Aanvaringsrisico’s voor thermiekende roofvogels door zonneparken bij windturbines te plaatsen

Kennis van Ecologie voor de Energietransitie: cluster Land

S. Moonen, K. Vimalakanthan, R. Buij, J. Breuer, R. Klaassen, T. Hoenders, T. Schaub, K.L. Krijgsveld
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Voorwoord

Het Ministerie van EZK heeft in 2025 opdracht gegeven om het onderzoeksprogramma Kennis van Ecologie voor Energietransitie (KEEN) te starten. Doel van dit programma is te voorkomen dat de energietransitie leidt tot ongewenste ecologische gevolgen en tegelijkertijd te voorkomen dat de energietransitie vertraging ondervindt als gevolg van onzekerheid over de ecologische effecten van hernieuwbare energieopwekking. Het project is begeleid door TKI Urban Energy (Topconsortia voor Kennis & Innovatie) en RVO Rijksdienst voor Ondernemend Nederland.

De energietransitie zal een impact hebben op de kwaliteit en het leven in het water, op het land en in de bodem. Deltares, TNO, WUR en KWR onderzoeken de effecten van het opschalen van hernieuwbare energiebronnen zoals wind, zon, aquathermie en bodemenergie, om ervoor te zorgen dat onze overgang naar een duurzame toekomst zowel effectief als ecologisch verantwoord is. Er is nieuw onderzoek gestart binnen KEEN maar ook lopend onderzoek wordt gebruikt, gebundeld en aangevuld binnen KEEN. In dit rapport worden de eerste onderzoeksresultaten gepresenteerd, de wens is om een langjarige monitoringreeks te kunnen opbouwen.

Het onderzoek is georganiseerd in drie clusters:

Cluster Land:

1. Onderzoek naar de verdeling van bodemvocht onder zonnepanelen
2. Onderzoek naar aanvaringsrisico's voor roofvogels bij het combineren van zon- en windenergie, met modellering van de luchtstromen.

Cluster Water:

1. Onderzoek op één locatie naar de effecten van een aquathermie installatie op de ecologie. Er is gekeken naar de effecten van waterfiltering, koudelozing en stroming.
2. Onderzoek naar de relatie tussen bedekking door zonnepanelen op water en de impact op primaire productie van biomassa.

Cluster Bodem:

1. Onderzoek naar de temperatuureffecten van MTO- en HTO-systemen op de grondwaterkwaliteit.

In deze notitie leest u de resultaten van het onderzoek naar de impact op roofvogels van het in elkaars nabijheid realiseren van zon- en windenergie. Dit onderzoek vormt een onderdeel van het Cluster Land.

Het onderzoek is in deze notitie in het Engels gepresenteerd, voorafgegaan door een uitgebreide Nederlandse managementsamenvatting. In deze samenvatting vindt u de belangrijkste aspecten van het onderzoek terug: achtergrond, aanpak, resultaten en conclusies van het onderzoek, alsook de aanbevelingen die eruit volgen.

Managementsamenvatting

Aanleiding

Windturbines vormen een risico voor roofvogels. Windturbines kunnen negatieve effecten hebben op vogels, doordat zij verhoogde sterfte veroorzaken door aanvaringen en door veranderingen in het leefgebied. Roofvogels zijn van de vogels een bijzonder kwetsbare groep, omdat zij vaak op rotorhoogte vliegen, in het algemeen weinig vermijdend gedrag rond turbines tonen, en bovendien veelal gebruik maken van thermiek — opwaartse luchtstromen die hen juist naar turbinehoogte en in de gevarenzone van rotorbladen kunnen brengen. Doordat roofvogels bovendien een lage voortplantingssnelheid hebben, kan extra sterfte snel effect hebben op populatieniveau, wat betekent dat de extra sterfte door aanvaringen met turbines kan leiden tot structurele afname van roofvogels. Om deze risico's te verminderen worden allerlei maatregelen toegepast; zoals windturbines niet plaatsen in voor vogels risicovolle gebieden, turbines stilzetten bij verhoogd aanvaringsrisico, rotorbladen zichtbaarder maken, en het prooiaanbod rondom turbines verminderen.

Zonneparken bij windturbines: kans of risico? Een nieuwe ontwikkeling in dit veld is de combinatie van zonneparken met windturbines. Deze combinatie vermindert de huidige problemen met de netcongestie en verhoogt de energieopbrengst per hectare. Een zonnepark onder turbines kan bovendien een goede manier zijn om het leefgebied rond de turbines minder aantrekkelijk te maken voor roofvogels en daardoor sterfte door aanvaringen te verminderen. Anderzijds kan de combinatie ook leiden tot extra thermiek, door de warmte-uitstraling van zonnepanelen. Hierdoor zouden roofvogels juist vaker op rotorhoogte en in de buurt van de turbines kunnen gaan vliegen, wat het aanvaringsrisico potentieel vergroot.

Doel van het onderzoek

Thermiekvorming boven panelen en thermiekvluchten van roofvogels. In dit onderzoek hebben we onderzocht hoe de aanwezigheid van zonnepanelen de luchtstroming beïnvloedt boven zonneparken die naast windturbines zijn geplaatst, en of dit leidt tot veranderd vlieggedrag van de buizerd (*Buteo buteo*).

Voor de buizerd is gekozen als onderzoekssoort om 3 redenen. Allereerst is het een algemene soort in Nederland en andere Europese landen, met een groot verspreidingsgebied tot diep in Rusland en Zuid-Afrika. Het algemene voorkomen maakt dat het specifieke vlieggedrag in relatie tot zonneparken goed te onderzoeken is. Daarnaast is het een soort die veel gebruik maakt van thermiek. Het is dus bij uitstek een soort die beïnvloed kan worden bij veranderingen in opwaartse luchtstromen die potentieel wordt veroorzaakt door zonnepanelen. Tot slot is de buizerd, net als veel andere soorten roofvogels en thermiekende vogels zoals gieren, relatief vaak slachtoffer van aanvaringen met windturbines, en waarvoor een verhoogd aanvaringsrisico potentieel effecten kan hebben op populatieniveau. De resultaten van deze pilot zijn ook internationaal van belang omdat ze inzicht geven in de thermiek rond zonnepanelen en daarmee in de aanvaringsrisico's voor alle vogelsoorten die gebruik maken van die thermiek.

Aanpak

Voor het onderzoek hebben we twee benaderingen gecombineerd:

1. **Modelleren** hoe zonnepanelen de **luchtstromen** (opwaarts en zijwaarts) rondom windturbines veranderen, om te bepalen of en in welke mate de panelen extra thermiek genereren, wat een aantrekkende werking kan hebben op vogels die gebruik maken van die thermiek.
2. Het **vlieggedrag meten** van 21 buizerds in en rond zonneparken; met behulp van GPS-zenders waarmee vlieghoogte, stijgsnelheid en het optreden van thermiekvluchten bepaald konden worden.

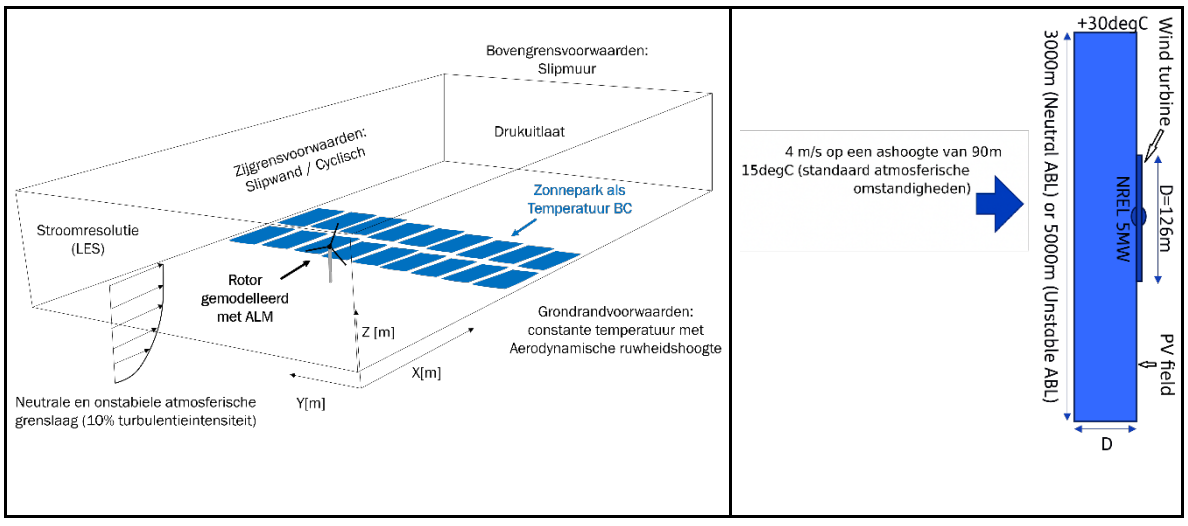
Door de modelresultaten en de gedragsgegevens te integreren, konden we bepalen of door zonnepanelen opgewekte thermiek leidt tot meer en langer verblijf van roofvogels boven zonneparken en op rotorhoogte, en daarmee of zonneparken in de nabijheid van windturbines het risico op aanvaringen vergroten.

Buizerd wordt losgelaten nadat hij een zender heeft gekregen. Foto T. Hoenders.

Track van de vlucht van een gezenderde buizerd die over een zonnepark vliegt (gele lijn). De track laat op meerdere plekken de cirkelbewegingen zien als de buizerd aan het 'thermieken' is.

Configuratie van het model

Alle modelsimulaties waren gebaseerd op een zogenaamde 'single reference configuratie' (Figuur A). Deze configuratie bestond uit een windturbine, een zonnepark op land, en een set aan model-vlakken (sampling planes) waarin geanalyseerd wordt hoe het zog achter de turbines zich ontwikkelt, alsook temperatuurveranderingen en verticale luchtsnelheden.

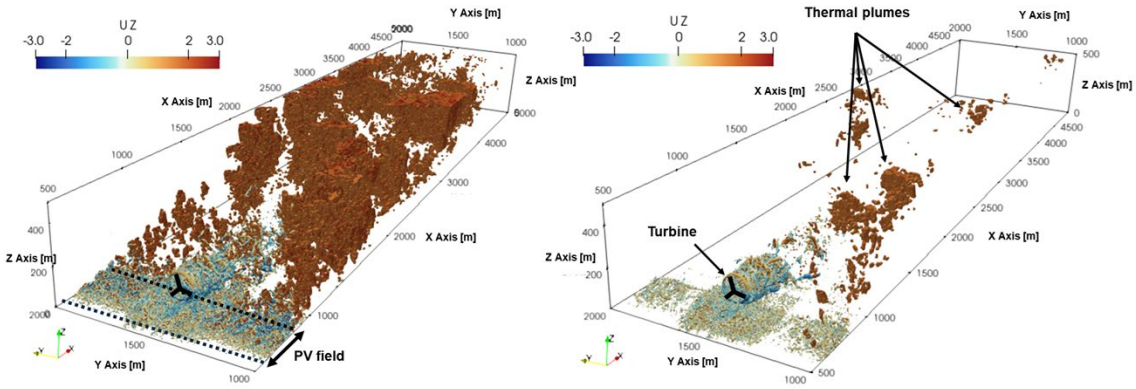


Figuur A: Configuratie voor het modelleren van luchtstromingen achter een windturbine en boven en voorbij zonnepanelen. De luchtstroom wordt (linksonder) het systeem ingevoerd, passeert eerst een turbine, vervolgens de zonnepanelen (blauwe vlakken), en kan zich daarna verder ontwikkelen. Voor deze configuratie is gekozen omdat die op voorhand als het risicovolst werd ingeschat, aangezien bij thermiek boven de panelen de buizerd in de windturbine zou waaien.

Belangrijkste bevindingen

Turbulentie achter turbines en boven – en voorbij - zonneparken

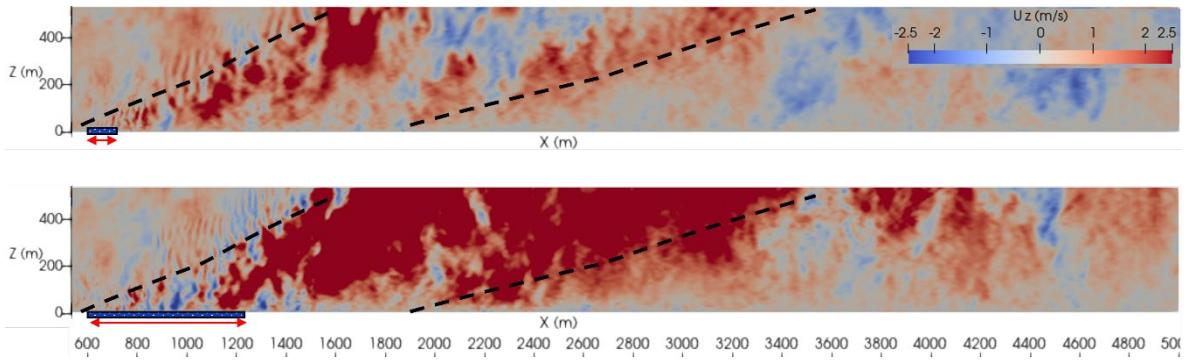
Situatie typerend voor de zomer, met onstabiele atmosferische luchtlagen. Door de hitte van de zonnepanelen ontstonden samenhangende, door opwarming aangedreven opwaartse luchtstromen benedenwinds van de panelen (figuur B). De structuur en verticale ontwikkeling van deze opwaartse luchtstroom / thermische pluim was sterk afhankelijk van de aanwezigheid van een zog van de turbine. Als dat zog er was, werd de pluim verder benedenwinds vervoerd, bleef dichter bij het oppervlak over een grotere afstand, en vertoonde een duidelijke helling in stroomrichting met minder verticale samenhang. Wanneer de analyse werd uitgevoerd in een gebied dat voldoende ver van het turbine-zog lag (en daardoor niet door het zog werd beïnvloed), steeg de thermische pluim sneller op en vormde zich een sterkere, meer verticaal samenhangende opwaartse stroming dichter bij de rand van het zonnepark. Dit betekent dat de turbulentie van de turbine in combinatie met de hitte van de panelen niet optrad boven de zonnepanelen maar ruimschoots voorbij de panelen.



Figuur B. Visualisatie van thermische opwaartse stromingen bij onstabiele atmosferische condities, met (links) en zonder (rechts) opwarming door zonnepanelen, beide mét turbine-zog.

Groter zonnepark vergroot de turbulentie

Wanneer een groter zonnepark werd gemodelleerd, was het effect op de turbulentie in de lucht groter. Vooral de verticale luchtsnelheden waren groter dan bij een kleiner zonnepark. De vorm en structuur van de turbulentie was echter vergelijkbaar in beide situaties (figuur C), wat erop wijst dat met name de breedte van het zonnepark de intensiteit van de opwaartse stroming (de uplift) bepaalt, en niet zo zeer de vorm ervan.



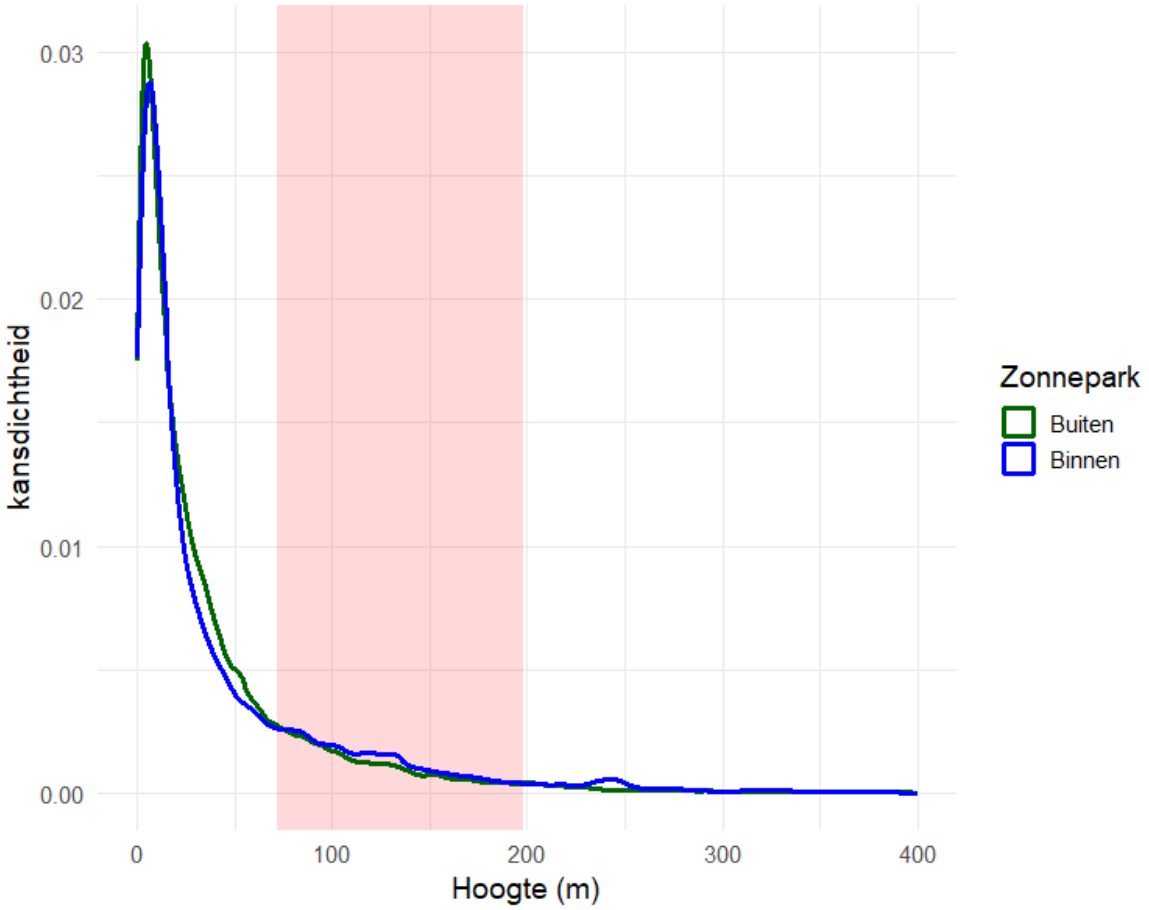
Figuur C. Vergelijking van de ontwikkeling van turbulentie bij een smal zonnepark (boven) en een breder zonnepark (onder). Een breder zonnepark versterkt de opwaartse stroming pluim. Positie van het zonnepark is aangegeven met blauwe en rode lijnen linksonderin beide panelen. Situatie met onstabiele atmosferische condities en zonder turbine-zog.

Samenvattend laten de modellen zien dat de combinatie van turbine-zog en zonneparkverwarming leidt tot thermiekvorming stroomafwaarts van het zonnepark, en niet direct boven de panelen.

Vlieggedrag van buizerds

De vlieghoogtes waren marginaal lager boven zonneparken dan daarbuiten (3.2% lager). Vogels vlogen hoger bij hogere temperaturen. Seizoen had een effect op vlieghoogtes, waarbij de vlieghoogtes het laagst waren in de herfst, en in de andere drie seizoenen vergelijkbaar waren met de hoogste gemiddelde waarden in de zomer.

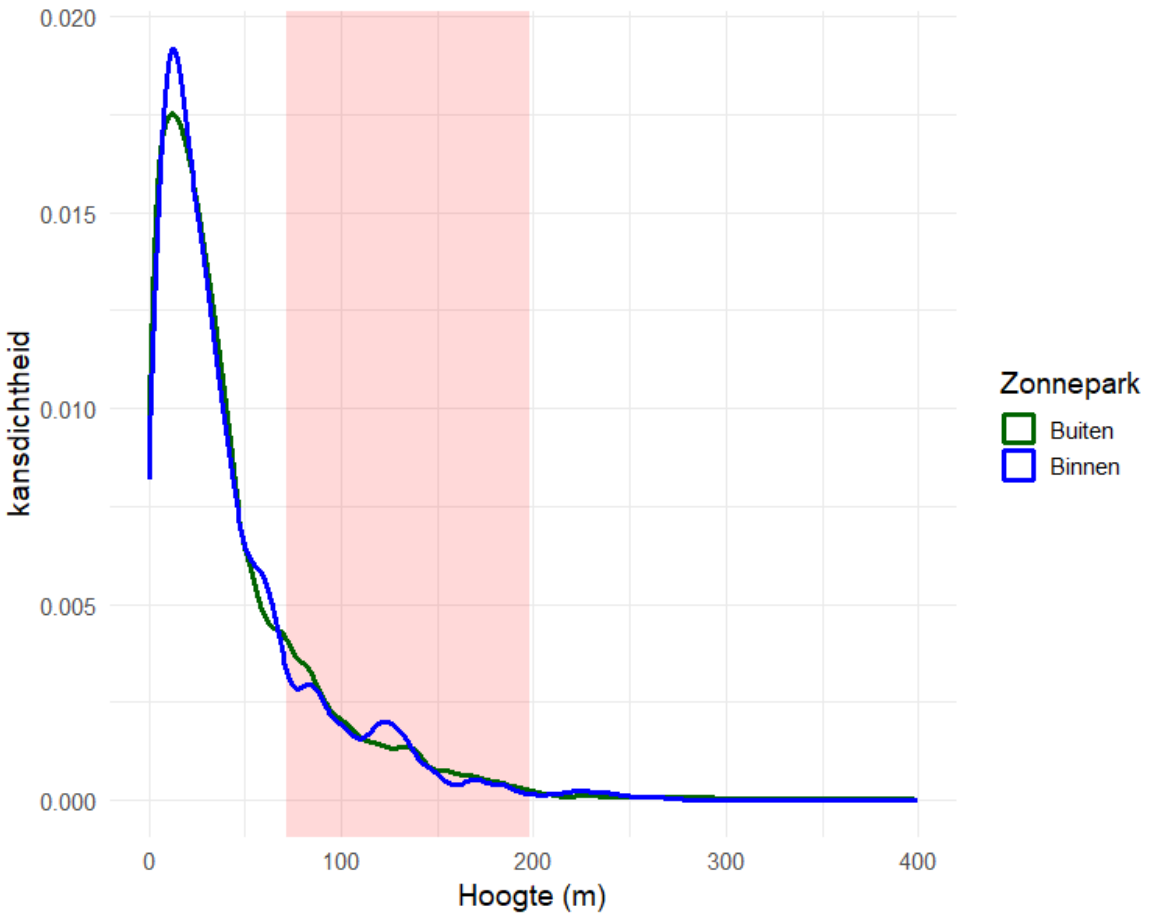
Het grootste deel van de vluchten vond plaats onder gedefinieerde tiplaagte van 72 meter (Figuur D), de kans om op rotorhoogte te vliegen was groter boven zonneparken dan daarbuiten. Dit effect werd versterkt bij lagere windsnelheden; dus de kans dat buizerds op rotorhoogte vlogen was groter bij lage windsnelheden. Ook bij hogere omgevingstemperaturen lag het percentage vluchten op rotorhoogte hoger.



*Figuur D. De dichtheid van GPS-punten op verschillende vlieghoogtes **tijdens alle geregistreerde vluchten** binnen en buiten zonneparken. Vlieghoogte binnen zonneparken lag iets lager dan erbuiten. Het roze vlak geeft de rotorhoogtes van de windturbines weer. De meeste waarnemingen waren van vogels die onder rotorhoogte vlogen (hoogste dichtheden liggen links van het roze vlak).*

Vlieghoogtes tijdens thermiekvluchten

Voor 20 van de 21 buizerds werd een groot aantal thermiekvluchten geregistreerd (bijna 51.000 GPS-posities tijdens 871 thermiekvluchten); slechts 1 buizerd genereerde geen enkele thermiekvlucht. Boven zonneparken was de hoogte van deze vluchten marginaal maar consistent lager dan daarbuiten (figuur E).



*Figuur E. De dichtheid van GPS-punten op verschillende vlieghoogtes **tijdens alleen thermiekvluchten** binnen en buiten zonneparken. Vlieghoogte binnen zonneparken lag iets lager dan erbuiten. Het roze vlak geeft de rotorhoogtes van de windturbines weer. De meeste waarnemingen waren van vogels die onder rotorhoogte vlogen (hoogste dichtheden liggen links van het roze vlak).*

Bij hogere omgevingstemperaturen was de hoogte van thermiekvluchten groter dan bij lagere temperaturen, en bij hoge windsnelheden werd lager gevlogen. De kans dat een buizerd op rotorhoogte thermiekvluchten uitvoerde, was kleiner boven zonneparken dan daarbuiten. Dit verschil was significant maar klein, dit is een belangrijk resultaat omdat de zonnepanelen dus geen verhoogd risico op thermiekvluchten op rotorhoogte opleveren.

Veranderingen in vlieghoogtes tijdens thermiekvluchten

Er werden geen verschillen gevonden in de gemiddelde verandering van vlieghoogte tijdens thermiek vluchten. Ook verschillen in temperatuur en wind bleken hier geen meetbare invloed op te hebben.

Conclusies

Uit de simulaties blijkt dat de warmte van zonnepanelen opwaartse luchtstromen kan veroorzaken die sterk genoeg zijn om door thermiekende vogels te worden gebruikt. De structuur en sterkte van deze thermiek worden echter sterk beïnvloed door het zog van nabijgelegen windturbines. Dit zog verstoort en verplaatst de opwaartse stroming, waardoor deze minder verticaal samenhangend is en verder stroomafwaarts ontstaat. Grotere zonnevelden leveren daarbij wel sterkere opwaartse stroming, maar veranderen het algemene patroon niet wezenlijk.

Over het geheel genomen wijzen de resultaten van de simulaties erop dat zonneparken weliswaar bruikbare thermiek kunnen produceren, maar dat die thermiek niet direct boven de panelen optreedt, maar er voorbij. Daardoor vergroten combinaties van wind- en zonneparken niet automatisch het risico dat thermiekende vogels dichter bij windturbines komen.
Gezenderde buizerds laten zien dat ze boven zonneparken gemiddeld iets lager vliegen dan daarbuiten, al is dit verschil beperkt. Hoewel ze boven zonneparken iets vaker op rotorhoogte voorkomen, maken ze daar minder gebruik van thermiek en ze winnen er ook niet sneller hoogte. Dit bevestigt dat zonneparken voor de vogels geen extra aantrekkelijke locaties zijn voor thermisch zweven.

Het botsingsrisico blijft vooral afhankelijk van de tijd die vogels op rotorhoogte doorbrengen; bij de gezenderde buizerds gebeurde dit in ongeveer 17% van de vluchten. Weersomstandigheden spelen hierbij een belangrijke rol: hogere temperaturen leiden tot hogere vlieghoogtes, terwijl sterke wind juist lagere zweefhoogtes veroorzaakt. Ook seizoensinvloeden en de afmetingen van windturbines bepalen mede dit risico.

Aanbevelingen

Uit deze studie blijkt dat het plaatsen van zonneparken in de buurt van windturbines niet direct leidt tot hogere aanvaringsrisico’s voor vogels die gebruik maken van thermiek, omdat de thermiek niet direct boven de panelen ontstaat maar enkele kilometers benedenwinds van de panelen.

De combinatie van zonne- en windparken kan in principe gunstig zijn vanuit het oogpunt van ruimtegebruik, en ook voor de bescherming van roofvogels. Immers, het aanvaringsrisico van thermiekende buizerds boven zonnepanelen was lager dan daarbuiten, en de panelen bleken niet aantrekkelijk voor de vogels om hoogte boven te winnen. Tegelijkertijd blijkt uit alle vliegdata gecombineerd dat buizerds boven zonneparken vaker op rotorhoogte vlogen. Dit resultaat vraagt om nader onderzoek, en ook om een grotere minimale rotorhoogte. Het combineren van zonne- en windparken vraagt daarbij om zorgvuldige inrichting van de opstellingen en van het beheer van de vegetatie. Zonneparken kunnen namelijk prooidieren aantrekken en zo roofvogels aantrekken. In voorliggend onderzoek is deze relatie niet onderzocht. De focus lag hier op verandering in thermiek boven zonneparken. Een vervolgstap zou kunnen zijn te onderzoeken hoe roofvogels natuurinclusieve of natuurpositieve zonneparken gebruiken om te foerageren, en hoe dit van invloed is op hun vlieggedrag (gebruik van het zonnepark en vlieghoogte). Daarmee kan achterhaald worden de aanvaringskans is als dit type zonneparken wordt gecombineerd met windturbines, en wat vanuit dat perspectief de voorwaarden zijn qua opstelling en inrichting.

1 Introduction

Wind turbines affect wildlife primarily through elevated mortality due to collision with turbine blades, habitat fragmentation, habitat degradation and habitat loss, as well as mortality resulting from collisions and electrocutions with associated power lines (Drewitt and Langston 2006). Birds and bats are the vertebrates most vulnerable to collisions (Osborn et al. 2000), but impacts vary considerably by species, with raptors (Accipitriformes, Cathartiformes, Falconiformes, Strigiformes, Cariamiformes; McClure et al. 2019) facing some of the highest turbine collision rates generally among birds (Thaxter et al. 2017). Raptors are relatively vulnerable to collisions with wind turbines due to flight behaviours that bring them inside rotor-swept heights, low avoidance of turbines compared to other birds, and a preference for soaring in locations suitable for wind energy generation (Estellés-Domingo and López-López 2025). Thermals, or rising columns of warm air are a significant factor bringing soaring raptors into the rotor-swept zone of wind turbines, increasing their collision risk. Raptors rely on these updrafts to gain altitude without expending energy, allowing them to soar for long periods (Murgatroyd et al. 2018). If wind farms are located in areas with high uplift potential, they may coincide more frequently with the raptors' preferred flight paths leading to increased collision risk. Apart from their high collision risk, raptors' slow reproduction and high longevity make population recovery slower than for most other birds (Linder et al. 2022); indeed, elevated mortality from turbine collisions has been shown to lead to the population decline of a range of raptor species (Estellés-Domingo and López-López 2025).

To prevent raptor population decline from cumulative mortality arising from collisions with wind parks inside the range, various mitigation measures have proven effective. This includes a combination of enhancing turbine visibility to prevent collisions, using technology to detect approaching raptors and shutdown turbines, and modifying the habitat surrounding turbines to reduce prey availability for raptors. For example, painting the blades of a wind turbine can reduce bird collisions by up to 70% (May et al. 2020, Blary et al. 2023) and temporarily shutting down turbines when collision risks are high can considerably reduce mortality (e.g., de Lucas et al. 2012; McClure et al. 2021). Importantly, raptors are attracted to areas with high prey density and perching opportunities, so making a windfarm less appealing in that respect reduces raptor numbers and associated collision risks (Allison et al. 2017).

One way of lowering the attractiveness of wind parks to raptors is combining them with photovoltaic (PV) panels, which may reduce the accessibility and abundance of ground-dwelling raptor prey directly around and underneath wind turbines. Combining wind and solar farms into hybrid systems also maximizes renewable energy output per unit area and reduces land-use footprint by sharing infrastructure. These combined systems capitalize on complementary generation profiles—wind often peaks at night/winter, while solar peaks during the day/summer—leading to a more consistent, reliable power supply. However, the combination of solar and wind energy may lead to elevated risks of collisions when the heat generated by photovoltaic panels creates thermals that are utilized by raptors, possibly bringing them more frequently inside rotor-swept zones. While photovoltaic panels convert sunlight into electricity, they also absorb a significant amount of solar energy, and this heated surface acts as a "radiator," warming the air directly above it. This warmer air is lighter than cool air and rises, forming thermals (Smith et al., 2022; Fthenakis & Yu, 2013; Glick et al., 2020).

Here, we examine how photovoltaic panels influence the occurrence of thermals inside solar parks and the flight behaviour of Common Buzzard Buteo buteo (henceforth: buzzard). This species is among the most frequent collision casualties due to relatively frequent flights at rotor height (Bose et al. 2020; Schaub et al. 2024). We modeled airflow and deployed GPS trackers on buzzards to allow for detailed examination of thermal soaring strategies driven by uplift sources in raptors (e.g., Murgatroyd et al. 2018). First, we modeled how the presence of photovoltaic panels changed the thermals around wind turbines, thereby altering flight conditions for buzzards. Second, we examined whether these altered flight conditions affected the soaring behaviour of buzzards; more specifically, we tested (1) whether

buzzards soar more often at rotor height above than away from solar panels, and (2) whether their height gain in thermal soaring flight was more rapid above solar panels, making solar panels near turbines attractive for soaring buzzards. By integrating our findings, we assess whether solar parks situated close to wind turbines could exacerbate collision risk for buzzards if solar-panel induced changes in thermal updrafts increase the time birds spend flying within rotor-swept heights.

2 Methods

Modelling of thermals

To examine how heat released by solar panels (also PV or photovoltaic panels) modifies airflow near wind turbines, we used large-eddy simulations (LES). The objective of the modelling was to quantify whether heating induced by solar panels can generate buoyancy-driven vertical motion and how such buoyancy interacts with the wake of a wind turbine. The simulations were used to provide a physical context for interpreting observed soaring behaviour, rather than to predict bird behaviour directly.

Model configuration
All simulations were based on a single reference configuration (Figure 1), which was kept fixed across cases. This configuration consisted of a wind turbine, a ground-mounted solar field, and a set of sampling planes used to analyse wake development, temperature anomalies, and vertical velocity. Using a common geometry ensured that differences between cases could be attributed to atmospheric stability and solar field characteristics rather than to layout changes.

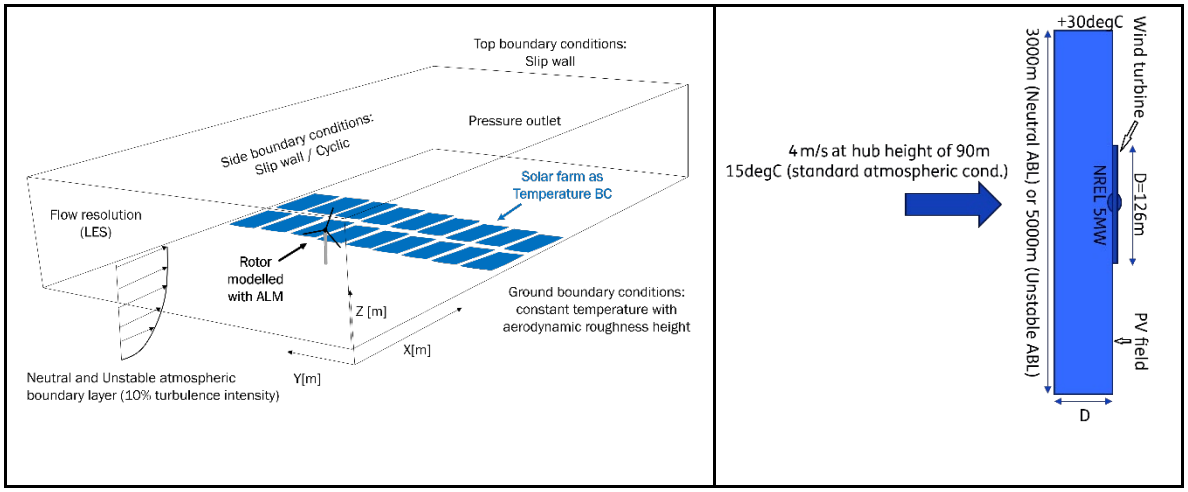


Figure 1: Computational domain and boundary conditions (left) and top view of the refence configuration (right)

The wind turbine was represented using an actuator-line approach, allowing realistic wake formation without resolving blade geometry in detail. Turbulent inflow conditions were generated using precursor simulations.

The solar park was represented as a heated surface patch positioned relative to the turbine such that the downstream interaction between the turbine wake and the air mass heated by the solar panels could be analysed. Simulations were conducted both with and without a turbine wake, using identical geometry and diagnostics, to isolate the effect of wake–buoyancy interactions.

Atmospheric conditions
The simulated atmospheric conditions were selected to represent periods when thermal soaring is most likely to occur. Observations indicated that soaring activity peaked around midday during summer, coinciding with mean hub-height wind speeds of approximately **4 m s^{-1}**. These conditions are consistent with an **unstable atmospheric boundary layer (ABL)**, and unstable ABL simulations were therefore used to represent midday conditions. In addition, **neutral ABL** simulations were performed at the same inflow wind speed to provide a baseline for isolating buoyancy effects. These neutral cases allowed the influence of PV-induced heating on wake recovery and turbulence to be evaluated in the absence of sustained buoyancy-driven updraft formation.

Parameter variation
To assess the sensitivity of buoyancy-driven uplift to the spatial extent of PV heating, the width of the PV field was varied between a narrower configuration corresponding to **one turbine rotor diameter (1D)** and a wider configuration corresponding to **five turbine rotor diameters (5D)**. Apart from atmospheric stability and PV-field width, all other aspects of the simulations were kept constant.

Flow diagnostics
The analysis focused on flow quantities directly relevant to wake behaviour and thermal formation. Vertical velocity was analysed to identify the presence, structure, and coherence of buoyancy-driven updrafts downstream of the PV field. Streamwise velocity was analysed to quantify wake recovery and to assess whether PV heating altered the downstream momentum deficit. Together, these diagnostics allowed separation of buoyancy-driven effects from wake-induced turbulence.

Buzzard thermal soaring behaviour

Study sites
We investigated 14 solar parks on former agricultural fields located throughout the Netherlands. Solar parks ranged in sizes ranging from 1 to 87 hectares. The combination of solar parks with wind turbines in proximity as well as with an active buzzard territory was limited (5 in the current study). Rather than limiting the research to these combinations, we investigated all flight behaviours of buzzards above solar parks, both with and without turbines nearby, and related flight behaviour to rotor-swept heights, which was also used in the thermal models (between 72 and 198 m high).

Tracking buzzards
To analyse thermal soaring flight behaviour, we equipped 21 buzzards breeding near solar parks (nest tree <300 m to the edge of the nearest panels) with GPS-GSM transmitters (OrniTrack-25 - solar powered GPS-GSM tracker). Birds were captured during the nesting period when nestlings were approximately two weeks old. Capture was achieved using a decoy near the nest and a mistnet. After capture, each bird was fitted with a transmitter mounted in a backpack harness made of Teflon. Devices weighed <3% of buzzard body mass (23-25 g or 2.7-2.9 % to an average body mass of tagged birds of 851 gram), which is considered to not impact flight behaviour and survival of raptors (Kenward 2000). Tagging procedures followed an experimental design and were approved by the animal welfare committee (2024: 2022.D-0028.004; 2025: 2022.D-0028.008).

Transmitters recorded GPS positions at two sampling regimes: every 5 minutes (hereafter "low-resolution data") or in high-frequency bursts at 3-second intervals (hereafter "high-resolution data"). High-resolution bursts were triggered either by a geofence (areas of high interest) or at regular intervals of 5 minutes. As described by Shaub et al. (2023), height data gathered by GPS transmitters is more accurate when collected in high resolution. This is because during these periods of high-resolution data the GPS system remains active and retains its connection with satellites and possibly finds new satellites ensuring increased accuracy.

Flight heights

The GPS devices collect height above sea level which is accurate for high-resolution data. However, as we are interested in height adjustments above solar parks inland and in the proximity of turbines, height above ground level was calculated. This was done by subtracting local terrain altitude from the height above sea level as collected by the GPS transmitters. Altitude data were collected from SRTM satellite imagery (terrain elevation was extracted from the SRTM 1 arc-second (~30 m) digital elevation model provided by NASA and distributed by the USGS. The data were downloaded from the USGS EarthExplorer portal (https://earthexplorer.usgs.gov/).

Selection of thermal soaring flights

We defined a thermal soaring flight as the characteristic circular soaring strategy in which the buzzard gains altitude while intermittingly flapping its wings. To identify GPS fixes that corresponded to thermal soaring flight, we first classified each fix as either stationary or in-flight using two-dimensional instantaneous speed, following Schaub et al. (2019). We applied a general two-dimensional instantaneous speed threshold, that was different for the two sampling regimes, above which a fix is considered to be 'in flight'. This threshold value was **4.1 m s^{-1}** for low-resolution data and **2.4 m s^{-1}** for high-resolution data.

From the 'in flight'-fixes in the high-resolution data, we grouped consecutive points into flight bursts; where a burst comprised of consecutive fixes separated by ≤ 3 s. Whenever the interval between two fixes exceeded 30 s, a new burst ID was assigned. Next, we computed turning angles at each intermediate point B by calculating the bearing A→B and the bearing B→C and taking the (smallest) angular difference between these two bearings (Figure 2). For example, if A→B ≈ 200° and B→C ≈ 160°, the turning angle at B is |200° − 160°| ≈ 40° (bearing differences were wrapped to the range −180° to +180° when computed).

Finally, we classified a flight burst as thermal soaring flight when the burst contained more than six GPS fixes and at least 60% of the turning angles within the burst exceeded 20°. These bursts were retained as thermal flight events for subsequent analyses.

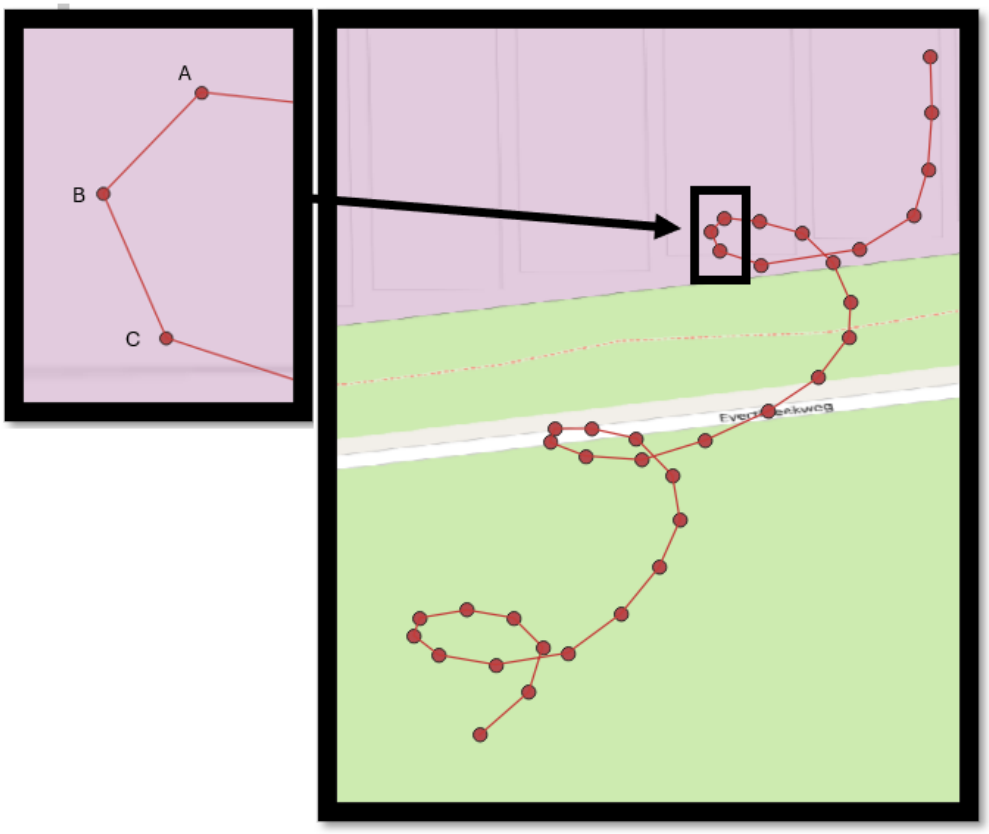


Figure 2. Thermal soaring flight of a buzzard inside (pink) and outside (green) a solar park.

Data analyses

*Flight heights inside and outside solar parks***.** To investigate the effect of solar parks on flight behaviour, we used Generalized Linear Mixed Models (GLMMs) implemented in R using the package glmmTMB (R version 4.4.1). Analyses were conducted on all GPS fixes classified as in flight. Flight height was used as the response variable and was log-transformed prior to analysis to improve model assumptions. Flight height data are typically right-skewed and strictly positive, and log transformation reduces skewness, stabilizes variance, and improves the normality of residuals, thereby making the Gaussian error structure more appropriate.

To ensure that any differences in flight height were attributable to the presence of solar parks rather than environmental conditions known to influence flight behaviour in raptors, local hourly weather conditions were linked to each GPS fix using data from the Royal Netherlands Meteorological Institute (KNMI, 2026). Specifically, wind speed and air temperature were included as explanatory variables. Because the energetic cost of flight in birds of prey is often minimized at intermediate wind speeds, wind speed was included as both a linear and quadratic fixed effect, allowing for a non-linear relationship between wind conditions and flight height. To identify seasonal differences, we added season as a categorical (autumn, winter, spring, summer) and fixed effect. The presence of a solar park was included as a categorical fixed effect (present vs. absent). To account for repeated measurements and individual variation in flight behaviour, individual bird identity (ID) was included as a random effect.

Because GPS tracking data consist of temporally ordered observations, consecutive locations within the same flight are not statistically independent. To account for this, we added flight ID as a nested random effect with Individual ID. This structure accounts for within-flight clustering of observations and reduces the influence of temporal autocorrelation among consecutive GPS fixes. To ensure reliable

estimation of flight-level random effects and to avoid instability from very short flight clusters or single flight points, we retained only flights containing at least six GPS fixes.

We additionally analysed whether the probability of flying at wind turbine rotor-swept height differed between locations inside and outside solar parks. For this analysis we fitted a GLMM with a binomial error distribution, where the response variable indicated whether a flight occurred within the rotor-swept height range (yes/no). The same set of fixed effects (solar park presence, wind speed, wind speed², temperature, and season) and the nested random effects (bird ID and flight ID) were retained to ensure consistency between models.

Thermal flight heights. After analysing overall flight patterns, we focused specifically on thermal soaring flights, which represent an important flight mode used by soaring raptors to gain altitude efficiently. For this subset of the data, we fitted the same Gaussian and binomial GLMMs as described above. However, the response variable 'log-transformed flight height' was calculated only for GPS fixes belonging to thermal flight bursts. This allowed us to assess whether potential effects of solar parks differed during thermal soaring behaviour, when birds are most influenced by vertical updrafts that might be influenced by solar panels. Due to large variation in thermal flights over the seasons (almost no thermal flight during winter) we removed season from the thermal flight analyses.

Environmental influences on height gain (vertical speed). To further examine factors influencing soaring performance, we analysed the vertical climb rate during thermal flights. For each identified thermal flight burst, we calculated the average vertical speed (height gain; m s^{-1}). Using GLMMs, we assessed whether vertical speed differed between flights occurring inside versus outside solar parks, while accounting for repeated observations from the same individuals by including individual bird identity (ID) as a random effect. Fixed effects again consisted of air temperature and quadratic wind speed.

Model validation

To evaluate the adequacy of the fitted mixed-effects models, we performed model validation using the DHARMa package (Hartig 2022). Because the used datasets contained a large number of observations, we followed DHARMa's recommendations for large-sample settings. Specifically, we generated 100 simulated residual datasets (n = 100).

3 Results

Modelling of thermals

Unstable atmospheric boundary layer
Under unstable atmospheric conditions, which are representative of midday summer, heating from the solar panels generated **coherent buoyancy-driven updraft plumes** downstream of the solar field (Figure 3). The structure, coherence, and vertical development of these plumes depended strongly on the presence of a wind turbine wake.

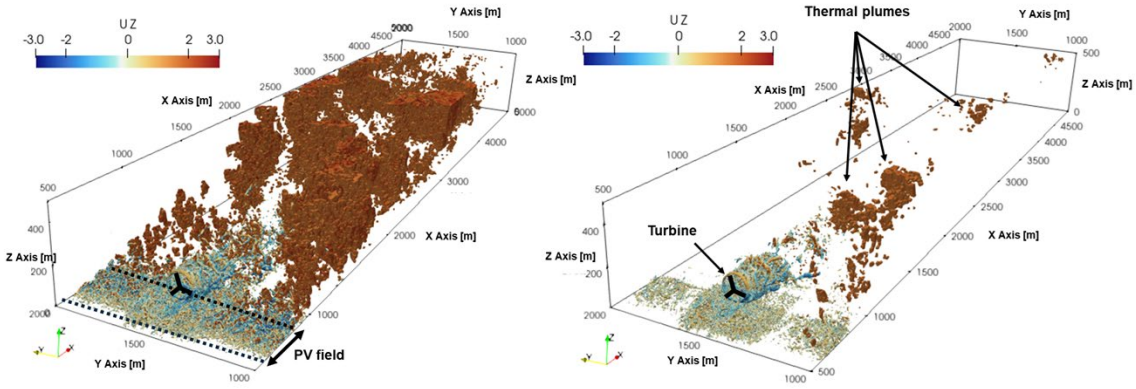


Figure 3. Thermal plumes (iso-volume 1.5m/s<Uz>2.5m/s) for a situation with (left) and without (right) solar panel heating. The plume increases its vertical velocity from low or absent (grey and blue colours) to high velocities (brown) behind the turbine and solar panel array.

When a turbine wake was present, the buoyant plume was more strongly advected downstream, remained closer to the surface over an extended distance, and exhibited a pronounced streamwise tilt with reduced vertical coherence. In contrast, in the absence of a turbine wake, the thermal plume rose more directly and formed vertically coherent updraft structures closer to the PV trailing edge. Peak vertical velocities were systematically higher in the no-wake configuration than in the wake case, indicating that, without wake-induced velocity deficits and enhanced turbulence, a larger fraction of the buoyant forcing was converted into vertical acceleration rather than being consumed by wake erosion and mixing.

Effect of width of solar park
Increasing the spatial extent of heating by solar panels strengthened the buoyancy-driven updrafts under unstable atmospheric conditions. Simulations with a solar field width corresponding to **five times the turbine rotor diameter (5D)** produced stronger vertical velocities than simulations with a **1D-wide** solar field. While the magnitude of the updrafts increased with increasing width of the solar field, the overall organisation and qualitative structure of the plume remained similar (Figure 4), indicating that solar field width primarily controlled the intensity of uplift rather than the fundamental plume morphology.

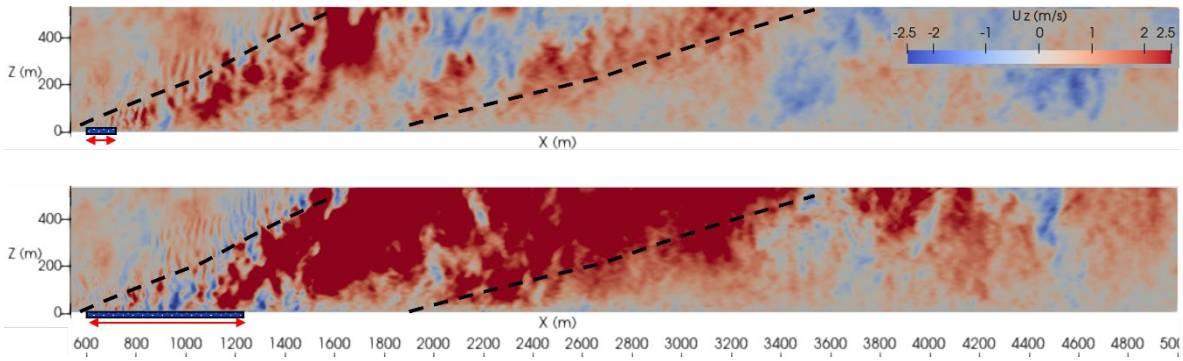


Figure 4. Case with unstable atmospheric conditions (ABL, atmospheric boundary layer), and no turbine wake. Comparison of a narrow solar park of 1D width (top) to a wider solar park (5D, bottom), showing that a wider solar park strengthens the updraft plume. Position of solar park indicated by blue and red lines in the lower left corner of the panels.

Neutral atmospheric boundary layer

Under neutral atmospheric boundary layer (ABL) conditions, persistent buoyancy-driven updrafts did not develop downstream of the solar panels. Vertical velocities remained close to zero, indicating the absence of sustained organised vertical motion.

Despite the lack of coherent updrafts under these neutral atmospheric conditions, heating from the solar panels had a measurable influence on turbine wake behavior. At an inflow wind speed of **4 m s^{-1}**, the turbine wake recovered more rapidly when heating from the panels was included (Figure 5). Specifically, the **rotor-averaged, time-averaged streamwise velocity reached 100 % of the hub-height inflow speed by approximately six rotor diameters (6D)** downstream in the heated case, compared with a **slower recovery of about 90 %** at the same downstream location in the unheated case. In addition, intermittent increases in wake velocity of up to approximately 5 m s^{-1} occurred downstream due to buoyancy-enhanced turbulent mixing when the air was heated by the solar panels. These results indicate that, under neutral stratification, heating from the panels enhanced wake mixing and accelerated wake recovery without generating persistent thermal updrafts.

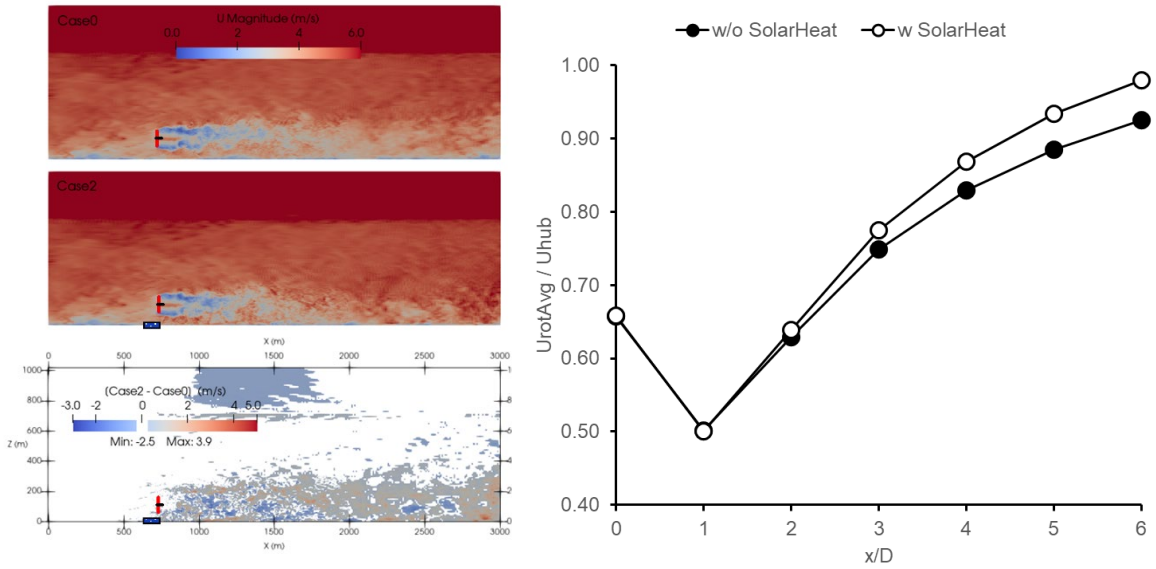


Figure 5. Wake recovery under neutral atmospheric conditions at an inflow wind speed of 4 m s⁻¹. Left: Streamwise velocity magnitude on a vertical streamwise slice through the wake, shown for the case without solar-panel heating (top), with solar-panel heating (middle), and their difference (heated minus unheated; bottom). Right: Rotor-averaged streamwise velocity normalized by the hub-height inflow velocity as a function of downstream distance (x/D). Solar-panel heating enhances turbulent mixing and results in faster wake recovery, even though no persistent thermal updrafts form under neutral stratification.

Buzzard thermal soaring behaviour

High-resolution flights heights

The 21 tagged buzzards accumulated more than 10 million GPS positions. After sub-setting for high-resolution fixes, 309,318 GPS positions of birds in flight remained. When filtering for flights with more than six GPS positions, 274,764 positions remained that were taken during 7843 flights by 20 of the tagged buzzards.

Our GLMM revealed a significant negative effect of solar park presence on flight height ($\beta = -0.032$, SE = 0.004, $z = -7.65$, $p < 0.05$), indicating that buzzards flew lower above solar parks. Although statistically strong, the effect size is modest, with a 3.2% reduction in geometric mean flight height (see Figure 6).

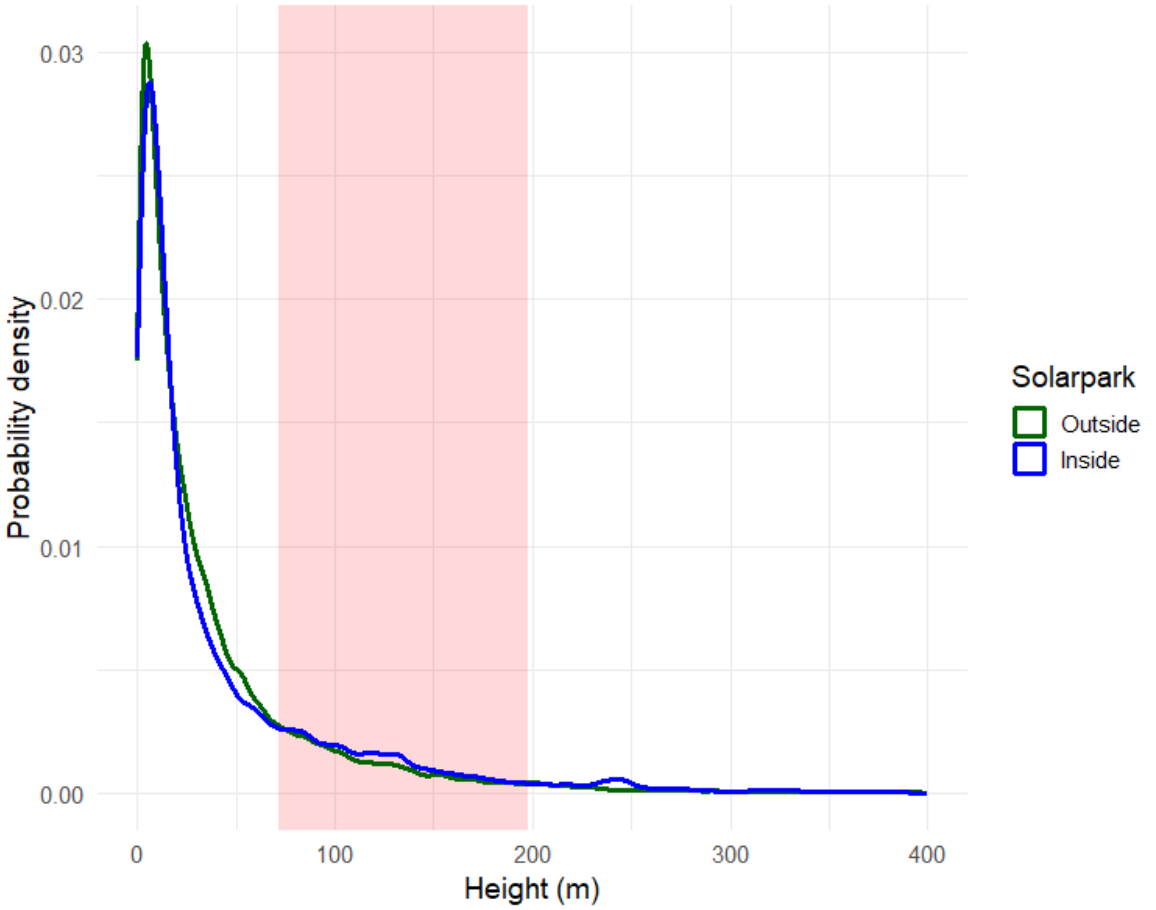


*Figure 6. Kernel density estimates of flight height distribution during high-resolution flights (**all flights** recorded), within (blue line) and outside solar parks (green line). The colored area indicates the rotor height of the wind turbines. Flight heights were slightly lower within than outside solar parks, and most observations were of birds flying below rotor height.*

Temperature had a significant positive effect on flight height, this indicates that buzzards increase their flight height when temperature increases (β = 0.11, SE = 0.02, z =7.14, p <0.05). Season also had a strong effect on flight height. Compared to autumn, spring (β = 042, SE = 0.05, z =8.84, p <0.05), summer (β = 0.24, SE = 0.05, z = 5.65, p <0.05), and winter (β = 061, SE = 0.04, z = 2.81, p <0.05) all showed significantly higher flight heights.

In general, buzzards flew much more outside of the rotor swept zone (17% of flights at rotor height). However, buzzards were more likely to fly at rotor height above solar parks (β = 0.13, SE = 0.03, z = 4.69, p <0.05). The odds were about 13% higher above solar parks as compared to outside solar parks. Wind speed had a negative effect, meaning that the odds of flying at rotor height were higher when wind speed was lower (β = -1.24, SE = 0.34, z = -3.69, p <0.05). The positive quadratic terms indicate a U-shaped effect which means that at higher wind speeds the odds of flying on rotor height increase again (β = 0.81, SE = 0.36, z = 2.25, p <0.05). In addition, temperature had a significant positive effect indicating that the probability of flying at rotor height was larger at higher temperatures (β = 0.47, SE = 0.13, z = 3.67, p <0.05). The only season that showed significantly higher probabilities of flying at rotor height as compared to autumn was spring (β = 1.05, SE = 0.52, z = 2.03, p <0.05).

Thermal soaring flight heights

Twenty of the GPS-tagged buzzards gathered almost 51 thousand GPS positions during thermal soaring flights, while for one buzzard no thermal soaring flights were derived. These positions were taken during 871 thermal soaring flights. Solar parks showed a significant negative effect on flight height during thermal soaring (β = -0.05, SE = 0.01, z = -4.41, p <0.05), indicating a small but consistent reduction in thermal soaring flight heights above solar parks (figure 7). During thermal flights temperature had a positive effect on height, which means buzzards flew higher when temperature increased (β = 0.13, SE = 0.04, z = 3.34, p <0.05). We did not find any linear effect of wind speed, however a significant quadratic wind effect indicated that at high wind speeds the buzzards decreased their flight height during thermal flights (β = -0.28, SE = 0.13, z = -2.25, p <0.05).

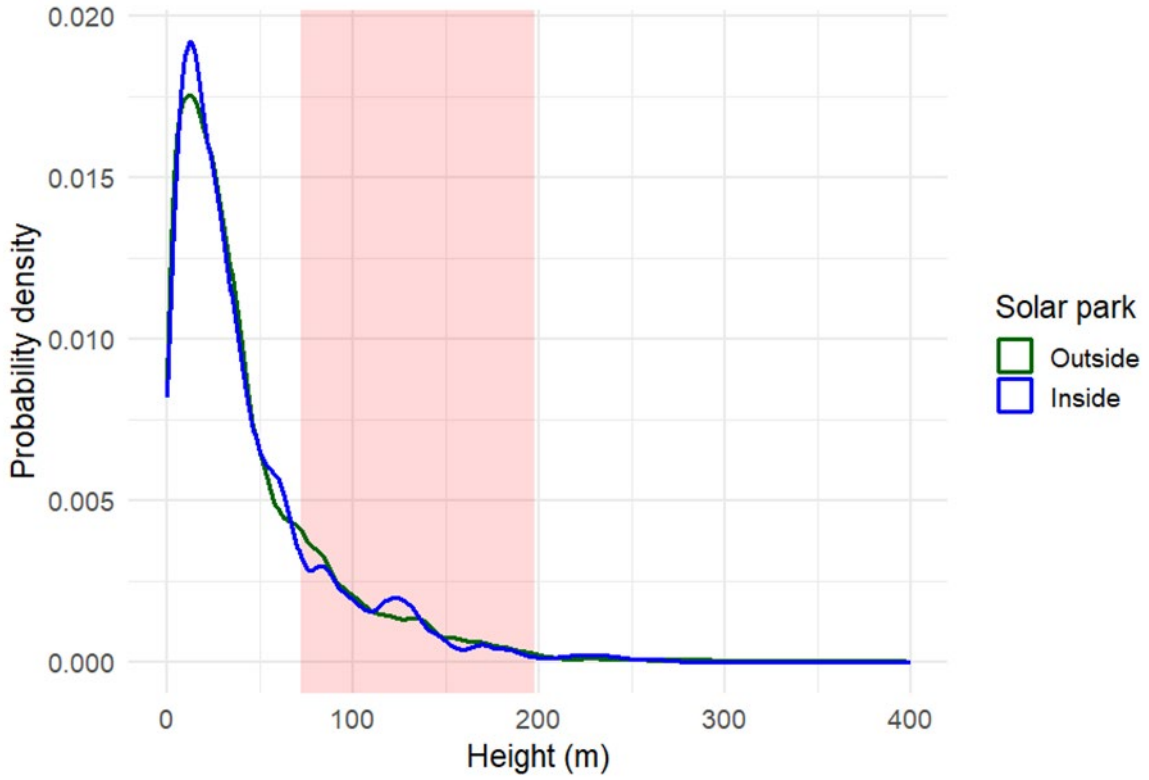


*Figure 7. Kernel density estimates of flight height distribution during high-resolution **thermal flights only**, within (blue line) and outside solar parks (green line). The colored area indicates the rotor height of the wind turbines. Flight heights were slightly lower within than outside solar parks, and most observations were of birds flying below rotor height.*

The binomial GLMM only showed a negative effect of solar parks, indicating that the probability of a buzzard flying at rotor height decreased above solar parks during thermal flights (β = -0.48, SE = 0.06, z = -7.59, p <0.05).

Thermal flight vertical height gain

Mean vertical height gain during the thermal flights was not influenced by the proportion of time thatbuzzards were flying above solar parks. In addition, vertical height gain was not influenced by temperature or wind.

4 Discussion and conclusions

Modelling of thermals

The large-eddy simulations demonstrated that heating from photovoltaic (PV) panels can modify the local uplift environment under unstable atmospheric conditions and that this modification is strongly influenced by the presence of a wind-turbine wake. These findings provide a physical framework for interpreting whether co-located PV–wind systems can plausibly influence thermal soaring behaviour, without assuming a direct behavioural response.

Under unstable atmospheric boundary layer (ABL) conditions representative of midday summer, PV heating generated coherent buoyancy-driven updraft plumes downstream of the PV field. The magnitudes of these updrafts fell within a range that is comparable to reported mean thermal climb rates for large soaring birds, which are typically of order **0.6–1.5 m s^{-1}** over land (Harel et al., 2016; Škrábal et al., 2023; Williams et al., 2020). This indicates that, from a physical perspective, PV-induced uplift can reach strengths that are potentially usable for thermal soaring.

At the same time, the simulations showed that the **structure and coherence** of these updrafts depended strongly on turbine-wake dynamics. When a turbine wake was present, the buoyant plume was more strongly advected downstream, remained closer to the surface over an extended distance, and exhibited reduced vertical coherence. In contrast, in the absence of a turbine wake, the thermal plume rose more directly and formed vertically coherent updraft structures closer to the PV field. These differences indicate that wake-induced turbulence, velocity deficits, and shear initially suppress vertical organisation of buoyant motion, redistributing a portion of the buoyant forcing into wake erosion and horizontal transport before coherent uplift becomes established farther downstream. The sensitivity of updraft strength to PV-field width further suggests that the **spatial extent of PV heating** influences the intensity of available uplift. Wider PV fields generated stronger buoyancy-driven updrafts under unstable ABL conditions, while the overall plume structure remained qualitatively similar. This implies that PV-field size primarily controls the magnitude of uplift rather than the fundamental organisation of the plume, which is instead governed by atmospheric stability and wake dynamics.

Taken together, these results indicate that PV-induced heating can create physically plausible uplift conditions for soaring birds, but that the **availability and spatial organisation of this uplift are not uniform** and are strongly modulated by turbine wakes. Importantly, the simulations do not suggest that the strongest uplift necessarily occurs directly above PV installations or immediately adjacent to turbines. Instead, uplift develops downstream and is shaped by wake–buoyancy interactions, implying that any influence on soaring behaviour is likely indirect and context-dependent.

These findings help to reconcile concerns that PV-induced thermals near wind turbines might systematically increase collision risk. While PV heating can generate coherent updrafts under unstable conditions, turbine wakes tend to disrupt and redistribute these updrafts rather than concentrate strong, vertically coherent uplift near the rotor-swept zone. As such, the LES results support the interpretation that co-located PV–wind systems do not automatically create conditions that would draw soaring birds into increased collision risk, but instead modify the uplift environment in a more complex and spatially distributed manner.

Buzzard thermal soaring behaviour

The previous section showed that solar panel heating generated coherent buoyancy-driven updraft plumes downstream of the solar panels, which can reach strengths that are potentially usable for thermal soaring. Importantly, uplift develops downstream from the solar panels and is shaped by the presence of wind turbines. Given these results, we expect little or no effect from the presence of a solar park on soaring buzzards above them. Our models of flight height revealed that buzzards generally fly and soar significantly lower on average above solar parks than outside solar parks, although this effect was small. Although buzzards were 13% more likely to fly at rotor height above solar parks than away from them, the odds of thermal soaring at rotor height were lower above solar panels than away from them. Also, the height gain of buzzards in thermal soaring flight did not differ above and away from solar panels. Height gain in the thermal flight of raptors is primarily influenced by a combination of atmospheric conditions, topographical features, and the bird's own morphological and behavioral adaptations (Péron et al. 2017; Murgatroyd et al. 2018; Naves-Alegre et al. 2025). We hypothesized that solar panels may generate heat and consequently, thermal updraft for buzzards, making them attractive for soaring flight. Stronger, faster-rising thermals, caused by solar heating of the metal structures below, would allow for faster climbing rates. Conversely, we found a lack of thermal updraft directly above solar panels, and in line with this result, an absence of more rapid height gain of buzzards in thermal soaring flight above solar panels, suggesting they are not particularly attractive for soaring buzzards. Based on these results, we conclude that solar parks situated close to wind turbines can to some degree increase collision risk for flying buzzards, but not in thermal soaring flight, while solar panels are also not particularly attractive for soaring buzzards in terms of the vertical height gain.

In our analysis, we considered that flight height is a critical indicator of collision risk with wind turbines, as collision risk is to a large extent determined by the proportion of time raptors spend within the rotor swept area (e.g., Škrábal et al. 2025). One important question is whether our results are more widely applicable to other large soaring birds, or specifically raptors, and under different conditions. Our data shows that although most flights were below rotor height, a significant portion of buzzard flights (17%) occurs within the rotor range of turbine blades, which partly explains their relatively high collision probability (Bose et al. 2020). This differs from other raptor species with different flight altitudes (Schaub et al. 2024). Weather, including wind and temperature, also influences flight height differently for different raptor species and, consequently, their collision risk differs (Péron et al. 2017; Aschwanden et al. 2025; Naves-Alegre et al. 2025). Indeed, we found that temperature and wind are important predictors of flights heights for buzzards; buzzards flew and soared higher with increasing temperature, and decreased soaring flight height with strong winds. This also influenced the odds of flying at rotor height, which was highest at both the low and high range of wind speed, and increased with temperature. Apart from weather, season influences flight height, with buzzards flying more often at rotor height in spring compared to autumn. Importantly, different turbine dimensions influence collision risks. For example, some raptors face higher risk when turbine ground clearance is low while larger and taller turbines generally have a larger rotor area, increasing collision risks for certain species (Schaub et al. 2024; Škrábal et al. 2025). The combination of the absence of increased thermal updraft above solar panels, and the lower soaring flight and lack of vertical height gain of buzzards above solar panels, suggests that a higher ground clearance of turbine rotors near solar parks may reduce collision risk for buzzards.

Our results indicate that the combination of solar and wind energy may be potentially beneficial from the perspective of raptor conservation. Firstly, we found a lower collision risk of soaring buzzards above solar panels, and lower attractiveness of solar panels for height gain; although the increased odds of all in-flight positions at rotor height above solar panels warrants further examination and an increase in ground clearance of turbine rotors. Secondly, the sharing infrastructure increases renewable energy output per unit area, thus reducing the land-use footprint of such infrastructure. Thirdly, solar panels near wind turbines may reduce the attractiveness of the direct surroundings of a windfarm for foraging raptors, thus reducing raptor numbers and associated collision risks (Allison et

al. 2017; Pescador et al. 2019). However, we stress that such benefits may be obtained only if solar farms near wind farms are managed to minimize raptor prey availability near wind turbines. Presently, solar farms are increasingly managed to promote biodiversity on farmland (Montag et al. 2016, Boscarino-Gaetano & Nordberg 2024), and as such they can act as refuges for wildlife, including birds, insects and small mammals, thus attracting raptors. The combination of low human presence, lack of pesticides, sheltered habitats beneath panels and abundant vegetation creates an ideal environment for rodents compared to conventional farmland. In addition, solar panels and fencing serve as ideal vantage points for hunting buzzards and other raptors, further stimulating their use. To avoid attracting raptors to wind turbines, we propose that the vegetation of solar parks near turbines is managed to reduce as much as possible the food resources for raptors, which includes the removal of collision casualties on the solar farm (Allison et al. 2017).

5 Literature

Allison, T.D., Cochrane, J.F., Lonsdorf, E. and Sanders-Reed, C., 2017. A review of options for mitigating take of Golden Eagles at wind energy facilities. Journal of Raptor Research, 51(3), pp.319-333.

Aschwanden, J., Stark, H. and Liechti, F., 2025. Flight behaviour of Red Kites within their breeding area in relation to local weather variables: Conclusions with regard to wind turbine collision mitigation. Journal of Applied Ecology, 62(7), pp.1624-1635.

Blary, C.L.M., F. Bonadonna, E. Dussauze, S. Potier, A. Besnard & O. Duriez, 2023. Detection of wind turbines rotary motion by birds: A matter of speed and contrast. Conservation Science and Practice. https://doi.org/10.1111/csp2.13022

Boscarino-Gaetano, R., Vernes, K., & Nordberg, E. J. (2024). Creating wildlife habitat using artificial structures: a review of their efficacy and potential use in solar farms. Biological Reviews, 99(5), 1848-1867.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K., 2020. Assessing the spatial distribution of avian collision risks at wind turbine structures in Brandenburg, Germany. Conservation Science and Practice, 2(6), p.e199.

Bose, A., Dürr, T., Klenke, R.A. and Henle, K., 2020. Assessing the spatial distribution of avian collision risks at wind turbine structures in Brandenburg, Germany. Conservation Science and Practice, 2(6), p.e199.

De Lucas, M., Ferrer, M., Bechard, M.J. and Muñoz, A.R., 2012. Griffon vulture mortality at wind farms in southern Spain: Distribution of fatalities and active mitigation measures. Biological Conservation, 147(1), pp.184-189.

Drewitt, A.L. and Langston, R.H., 2006. Assessing the impacts of wind farms on birds. Ibis, 148, pp.29-42.

Estellés-Domingo, I. and López-López, P., 2025. Effects of wind farms on raptors: A systematic review of the current knowledge and the potential solutions to mitigate negative impacts. Animal Conservation, 28(3), pp.334-352.

Estellés-Domingo, I. and López-López, P., 2025. Effects of wind farms on raptors: A systematic review of the current knowledge and the potential solutions to mitigate negative impacts. Animal Conservation, 28(3), pp.334-352.

Fthenakis, V. and Yu, Y., 2013. Analysis of the potential for a heat island effect in large solar farms. Proceedings of the IEEE 39th Photovoltaic Specialists Conference (PVSC), pp.3362–3367.

Glick, A., Smith, S., Ali, N., Bossuyt, J., Recktenwald, G., Calaf, M. and Cal, R.B., 2020. Influence of flow direction and turbulence intensity on heat transfer of utility-scale photovoltaic solar farms. Solar Energy, 208, pp.1351–1364.

Harel, R., Duriez, O., Spiegel, O., Fluhr, J., Horvitz, N., Getz, W.M., Bouten, W., Sarrazin, F., Hatzofe, O. and Nathan, R., 2016. Decision-making by a soaring bird: time, energy and risk considerations at different spatio-temporal scales. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1704), 20150397

Hartig, F., 2022. DHARMa: Residual diagnostics for hierarchical (multi-level/mixed) regression models (R package version 0.4.5). Available at https://CRAN.R-project.org/package=DHARMa.

Kenward, R.E., 2000. A manual for wildlife radio tagging. Academic press.

Linder, A.C., Lyhne, H., Laubek, B., Bruhn, D. and Pertoldi, C., 2022. Quantifying raptors' flight behavior to assess collision risk and avoidance behavior to wind turbines. Symmetry, 14(11), p.2245.

May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø. and Stokke, B.G., 2020. Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. Ecology and evolution, 10(16), pp.8927-8935.

McClure, C.J., Rolek, B.W., Dunn, L., McCabe, J.D., Martinson, L. and Katzner, T., 2021. Eagle fatalities are reduced by automated curtailment of wind turbines. Journal of Applied Ecology, 58(3), pp.446-452.

McClure, C.J., Schulwitz, S.E., Anderson, D.L., Robinson, B.W., Mojica, E.K., Therrien, J.F., Oleyar, M.D. and Johnson, J., 2019. Commentary: defining raptors and birds of prey. Journal of Raptor Research, 53(4), pp.419-430.

Montag, H., Parker, G., & Clarkson, T. (2016). The effects of solar farms on local biodiversity: a comparative study. Clarkson and Woods and Wychwood Biodiversity.

Murgatroyd, M., Photopoulou, T., Underhill, L.G., Bouten, W. and Amar, A., 2018. Where eagles soar: Fine-resolution tracking reveals the spatiotemporal use of differential soaring modes in a large raptor. Ecology and Evolution, 8(13), pp.6788-6799.

Naves-Alegre, L., García-Mayoral, H., Morant, J., Pérez-García, J.M., Dias, A., Cano-Montes, E., Sánchez, Á. and García-Matarranz, V., 2025. Differential flight responses of sympatric raptor species to weather conditions and extreme temperature events. Ecology and Evolution, 15(2), p.e70658.

Osborn, R.G., Higgins, K.F., Usgaard, R.E., Dieter, C.D. and Neiger, R.D., 2000. Bird mortality associated with wind turbines at the Buffalo Ridge Wind Resource Area, Minnesota. The American Midland Naturalist, 143(1), pp.41-52.

Péron, G., Fleming, C.H., Duriez, O., Fluhr, J., Itty, C., Lambertucci, S., Safi, K., Shepard, E.L. and Calabrese, J.M., 2017. The energy landscape predicts flight height and wind turbine collision hazard in three species of large soaring raptor. Journal of Applied Ecology, 54(6), pp.1895-1906.

Pescador M., Gómez Ramírez J.I. & Peris S.J. (2019). Effectiveness of a mitigation measure for the lesser kestrel (Falco naumanni) in wind farms in Spain. Journal of Environmental Management 231: 919-925. Doi: 10.1016/j.jenvman.2018.10.094

Schaub, T., Klaassen, R.H., De Zutter, C., Albert, P., Bedotti, O., Bourrioux, J.L., Buij, R., Chadœuf, J., Grande, C., Illner, H. and Isambert, J., 2024. Effects of wind turbine dimensions on the collision risk of raptors: A simulation approach based on flight height distributions. Science of the Total Environment, 954, p.176551.

Schaub, T., Klaassen, R.H., De Zutter, C., Albert, P., Bedotti, O., Bourrioux, J.L., Buij, R., Chadœuf, J., Grande, C., Illner, H. and Isambert, J., 2024. Effects of wind turbine dimensions on the collision risk of raptors: A simulation approach based on flight height distributions. Science of the Total Environment, 954, p.176551.

Škrábal, J., Krejčí, Š., Raab, R., Sebastián-González, E. and Literák, I., 2023. Soaring over open waters: horizontal winds provide lift to soaring migrants in weak thermal conditions. Movement Ecology, 11, 76.

Schaub, T., Millon, A., De Zutter, C., Buij, R., Chadœuf, J., Lee, S., Mionnet, A., & Klaassen, R. H. G., 2023. How to improve the accuracy of height data from bird tracking devices? An assessment of high-frequency GPS tracking and barometric altimetry in field conditions. Animal Biotelemetry, 11, 31. https://doi.org/10.1186/s40317-023-00342-1.

Škrábal, J., Raab, M., Raab, R., Grüebler, M.U., Kormann, U.G., Scherler, P., Sumasgutner, P., Åkesson, S., Bermejo, A., Chakarov, N. and Fiedler, W., 2025. Red kite (Milvus milvus) collision risk is higher at wind turbines with larger rotors and lower clearance, evidenced by GPS tracking. Biological Conservation, 312, p.111482.

Smith, S.E., Stanislawski, B.J., Eng, B.K., Ali, N., Silverman, T.J., Calaf, M. and Cal, R.B., 2022. Viewing convection as a solar farm phenomenon broadens modern power predictions for solar photovoltaics. Journal of Renewable and Sustainable Energy, 14(6), 063701.

Thaxter, C.B., Buchanan, G.M., Carr, J., Butchart, S.H., Newbold, T., Green, R.E., Tobias, J.A., Foden, W.B., O'Brien, S. and Pearce-Higgins, J.W., 2017. Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. Proceedings of the Royal Society B: Biological Sciences, 284(1862).

Williams, H.J., Shepard, E.L.C., Holton, M.D., Alarcón, P.A.E., Wilson, R.P. and Lambertucci, S.A., 2020. Physical limits of flight performance in the heaviest soaring bird. Proceedings of the National Academy of Sciences of the United States of America, 117(30), pp.17884–17890.

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