the resulting changes in generation dispatch and hourly market-clearing prices to be evaluated within a consistent electricity-system configuration.

The specific offshore wind availability reductions considered in the simulation cases are introduced in Section 4, where the reference and curtailment scenarios are defined and compared.

4. Results and Discussion

This section presents the electricity-system and market consequences of bird-related offshore wind curtailment under the National Drivers 2030 scenario. The analysis first examines how progressively lower offshore wind availability affects generation dispatch, imports, and the utilisation of flexibility resources across the modelled electricity system. It then focuses on the hourly market-price response during a representative Start/Stop event, before discussing the implications of these effects for offshore wind operators, system operators, consumers, and other relevant stakeholders. Together, the results illustrate how the consequences of curtailment depend not only on the severity of the imposed restriction, but also on the timing of the event and the electricity-system conditions prevailing during the affected hours.

4.1. Electricity-System Response to Reduced Offshore Wind Availability

Four offshore wind availability cases are evaluated using the EYE model. The reference case represents the National Drivers 2030 electricity system with 21.5 GW of offshore wind capacity available. Three sensitivity cases are constructed by reducing offshore wind availability by 40%, 60%, and 90% relative to the reference case, corresponding to remaining offshore wind capacities of 12.9 GW, 8.6 GW, and 2.15 GW, respectively.

In terms of the offshore wind availability factor introduced in Equation 1, the reference case corresponds to $\alpha_t = 1.0$, while the 40%, 60%, and 90% reduction cases correspond to $\alpha_t = 0.6$, 0.4, and 0.1, respectively. These values are introduced as sensitivity assumptions and should not be interpreted as curtailment fractions derived directly from the historical Start/Stop observations. As discussed in Section 2, the available historical data do not permit the fraction of offshore wind generation lost solely because of Start/Stop operation to be determined directly.

For the system-level comparison shown in Figure 4, the different offshore wind availability levels are evaluated over the simulated period from 8 to 14 October 2030. All other electricity-system assumptions, including demand, generation capacities, renewable-generation profiles, and available flexibility, remain unchanged between the simulations. The comparison therefore provides a sensitivity assessment of how the electricity system responds as offshore wind availability is progressively reduced.

Figure 4 shows that offshore wind production varies substantially over the simulated week. In the reference case, its contribution is comparatively moderate during the first part of the period and increases considerably from approximately 12 October onwards, becoming one of the major components of electricity supply around 13 October. The dotted boundaries make the offshore wind contribution directly visible within the broader generation stack.

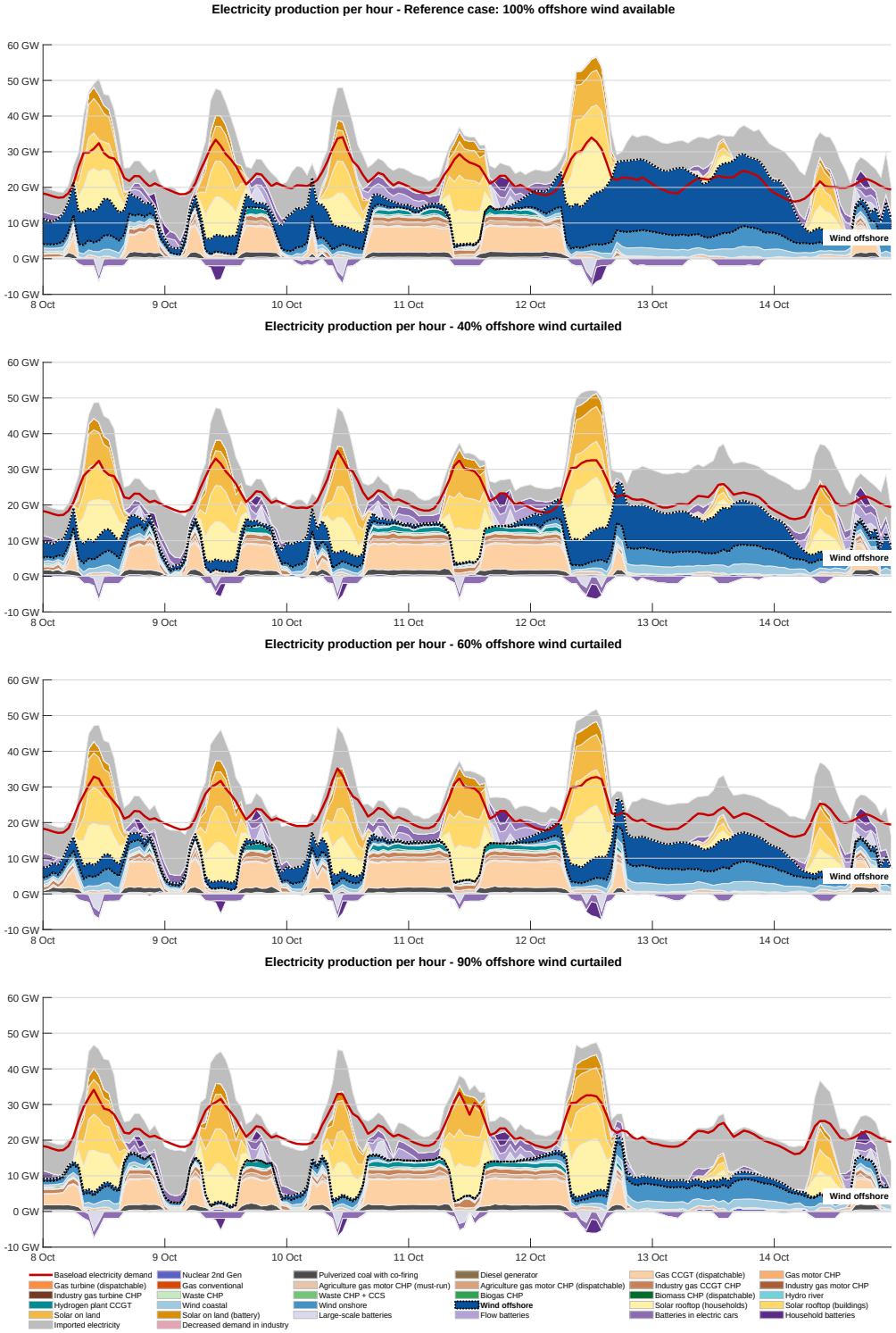


Figure 4. Hourly electricity-production profiles for the reference, 40%, 60%, and 90% offshore wind availability-reduction cases over the simulated period from 8 to 14 October 2030. Offshore wind is identified by the blue-filled band with black dotted boundaries to facilitate comparison between the four cases. All remaining electricity-system assumptions are unchanged between the simulations.

This temporal variation is important because a given percentage reduction in offshore wind availability does not correspond to the same absolute quantity of electricity in every hour. When offshore wind production is relatively low, the absolute reduction associated with the imposed availability factor is also limited. During periods of high offshore wind production, the same percentage reduction removes substantially more low-marginal-cost generation from the electricity system.

The resulting generation deficit is compensated through changes elsewhere in the system. Total electricity supply therefore does not decrease by the same amount as offshore wind generation because EYE redispatches other generation technologies and flexibility resources to maintain the supply–demand balance. Both the magnitude and composition of this response vary across the simulated period.

One of the clearest responses is the increased contribution from imported electricity as offshore wind availability is progressively reduced. This response becomes particularly visible during periods in which offshore wind would otherwise provide a substantial share of electricity supply. Dispatchable generation also changes between the cases as additional technologies are required to compensate for the lower offshore wind contribution.

The replacement response is not uniform throughout the week. During daylight hours, solar generation can contribute substantially to electricity supply and is unaffected by the offshore wind availability assumption. Evening and night-time periods provide a different system context because solar generation is reduced or absent. Consequently, the combination of imports, dispatchable generation, storage, and other flexibility resources required to compensate for reduced offshore wind depends strongly on the conditions prevailing during each hour.

Changes are also visible in electricity-consuming flexibility, including storage charging. During periods of abundant renewable generation, part of the available electricity can be absorbed by these flexibility options. Reducing offshore wind availability therefore affects not only the positive generation stack, but also the timing and utilisation of flexible demand and storage.

The system-level comparison consequently reinforces the central observation from the historical analysis: the significance of an offshore wind restriction cannot be described adequately by its duration or percentage reduction alone. The offshore wind generation available at the time of the restriction and the wider electricity-system conditions determine both the absolute generation deficit and the resources required to compensate for it.

4.2. Event-Specific Market-Price Response

The preceding analysis illustrates the broader electricity-system response to progressively lower offshore wind availability. Bird-related Start/Stop operation, however, occurs during discrete operational windows. The market-price response is therefore examined separately at event scale by applying the prescribed offshore wind availability reduction during an evening period on 14 October 2030.

Figure 5 compares the resulting hourly market-clearing prices for the reference simulation and the three curtailment cases. The 14 October case is used as an illustrative event within the National Drivers 2030 electricity-system configuration. It should not be interpreted as a direct reproduction of the historical 14 October 2025 recommendation, but rather as an assessment of how a temporary evening reduction in offshore wind availability can propagate through a future electricity market.

For most of the day, the four simulations produce effectively identical market-clearing prices. The price trajectories begin to diverge only during the evening period in which offshore wind availability is reduced. This provides an important distinction between the



Figure 5. Hourly electricity-market clearing price on 14 October 2030 for the reference case and offshore wind availability reductions of 40%, 60%, and 90%. The shaded region identifies the prescribed 20:00–23:00 evening curtailment period. Outside this window, offshore wind availability and the remaining electricity-system assumptions are identical across the simulations.

broader system-sensitivity comparison shown in Figure 4 and the event-specific market response shown in Figure 5.

Reducing offshore wind availability removes part of the low-marginal-cost generation from the supply stack. The missing generation must subsequently be replaced by the remaining generation and flexibility resources. When this replacement requires a technology further along the merit order to become marginal, the market-clearing price increases. This mechanism is consistent with the well-established merit-order effect of renewable electricity generation on wholesale electricity prices [23].

The daily-average market-clearing price increases from 49.42 €/MWh in the reference simulation to 50.42 €/MWh under 40% curtailment, 50.75 €/MWh under 60% curtailment, and 51.88 €/MWh under 90% curtailment. These values correspond to increases of approximately 2.0%, 2.7%, and 5.0%, respectively, relative to the reference simulation.

The daily averages, however, include many hours during which the four simulations are identical and consequently understate the magnitude of the event-specific response. A visual estimate from Figure 5 indicates that the mean market-clearing price during the 20:00–23:00 curtailment window is approximately 65 €/MWh in the reference case, compared with approximately 70 €/MWh, 73 €/MWh, and 81 €/MWh under the 40%, 60%, and 90% curtailment cases, respectively. These values correspond to approximate event-window price increases of 8%, 12%, and 25% relative to the reference case. The event-specific response is therefore substantially larger than the 2.0–5.0% increases obtained when prices are averaged over the complete day.

These event-window values are approximate readings of the plotted hourly results rather than exact numerical outputs from the EYE simulation. They are included to illustrate the magnitude of the temporal concentration visible in Figure 5.

The market-price response is also nonlinear with respect to the imposed reduction in offshore wind availability. The 90% curtailment case does not simply produce a scaled version of the 40% case. As progressively more low-marginal-cost offshore wind generation is removed, increasingly expensive generation or flexibility resources can become marginal, resulting in a disproportionately stronger price response.

Although the average market-clearing price increases with stronger curtailment over the complete event window, the hourly response is not strictly monotonic. Individual hours can exhibit smaller or negligible price differences, and the formulation in Equation 5 also permits negative values if the resulting dispatch produces a lower marginal price than in the reference simulation. The relevant quantity is therefore the time-dependent market

response rather than an assumption that every curtailed hour results in the same price increase.

The timing of the selected event contributes to the observed response. During the evening period, solar generation is reduced or absent and fewer low-marginal-cost alternatives are available to replace offshore wind. An equivalent physical reduction occurring during a period of higher solar production, lower electricity demand, or greater availability of low-cost flexibility could therefore result in a different market-price response.

The economic significance of bird-related offshore wind curtailment therefore depends on both the physical quantity of generation removed and the electricity-market conditions prevailing during the affected hours. This is consistent with the broader literature on the market value of variable renewable generation, which shows that the value of wind and solar electricity depends strongly on its temporal coincidence with electricity-system and market conditions [24].

4.3. Stakeholder Implications

For offshore wind-farm operators and developers, bird-related curtailment reduces the quantity of electricity that can be generated and sold during the affected hours. The financial consequence depends on the amount of generation removed, the electricity price prevailing during the event, and the revenue structure of the project. Offshore wind projects operate under different auction and support arrangements, which result in different levels of exposure to wholesale electricity-price fluctuations [3]. Consequently, an identical quantity of curtailed generation can have different financial consequences for different projects.

For the transmission system operator, the principal concern is maintaining supply–demand balance and secure system operation when offshore wind availability is temporarily reduced. Depending on the system conditions, this may require additional imports, dispatchable generation, storage discharge, demand response, or other flexibility resources. The importance of these resources increases as the contribution of variable renewable generation grows. The International Energy Agency similarly identifies dispatchable generation, storage, grid reinforcement, demand response, improved forecasting, and improved system operation as important elements for integrating increasing shares of wind and solar generation [25]. Advance notice of Start/Stop events can therefore provide valuable preparation time for system operators and market participants.

Electricity consumers and suppliers can experience the consequences through changes in wholesale electricity prices during the affected hours. The 14 October simulation demonstrates that the event-window price response can be substantially larger than indicated by the corresponding daily-average value. Consumers directly exposed to spot-market prices may therefore experience the effect more directly, while electricity suppliers may face higher short-term procurement costs. The extent to which these wholesale-price effects are transmitted to final consumers will depend on the applicable retail contracts and market arrangements.

Temporary reductions in offshore wind availability can have different implications for dispatchable generators, electricity-storage operators, and interconnector users. Additional generation, imports, or stored electricity may be required to replace offshore wind production that would otherwise have been available. These resources may therefore experience greater utilisation during Start/Stop periods. Bird-related curtailment should consequently not be interpreted as producing an identical economic effect for all electricity-system participants; part of the response represents a redistribution of generation, flexibility utilisation, and market value between different technologies and actors.

For public authorities and ecological regulators, the primary objective of Start/Stop operation remains the reduction of bird-collision risk during periods of intense migration. Operational adjustment of wind turbines has been identified as a potential measure for reducing avian mortality [26]. Improved migration forecasting can support more targeted Start/Stop decisions by concentrating the operational restriction within the periods in which it is ecologically required. Information on expected wind generation and electricity-system conditions can subsequently support preparation for the resulting operational and market consequences without altering the ecological basis of the Start/Stop decision itself.

The wider public dimension is also relevant because Start/Stop operation represents a direct interaction between biodiversity protection and renewable electricity production. Transparent communication of why curtailment is required, when it occurs, and what its electricity-system consequences are can support broader understanding of ecological mitigation measures associated with offshore wind development.

Overall, the results demonstrate that bird-related offshore wind curtailment should not be evaluated solely in terms of the annual number of unavailable turbine hours. Its physical and economic significance depends on when those hours occur, the offshore wind generation available at that time, and the state of the electricity system. The timing of Start/Stop operation is therefore as important as its duration when evaluating the resulting energy and electricity-market consequences.

5. Conclusions

This study examined the physical and electricity-market consequences of bird-related offshore wind curtailment by combining historical observations of Dutch Start/Stop events with forward-looking electricity-system modelling. Historical notifications between 2023 and 2026 were analysed to characterise the timing and duration of Start/Stop periods and the offshore wind and generation conditions prevailing during the affected hours. These observations were subsequently used to motivate a time-specific representation of offshore wind curtailment in the EYE model under the National Drivers 2030 electricity-system scenario.

The historical analysis shows that Start/Stop events occurred under markedly different wind conditions, with mean offshore wind speeds during the selected notification windows ranging from approximately 5.0 to 10.5 m/s. Events at the lower end of this range coincided with comparatively limited wind-generation potential, whereas several events at higher wind speeds occurred while substantial offshore wind production would otherwise be expected. Selected March 2026 events also showed recorded offshore generation during the formal decision windows that was approximately 65–70% lower than levels observed shortly after the restrictions ended, while the regional offshore wind conditions remained broadly comparable. These comparisons are descriptive and should not be interpreted as direct estimates of curtailed energy, but they demonstrate that event duration alone is insufficient to characterise the potential energetic significance of Start/Stop operation.

The EYE simulations further show that the electricity-system response depends on both the severity and the timing of the imposed offshore wind restriction. As offshore wind availability is reduced, the unavailable generation is compensated through changes in imports, dispatchable generation, storage, and other flexibility resources. The response is not proportional to the imposed curtailment level because progressively larger reductions in low-marginal-cost offshore wind can cause different technologies to become marginal.

For the 14 October 2030 event, the daily-average market-clearing price increases from 49.42 €/MWh in the reference simulation to 50.42, 50.75, and 51.88 €/MWh under the 40%, 60%, and 90% curtailment cases, corresponding to increases of approximately 2.0%, 2.7%, and 5.0%, respectively. The market response is substantially more pronounced during the

actual curtailment period. Visual estimates from the hourly results indicate mean price increases of approximately 8%, 12%, and 25% during the 20:00–23:00 window for the three curtailment cases. The hourly response is not necessarily positive in every affected hour, however, because the resulting price difference depends on the dispatch and marginal generating technology at that specific time.

The principal finding is therefore that bird-related offshore wind curtailment should be treated as a time-specific and resource-dependent operational event, rather than solely as an annual number of unavailable turbine hours. The same duration of curtailment can have substantially different consequences depending on offshore wind availability, electricity demand, other renewable generation, market conditions, and available system flexibility during the affected hours. The consequences also extend beyond the curtailed wind farm itself by changing the utilisation of imports, dispatchable generation, storage, and other flexibility resources.

This has implications for both ecological mitigation and electricity-system operation. The ecological objective should remain the basis for Start/Stop decisions, while improved migration forecasting and advance notification can help concentrate restrictions within periods of highest ecological relevance. At the same time, information on expected offshore wind generation and electricity-system conditions can support system operators and market participants in preparing for the resulting temporary reduction in renewable generation. Clear communication of the timing, purpose, and system consequences of Start/Stop operation may also improve transparency for the wider public as the interaction between biodiversity protection and renewable-electricity production becomes increasingly visible.

Several limitations should be considered when interpreting the results. Historical generation data are available only at an aggregated Dutch offshore wind level, while the meteorological observations represent regional offshore conditions rather than wind-farm-specific hub-height measurements. The historical analysis therefore cannot provide a direct counterfactual estimate of the electricity lost solely because of Start/Stop operation. In addition, the EYE assessment considers a single National Drivers 2030 electricity-system configuration, while the 40%, 60%, and 90% offshore wind reductions are sensitivity assumptions rather than historical estimates of realised curtailment. The event-window price values reported here are also approximate readings of the plotted hourly results and should be replaced by exact numerical averages when the underlying simulation outputs are available.

Future work should therefore combine wind-farm-specific operational data, hub-height meteorological observations, and a larger set of formal Start/Stop events with multiple future electricity-system scenarios. Integrating migration forecasts, wind-generation forecasts, and electricity-market conditions within a common framework would allow the physical, ecological, and economic consequences of bird-related curtailment to be evaluated more consistently and could support increasingly targeted implementation of Start/Stop measures as offshore wind capacity continues to expand.

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Abbreviations

The following symbols and abbreviations are used in this manuscript:

α_t	Offshore wind availability factor during hour t
Δp_t	Change in market-clearing price during hour t
Δt	Simulation time step
E_t^{curt}	Curtailed offshore wind energy during hour t
p_t	Market-clearing price during hour t
p_t^{curt}	Market-clearing price with curtailment
p_t^{ref}	Reference market-clearing price
P_t^{base}	Offshore wind production under normal operation
P_t^{curt}	Offshore wind production after curtailment
EYE	TNO electricity-system simulation model
IEA	International Energy Agency
KNMI	Royal Netherlands Meteorological Institute
ND	National Drivers
NED	Nationaal Energie Dashboard
PV	Photovoltaic
TNO	Netherlands Organisation for Applied Scientific Research

Appendix A. Historical Electricity-Market Prices during Selected Start/Stop Events

This appendix provides additional historical electricity-market context for the Start/Stop events examined in Section 2. Historical Dutch wholesale electricity prices are presented for 13 and 14 October 2025 [27], corresponding to three six-hour Start/Stop recommendation periods. The prices are used here retrospectively as historical observations of the market conditions prevailing during the Start/Stop periods.

Figure A1 presents the historical electricity-price profiles at 15-minute resolution. The shaded regions identify the officially notified Start/Stop recommendation windows. On 13 October, recommendations applied from 00:00–06:00 and again from 18:00–24:00. On 14 October, the recommendation applied from 18:00–24:00. Prices are expressed in €/MWh and all times are shown in Dutch local time (Europe/Amsterdam).

The daily-average electricity price was 126.46 €/MWh on 13 October 2025. Considerable intraday variation occurred, however. The lowest price of the day was 75.19 €/MWh during 03:45–04:00, within the 00:00–06:00 Start/Stop recommendation period. By contrast, the maximum price of 366.71 €/MWh occurred during 18:45–19:00, within the second Start/Stop recommendation period from 18:00–24:00. The two six-hour recommendation periods on the same calendar day therefore coincided with markedly different electricity-market conditions.

On 14 October 2025, the daily-average electricity price was 144.58 €/MWh. The minimum price of 82.36 €/MWh occurred during 14:00–14:15, before the Start/Stop period, whereas the maximum price reached 437.97 €/MWh during 19:00–19:15, within the 18:00–24:00 recommendation window. The evening Start/Stop period therefore overlapped with some of the highest-price conditions of that day.

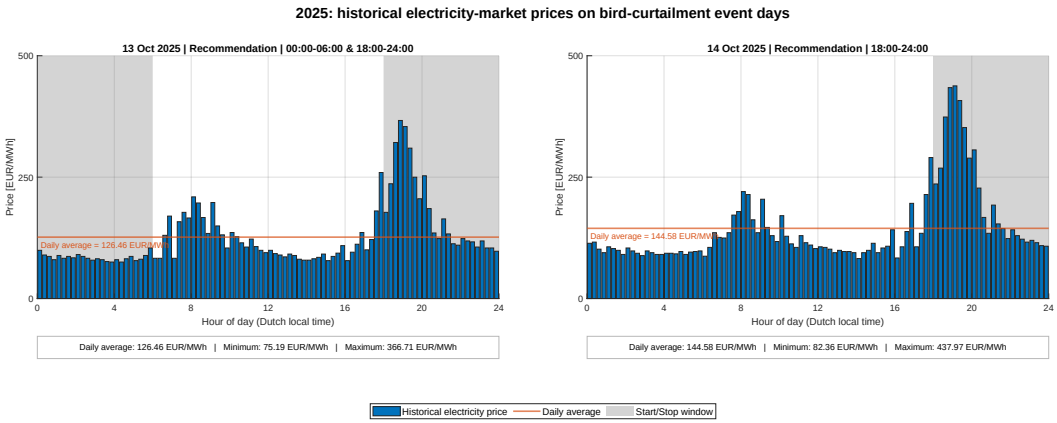


Figure A1. Historical Dutch wholesale electricity prices on 13 and 14 October 2025 at 15-minute resolution. Blue bars show the historical electricity price, the orange horizontal line indicates the corresponding daily-average price, and shaded regions identify the officially notified Start/Stop recommendation windows. On 13 October, recommendations covered 00:00–06:00 and 18:00–24:00; on 14 October, the recommendation covered 18:00–24:00. Prices are expressed in €/MWh and shown in Dutch local time (Europe/Amsterdam).

These observations should not be interpreted as estimates of the financial loss caused by Start/Stop operation. The 2025 notifications were recommendations rather than formal decisions, operator participation was not uniform, and the nationally aggregated offshore wind data do not provide the counterfactual generation that would have occurred in the absence of the recommendation. The historical price profiles instead demonstrate that the electricity-market conditions associated with individual Start/Stop events can differ substantially even when their duration is identical. This provides additional motivation for representing bird-related curtailment as a time-specific event in the electricity-system modeling undertaken in this study.

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