CONNECTIVITY CONSERVATION FOR HABITATS OF FLAGSHIP MIGRATORY BIRDS IN NORTH-EAST ASIA

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Executive Summary

A Region at a Crossroads: Balancing Energy Transition and Biodiversity Conservation

The North-East Asia (NEA) region stands at a critical juncture, hosting vital segments of the East Asian-Australasian Flyway (EAAF), one of the world's most significant and imperiled migratory corridors. This flyway, which extends from the Russian Far East and Alaska to Australia and New Zealand, supports over 50 million migratory waterbirds and spans 22 countries. The ecological integrity of the EAAF, which also intersects with other major pathways like the Central Asian Flyway (CAF), is dependent on a fragile and interconnected network of breeding grounds in the Arctic, essential stopover sites for rest and refueling, and vital wintering habitats further south.

For decades, the primary threats to this network have been well-documented: rapid habitat loss driven by extensive coastal reclamation, particularly in the Yellow Sea, coupled with pressures from urbanization and agricultural intensification. These forces have degraded and fragmented the wetlands and tidal flats crucial for the survival of countless species. Now, a new and accelerating threat has emerged, stemming from the very actions designed to secure a sustainable future for the region.

The global imperative to mitigate climate change has catalyzed a massive energy transition across NEA. Nations are rapidly expanding their renewable energy capacity, with a particular focus on offshore wind and large-scale solar projects. This has created a profound "green-on-green" conflict, where the infrastructure intended to combat climate change poses a direct and growing threat to the biodiversity that climate change also endangers. The scale and siting of these energy developments place them in direct competition with the critical habitats of migratory birds. This paradox reveals that climate and biodiversity policies can no longer operate in separate silos; a truly sustainable energy transition must be fundamentally nature-positive.

To navigate this complex challenge, a new strategic approach is required. The concept of "connectivity conservation" provides this essential framework, moving beyond the traditional focus on protecting isolated, designated sites. It emphasizes the maintenance of functional ecological linkages between all the geographically distinct areas a species relies on throughout its annual life cycle. This report utilizes the connectivity conservation lens to assess the impacts of energy development and to formulate effective, transboundary solutions. This approach is critical because it directly confronts the limitations of current environmental governance. Migratory birds do not experience the impact of a single wind farm in isolation; they navigate a cumulative "landscape of risk" composed of multiple energy projects, power grids, and other developments scattered across several countries. The prevailing paradigm of project-by-project Environmental Impact Assessments (EIAs), confined within national jurisdictions, is therefore fundamentally mismatched to the transboundary scale of the problem. By focusing on connectivity, this report argues for a shift toward a flyway-scale assessment and planning model capable of managing the systemic risks to this shared natural heritage.

The Flagship Species: Emblems of a Flyway in Peril

To illustrate the multifaceted nature of the conservation challenge across the EAAF, this report focuses on three flagship species: the Black-faced Spoonbill, the White-naped Crane, and the Hooded Crane. Their distinct population structures, habitat dependencies, and threat profiles serve as living case studies of the pressures facing the entire flyway. The unique vulnerabilities of these species are not merely isolated examples; they represent archetypal conservation challenges of the modern era. Understanding their stories provides a valuable template for assessing risks and planning interventions for other migratory species in the region.

The Black-faced Spoonbill: A Fragile Recovery on a Collision Course with "Green" Energy

The Black-faced Spoonbill stands as one of the EAAF's most celebrated conservation success stories. Through decades of coordinated international cooperation and habitat protection, its global population has rebounded from fewer than 300 individuals in the late 1980s to over 7,000 today. However, this remarkable recovery is both fragile and facing a new, insidious threat. Recent census data indicate the population's growth is now decelerating, suggesting it may be encountering new limiting factors. The primary emerging threat is the massive build-out of offshore wind farms (OWFs) directly within its core migratory corridor—the Yellow Sea—by China and the Republic of Korea (ROK). This places the species, a recovering icon, on a direct collision course with the infrastructure of the green energy transition.

The White-naped Crane: A Tale of Two Populations

The White-naped Crane presents a "tale of two populations," a narrative of starkly divergent fates that highlights how regional pressures and conservation responses can lead to vastly different outcomes within a single species.

The eastern population is stable or increasing. These birds benefit from well-managed and protected wintering grounds, primarily the Cheorwon Basin within the Korean Demilitarized Zone (DMZ) and the Izumi Feeding Station in Japan. The phenomenal increase of over 2,300% in cranes wintering in the ROK since 2000 demonstrates that targeted habitat protection and management can yield profoundly positive results.

In sharp contrast, the western population is in a state of severe and rapid decline. This population, which breeds in Mongolia and winters at Poyang Lake in China's Yangtze River basin, has plummeted from around 3,000 individuals to as few as 1,000-1,500. This decline is largely attributed to the degradation of its wintering habitat from the hydrological changes caused by large-scale water management projects, including the Three Gorges Dam, and agricultural intensification. This population is being squeezed by compounding pressures at both ends of its flyway, representing a species with fragmented populations facing divergent threats.

The Hooded Crane: A Population on a Knife's Edge

The Hooded Crane’s seemingly stable global population, estimated between 11,600 and 19,000 individuals, masks an extreme and precarious vulnerability. The core of its conservation challenge lies in the fact that over 80% of its entire population—and in some years, more than 90%—winters at a single location: the artificial feeding station and surrounding agricultural lands in Izumi, southern Japan. While this concentration is a testament to successful local management that has supported the population, it places the species on a knife's edge. This "all eggs in one basket" scenario creates an unparalleled risk of catastrophic collapse from a single localized event, such as a highly pathogenic disease outbreak, a severe weather event, or significant habitat degradation from nearby development. The Hooded Crane thus represents a species with a hidden, structural vulnerability, where apparent stability belies profound risk.

The following table provides a concise summary of the core issue for each species, orienting the reader to the nuanced nature of the threat landscape.

Table E1. Vulnerability Profiles of Flagship Species

Flagship species	Global IUCN Status	Primary Energy Infrastructure Threat	Core Vulnerability Profile
Black-faced Spoonbill	Endangered	Offshore Wind Farms	Sensitivity to Chronic, Cumulative Mortality
White-naped Crane	Vulnerable	Power Lines & Onshore Wind	Compounding pressures on declining population
Hooded Crane	Vulnerable	All Infrastructure near Izumi	Sensitivity to catastrophic, Single-site Events

Assessing the Impact: From Individual Risk to Population-Level Consequences

The scientific evidence of harm from energy infrastructure extends far beyond the simplistic view of direct mortality. A more sophisticated understanding of indirect, cumulative, and behavioral impacts reveals that these less visible threats may be more significant demographically. This analysis synthesizes the evidence of these impacts and uses population modeling to project their long-term consequences.

The Insidious Threat of Barrier Effects and Functional Habitat Loss

Recent research has illuminated a critical dimension of impact that goes beyond direct collision. A groundbreaking study by Lai et al. (2025) on the Black-faced Spoonbill used high-resolution GPS tracking to document a significant "barrier effect" from the dense cluster of OWFs in the Yellow Sea. The case of one young bird, M03, is particularly illustrative. On its first migration, after encountering a series of massive wind farms, the bird reversed its course and flew 376.8 km back towards the Korean Peninsula. Upon landing, it remained stationary for over 29 hours, a clear sign of extreme exhaustion. The bird never re-attempted the migration and was found dead a month later, providing powerful evidence that the energetic cost and stress of navigating the OWF barrier can lead to migration failure and indirect mortality. This impact represents a cumulative, energetic tax on migration that disproportionately affects young, inexperienced birds, with potentially severe consequences for the recruitment of new individuals into the breeding population.
For cranes, a similar indirect threat comes from displacement, which leads to "functional habitat loss." While direct studies on Asian cranes are scarce, extensive research on the similarly sized Whooping Crane in North America shows a significant "zone of influence," with cranes actively

avoiding areas within a 5-kilometer radius of wind turbines. This avoidance behavior renders vast areas of otherwise suitable habitat unusable. This displacement can create a second-order impact described as "economic displacement": as cranes are forced to concentrate in the remaining suitable areas, increased density can lead to greater competition for resources, elevated social stress, and a heightened risk of disease transmission. Focusing EIAs only on predicting direct collisions is therefore dangerously insufficient; the true risk may lie in the cumulative, system-wide degradation of the ecological network.

The Persistent Threat of Linear Infrastructure: Collision and Electrocution

Power line collision and electrocution are well-documented and significant sources of mortality for large-bodied, low-maneuverability birds like cranes, a key concern highlighted by experts from the Russian Federation. The risk is a function of both physiology and behavior. The high wing loading of cranes results in higher flight speeds and reduced agility, making it difficult to avoid obstacles like power lines, especially the thinner, nearly invisible uppermost earth wires. The risk is greatest where power lines intersect with daily flight paths between foraging and roosting sites, which often occurs in low-light conditions at dawn and dusk. The rapid expansion of electricity grids to connect new energy sources across the open landscapes of the Daurian Steppe, Mongolia, and the coastal plains of China and ROK directly exacerbates this persistent threat.

Projecting the Future: Insights from Population Viability Analysis (PVA)

To understand the long-term consequences of these threats, this report utilized Population Viability Analysis (PVA) to project future population trends under different scenarios. The results are stark:

a) Black-faced Spoonbill

The PVA projections reveal the fragility of its recovery. Under the baseline scenario, the population shows slow growth or stabilization. However, the introduction of a persistent, additional annual mortality of just 1-2%—a plausible outcome from the combined collision and barrier effects of the Yellow Sea OWF build-out—is sufficient to reverse its population growth and trigger a steep decline. The high-risk simulation projects a trajectory toward quasi-extinction thresholds within 50 to 60 years, demonstrating that the population is highly sensitive to small, chronic changes in survival.

b) White-naped Crane (Western Population)

The PVA confirms that this population has virtually no demographic resilience. The baseline scenario, using current estimates of its decline, already projects a high probability of extirpation. When the additional pressures of habitat loss from wind farm displacement and increased mortality from power lines are added, the model shows a significant acceleration of this decline, drastically shortening its time to extinction.

c) Hooded Crane

The PVA quantitatively demonstrates the species' "knife-edge" risk. While the population remains relatively stable under scenarios of chronic, diffuse threats, it is extraordinarily vulnerable to a single catastrophic event. A simulated disease outbreak at Izumi causing 25-50% mortality in a single year results in an immediate population crash from which recovery would take decades, if it is possible at all, pushing the species into a state of critical endangerment.

Case Study: Spatial Analysis of Black-tailed Gulls and Offshore Wind Farm Interactions

To ground-truth the assessment of risk from energy infrastructure, this report includes a case study on the Black-tailed Gull, based on an initiative by the Republic of Korea's Ministry of Environment (MoE) and the Korea Environment Institute (KEI). This research aimed to develop comprehensive spatial utilization maps for marine birds to inform the environmental review of the nation's growing offshore wind power sector. The Black-tailed Gull was selected as a focal species due to its ecological prominence, widespread distribution, and status as an indicator for the health of coastal and marine ecosystems.

a) Methodology: High-Resolution Tracking and Spatial Modeling

The study employed a robust, multi-year methodology to capture the species' spatial ecology. First, as **GPS Tracking,** beginning in June 2021, researchers deployed GPS tracking devices on 159 adult Black-tailed Gulls across eight different breeding islands. To minimize disturbance, birds were handled efficiently, and the device weight was kept to a conservative 2-3% of the bird's body mass. The devices recorded location data at 30-minute intervals, with a "booster mode" increasing the frequency to every 10 seconds during active flight to capture fine-scale movement. Second, using **Kernel Density Estimation (KDE)**, the vast amount of location data was analyzed, a standard ecological method for estimating an animal's home range and identifying areas of concentrated use. The analysis produced Utilization Distributions (UDs), which are probability maps of space use. These maps were used to classify habitats into "core areas" (representing the 50% most-used locations) and "general habitat areas".

b) Key Findings and Implications

The analysis yielded several critical findings with direct implications for conservation and energy planning. First, as **Extensive and Varied Habitat Use**, the tracking data revealed that Black-tailed Gulls utilize vast marine areas for breeding, foraging, and wintering, with some populations undertaking international migrations to Japan, China, and Taiwan. A notable concentration of gulls was observed along the maritime boundary between the ROK and China, likely drawn to fishery discards. Second, for the **Identification of Core Habitats**, the KDE analysis quantitatively confirmed that the gulls' activities are primarily concentrated in and around tidal flats, coastal zones, and their breeding islands. These core habitats are essential for survival and reproductive success. Third, for a **Proxy for Broader Biodiversity,** a crucial finding was the significant spatial overlap between the core habitats of the Black-tailed Gull and those of several endangered species, including the Black-faced Spoonbill, Chinese Egret, and Far Eastern Curlew. The core habitat areas (KDE 50%) of these threatened species were found to be entirely encompassed within the gulls' core habitat. This elevates the Black-tailed Gull to a valuable proxy, or "umbrella," species; its tracking data can be used to identify critically important habitats for a wider suite of conservation-priority birds. Fourth, for **Informing Environmental Impact Assessments (EIAs)** , the study demonstrates the inadequacy of simplistic EIA methods that rely on linearized migratory routes. It advocates for a more ecologically robust, area-based probabilistic approach using KDE to analyze actual habitat space use. This provides a more scientifically defensible method for assessing the potential impacts of fixed infrastructure like wind turbines. The results provide a foundational dataset for creating a strategic "siting information map" that can help resolve conflicts and guide OWF placement to balance renewable energy goals with biodiversity conservation.

The Governance Gap: Why Current Policies are Insufficient

The growing conflict between energy development and migratory bird conservation in NEA is exacerbated by a significant governance gap. The existing policy and regulatory landscape, largely reliant on national-level EIAs, is ill-equipped to manage the transboundary scale and cumulative nature of the threats identified in this report.

A Patchwork of National EIAs

While all major NEA countries—China, Japan, ROK, Mongolia, and Russia—have legal frameworks mandating EIAs for development projects, their implementation is uneven and they share common, critical flaws. China has recently strengthened oversight for large renewable projects, and ROK has a two-tiered system including Strategic Environmental Assessment (SEA). Japan's policies are reinforced by bilateral bird treaties, and Mongolia's are often guided by international standards for financed projects. However, across the region, administrative pressures to accelerate energy projects can undermine the rigor of biodiversity assessments, and enforcement in remote areas often remains inconsistent.

The Systemic Failure to Address Cumulative and Transboundary Impacts

The core critique of the current system is its fundamental inability to assess cumulative and transboundary impacts. The problem is not simply a lack of rules, but a fundamental mismatch between the scale of governance and the scale of the ecological process. Birds operate on an ecological scale—the flyway—that ignores political borders. In contrast, governance and regulation operate on a political scale of national laws and provincial permits. A wind farm in China, another in Korea, and a power line in Russia are each assessed in isolation, yet a migratory bird experiences their combined, cumulative impact. This systemic failure to look beyond project-level footprints and national borders is the central governance gap.

Data Deficiencies and Untested Mitigation

The effectiveness of these policies is further undermined by persistent data deficiencies and a lack of follow-up. As this report has shown, robust demographic data for many species are lacking. EIAs often proceed with inadequate baseline data, making accurate impact prediction impossible. Furthermore, there is a widespread failure to conduct rigorous, long-term post-construction monitoring to verify predicted impacts and assess the actual effectiveness of mitigation measures. This leaves decision-makers and the public with little knowledge of whether mitigation strategies work as intended. International frameworks like the Convention on Migratory Species (CMS) and partnerships like the EAAFP provide crucial platforms for cooperation, but their influence is often limited by voluntary commitments and a disconnect from the national-level energy and economic planning agencies that drive development. Simply improving each country's EIA process in isolation will not solve a problem that is inherently transboundary. The solution must involve creating new governance mechanisms that operate at the same scale as the problem—the flyway.

A Strategic Framework for Connectivity Conservation: Key Recommendations

Based on the comprehensive analysis of threats, population vulnerabilities, and policy gaps, this report proposes a strategic framework for action. These evidence-based recommendations are targeted at governments, the energy sector, and regional partnerships, and are designed to integrate connectivity conservation into the heart of energy planning in North-East Asia.

a) Proactive Spatial Planning and Siting: The Primacy of Avoidance

Recommendation 1: Adopt Strategic, Flyway-Scale Sensitivity Mapping. Governments and energy developers must move beyond reactive, project-level EIAs and collaboratively develop regional sensitivity maps to identify and designate "no-go" zones for energy development. This proactive spatial planning is the most effective form of mitigation.

Recommendation 2: Designate and Enforce High-Risk Zones and Buffer Areas. Based on the evidence presented, the core migratory bottleneck across the Yellow Sea should be formally designated as a high-risk zone for OWFs. Furthermore, a mandatory 5-kilometer "no development" buffer zone should be established around all key breeding, stopover, and wintering sites for the White-naped and Hooded Cranes for any new wind energy projects.

b) Mandatory Mitigation and Best Practices: Minimizing Unavoidable Harm

Recommendation 3: Mandate Best-Practice Operational Mitigation. For any OWFs permitted near sensitive areas, such as the Black-faced Spoonbill flyway, approval must be conditioned on the use of dynamic, operational mitigation. This includes seasonal or real-time shutdowns during peak migration periods, informed by radar and direct observational data. Rigorous post-construction monitoring must be required to assess both direct collision and behavioral barrier effects.

Recommendation 4: Enforce Avian-Safe Linear Infrastructure Design. All new power transmission and distribution lines constructed in or near crane habitats must be mandated to use the latest avian-safe designs to prevent electrocution and must be marked with high-visibility devices to reduce collision risk. The effectiveness of these measures must be validated through post-construction monitoring.

c) Targeted Research for Adaptive Management: Closing Critical Knowledge Gaps

Recommendation 5: Launch Coordinated, Flyway-Wide Telemetry Studies. A multi-partner research initiative, supported by governments and industry, should be established to conduct large-scale GPS tracking of all three flagship species. The primary goal is to collect the robust, long-term data on migratory connectivity, habitat use, and age-specific survival needed to fill the critical gaps identified by the PVA and to guide adaptive management.

Recommendation 6: Implement Emergency Research and Contingency Planning. An emergency, multi-national research program should be created to diagnose and reverse the decline of the western White-naped Crane population. Concurrently, a formal contingency and risk-spreading plan must be developed for the Hooded Crane, focused on identifying, securing, and managing a network of alternative wintering sites to reduce its extreme vulnerability.

d) Strengthening Transboundary Cooperation: Building Governance at the Flyway Scale

Recommendation 7: Develop Dynamic, Threat-Responsive Species Action Plans. The model of the revised Black-faced Spoonbill International Single Species Action Plan (ISSAP), which explicitly incorporates emerging threats like renewable energy, should be used to develop new or updated international action plans for the White-naped and Hooded Cranes.

Recommendation 8: Establish a NEASPEC/EAAFP Task Force on Energy and Migratory Birds. A dedicated regional task force should be created under the auspices of relevant regional bodies to harmonize EIA standards, develop flyway-wide mitigation guidelines, and facilitate the cross-border data sharing necessary to conduct meaningful cumulative impact assessments.

The following table provides a clear, actionable roadmap summarizing the key recommendations and assigning responsibility.

Table E2. Strategic Framework for Connectivity Conservation in NEA

Recommendation Category	Specific Action	Target Species	Lead Stakeholders
Proactive Spatial Planning	Adopt flyway-scale sensitivity mapping and designate "no-go" zones.	All migratory species	National Governments, Regional Bodies (NEASPEC, EAAFP)
	Mandate 5km buffer zones for wind energy around key crane sites.	White-naped & Hooded Cranes	National/Provincial Governments, Energy Regulators
Mandatory Mitigation	Require dynamic shutdowns for OWFs in high-risk migration corridors.	Black-faced Spoonbill	National Governments, Energy Developers
	Enforce avian-safe design and marking for all new power lines in crane habitat.	White-naped & Hooded Cranes	National Governments, Utility Companies
Targeted Research	Launch large-scale, coordinated telemetry studies.	All three flagship species	Research Institutions, Governments, NGOs
	Develop contingency and risk-spreading plan for population concentration.	Hooded Crane	National/Local Governments (Japan), International Partners (ICF)
Transboundary Cooperation	Develop threat-responsive International Species Action Plans.	White-naped & Hooded Cranes	CMS, EAAFP, National Governments
	Establish a regional task force on energy and migratory birds.	All migratory species	Regional Bodies (NEASPEC, EAAFP), National Governments

Acronyms and Abbreviations

AIOM	Avian-Impact Offset Method
BACI	Before-After-Control-Impact
BAG	Before-After-Gradient
BPLE	Basic Plan for Long-Term Electricity Supply and Demand
CAF	Central Asian Flyway
CEA	Cumulative Effects Assessment
CMS	Convention on Migratory Species
CR	Critically Endangered
CRM	Collision Risk Models
DMZ	Demilitarized Zone
EAAF	East Asian-Australasian Flyway
EAAFP	East Asian-Australasian Flyway Partnership
EEZ	Exclusive Economic Zones
EIA	Environmental Impact Assessment
EN	Endangered
ESIA	Environmental and Social Impact Assessment
FNS	Flyway Network Sites
GIS	Geographic Information System
IBA	Important Bird and Biodiversity Areas
IBM	Individual-Based Models
ICF	International Crane Foundation
IG	Impact-Gradient
IPM	Integrated Population Models
ISSAP	International Single Species Action Plan
IUCN	International Union for Conservation of Nature
KBA	Key Biodiversity Areas
KDE	Kernel Density Estimation
KEI	Korea Environment Institute
MoE	Ministry of Environment
NEA	North-East Asia

NEASPEC	North-East Asian Subregional Programme for Environmental Cooperation
NFC	Nocturnal Flight Call
NT	Near Threatened
OWF	Offshore Wind Farm
PTT	Platform Transmitting Terminals
PV	Photovoltaic
PVA	Population Viability Analysis
REF	Russian Far East
RFI	Regional Flyway Initiative
ROK	Republic of Korea
SEA	Strategic Environmental Assessment
SE-IBM	Spatially Explicit Individual-Based
SIA	Stable Isotope Analysis
UD	Utilization Distribution
UHV	Ultra-High Voltage
VU	Vulnerable
WPF	West Pacific Flyway
YS	Yellow Sea

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Introduction

Background and Objectives

Bird migration represents an extraordinary ecological phenomenon, characterized by the seasonal movement of billions of birds across extensive geographical distances. These migratory journeys typically occur along specific routes known as flyways, connecting northern breeding grounds in arctic and temperate zones with southern wintering areas in temperate and tropical regions. Within this global context, North-East Asia (NEA) is particularly critical, hosting vital segments of several key migratory routes, notably the East Asian-Australasian Flyway (EAAF). The EAAF extends from the Russian Far East (RFE) and Alaska through East and South-East Asia to Australia and New Zealand, spanning 22 countries. It is recognized as the world's most densely populated flyway, supporting almost two billion people and over 50 million migratory waterbirds across more than 250 distinct bird populations(see https://eaaflyway.net/the-flyway/ for more details)

NEA also intersects with other significant migratory pathways, such as the Central Asian Flyway (CAF), supporting approximately 605 migratory bird species. The ecological importance of this region is multifaceted, encompassing crucial breeding areas, essential stopover sites for rest and refueling, and vital wintering habitats. Northern Arctic zones, including the Russian tundra, serve as critical breeding habitats for numerous shorebird species. Further south, a variety of biomes - from expansive broadleaf forests to tundra - support nearly 400 migratory landbird species, highlighting the exceptional biodiversity supported by the EAAF (Mundkur et al. 2023).

Critical stopover locations within NEA are integral to migratory bird survival. The Yellow Sea, notably, serves as a significant migratory bottleneck and essential feeding area for thousands of shorebirds. Birds rely heavily on this region to replenish energy reserves during their extensive journeys. Additionally, NEA provides wintering grounds for numerous birds. For example, the Demilitarized Zone (DMZ) wetlands between North and Republic of Korea (ROK) are significant wintering habitats for cranes such as White-naped Crane (Antigone vipio) and Hooded Crane (Grus monacha), demonstrating the continuous year-round ecological value of these areas.

Despite its ecological significance, migratory birds in NEA face escalating threats primarily from habitat loss, driven by rapid urbanization and extensive coastal development. Economic growth and population expansion have led to significant degradation and loss of critical habitats, especially coastal wetlands and tidal flats vital to migratory waterbirds. Extensive land reclamation projects, particularly in the Yellow Sea (YS), have drastically reduced available intertidal habitats, negatively impacting populations of migratory shorebirds (Murray et al. 2014, Melville et al. 2016). Agricultural expansion and intensified agricultural practices further degrade habitats and diminish essential food resources (Murray et al. 2015).

Increasingly, energy infrastructure development, particularly renewable energy projects such as wind and solar farms, poses substantial threats to migratory birds. Offshore wind farms in sensitive areas like the Yellow Sea have led to documented changes in migratory behavior for endangered species such as the Black-faced Spoonbill (Platalea minor) (Lai et al. 2025). Large birds, including cranes, have demonstrated avoidance behaviors near turbine installations, highlighting the disruptive impacts of energy infrastructure. Similarly, solar farms and power grid expansions threaten migratory birds through habitat destruction, direct collisions, and electrocutions.

Additional threats to migratory birds in the region include illegal hunting, pollution, and climate change, which exacerbate existing pressures and potentially alter migration patterns (American Bird Conservancy 2021, Smith et al. 2016, International Crane Foundation 2024)

The concept of habitat connectivity is essential for the conservation of migratory birds, emphasizing the need for maintaining ecological linkages among geographically distinct sites utilized throughout their life cycle. Birds rely on interconnected habitats to access critical resources such as food, water, and shelter. Even minor disruptions or habitat losses within this network can significantly impact entire bird populations. Connectivity enables migratory birds to move freely, ensuring access to resources and allowing adaptive responses to environmental changes. However, increased habitat fragmentation due to human activities disrupts these connections, impeding migratory birds' ability to complete their life-history effectively (UNEP-WCMC 2023, Defenders of Wildlife 2021). Establishing and maintaining ecological corridors is therefore crucial for facilitating wildlife movements, mitigating fragmentation impacts, and sustaining population viability.

Given NEA's critical role in global bird migration and escalating threats confronting population in migration birds, targeted approach emphasizing connectivity conservation is urgently required. This region's strategic location within densely populated flyways, combined with rapid economic development, positions it as a focal point for conservation challenges. Traditional site-specific conservation measures alone are insufficient to address the complex requirements of migratory birds dependent on expansive habitat networks. Connectivity-based strategies provide a more comprehensive framework for conservation, ensuring the long-term viability of migratory bird populations by maintaining functional links between key habitats.

This report aims to provide foundational insights into the relationships between energy infrastructure development and migratory bird populations in NEA. It will incorporate scenario analyses based on foresight-informed approaches to evaluate and project potential impacts from energy developments on migratory bird populations. Outcomes from this research will generate valuable lessons and applicable conservation strategies specifically tailored to the NEA context, enhancing regional biodiversity conservation efforts and informing sustainable development practices.

Scope and Methods

This report specifically focuses on Offshore Wind Farms (OWF) as a cast study, excluding solar panels and onshore wind farms due to the predominantly aquatic habitats utilized by migratory birds in NEA. The document employs a systematic approach, beginning with a comprehensive literature review and data synthesis to assess the current status of migratory birds, critical habitats, and existing threats associated with OWF developments. Scenario analyses using Population Viability Analysis (PVA) methodologies are conducted to project the potential impacts of offshore wind farms on migratory bird populations. These scenarios will help identify key areas of conflict, critical habitat overlap, and the possible implications of habitat disruption and fragmentation. The findings aim to inform targeted conservation strategies, policy recommendations, and adaptive management approaches to effectively balance renewable energy objectives with biodiversity conservation goals in the region.

1 Energy Infrastructure and Migratory Birds in NEA

1.1 Status of Migratory Birds in NEA

1.1.1 General Status

Migratory birds are integral to ecosystems in North-East Asia (NEA), serving as key indicators of ecological health and contributing significantly to regional biodiversity. Their migration routes, known as flyways, connect diverse ecosystems across multiple countries, illustrating the interconnected nature of environmental conservation (EAAFP 2021). Migratory birds help maintain ecological balance by transporting nutrients and energy over large distances, thus influencing community dynamics and ecosystem functioning (Bauer and Hoye 2014).

NEA is uniquely positioned at the intersection of several major flyways, notably the East Asian-Australasian Flyway (EAAF), Central Asian Flyway (CAF), and West Pacific Flyway (WPF). The EAAF, in particular, is one of the most significant migration corridors globally, extending from the Russian Far East (RFE) and Alaska to Australia and New Zealand, encompassing 22 countries. It supports more than 50 million migratory waterbirds, representing over 250 distinct populations, along with approximately 400 migratory landbird species (EAAFP 2021). The CAF spans regions from Siberia to the Indian subcontinent, supporting over 600 species, many experiencing population declines (Convention on Migratory Species 2023). The WPF also overlaps considerably with the EAAF, connecting regions across the Pacific Ocean.

Despite their ecological importance, migratory birds in NEA face significant threats (Yong et al. 2021). Habitat degradation and loss driven by rapid urbanization, coastal development, and agricultural intensification have severely impacted vital habitats such as wetlands and coastal zones (Murray et al. 2014). Notably, the YS region, a critical stopover site, has experienced extensive habitat loss due to reclamation projects, significantly affecting shorebird populations.

The growth of renewable energy infrastructure, especially offshore wind farms (OWF), presents emerging challenges for bird conservation. These developments can cause direct collisions, habitat displacement, and behavioral changes in bird populations (Marques et al. 2019). Climate change, pollution, and illegal hunting further exacerbate these threats, highlighting the urgent need for integrated and cooperative conservation strategies across international boundaries.

1.1.2 Habitat Status

NEA provides essential breeding, stopover, and wintering habitats critical to migratory bird survival. The RFE, including Siberia, Kamchatka, and the Amur-Heilong Basin, hosts extensive tundra and wetlands supporting numerous waterbirds, shorebirds, and landbirds, such as the Siberian Crane (*Leucogeranus leucogeranus*) and Black-faced Spoonbill (*Platalea minor*) (Chen et al. 2021).
Similarly, North-East China, encompassing provinces like Heilongjiang and Inner Mongolia, provides vital breeding grounds for cranes, storks, and other waterbirds at reserves such as Zhalong and Momoge.

Mongolia's grassland and wetland ecosystems, notably the Khurkh-Khuiten River Valleys and Dauria International Protected Area, serve as key breeding sites for cranes and geese (UN ESCAP et al. 2017).

On the Korean Peninsula, especially along the western coast and border areas, critical habitats support species such as the Black-faced Spoonbill. Japan's Hokkaido region provides breeding grounds for resident Red-crowned Cranes (*Grus japonensis*) and other bird species.

Stopover sites in NEA are crucial for birds during migration. The YS intertidal wetlands, particularly the Yalu River Estuary and Chongming Dao, support substantial numbers of shorebirds such as the Great Knot (*Calidris tenuirostris*) and Spoon-billed Sandpiper (*Calidris pygmaea*). Major river estuaries and lakes, including Poyang Lake in China and Han River estuary in ROK, provide essential resting and feeding habitats (Melville et al. 2016). These sites act as "stepping stones," enabling birds to replenish energy reserves during migration.

Certain locations, known as "hub sites," are especially significant due to their high concentration of bird populations. For instance, Izumi in Japan supports over 80% of the global population of Hooded Cranes (*Grus monacha*), while Poyang Lake in China is the primary wintering site for the eastern population of Siberian Cranes. Protecting these hub sites is paramount due to their disproportionate role in sustaining migratory bird populations (Higuchi et al. 1996, Wetlands International 2012).

Wintering grounds across the region, such as the Yangtze River Delta and YS coast in China, the DMZ wetlands in Korea, and Izumi in Japan, are equally critical. These habitats support large populations of cranes, ducks, geese, and other waterbirds during winter months (UN ESCAP and NEASPEC 2018). The condition of these wintering sites significantly influences overall migratory success, emphasizing the interconnectedness of habitats throughout life-history in migratory birds.

Conservation in migratory birds must recognize the dynamic nature of bird habitats, adapting strategies to shifting distributions due to environmental changes or successful restoration efforts. For instance, species such as Baer's Pochard (*Aythya baeri*) have adapted to new breeding sites south of their traditional range, indicating the need for flexible and adaptive conservation management approaches (Wu et al. 2022). Ensuring ecological connectivity and protecting habitat networks across flyways is vital for the long-term survival of migratory bird populations.

1.2 Species-based Research and Available Data Status in NEA

NEA supports an exceptional diversity of migratory birds, each with distinct ecological roles and unique conservation challenges. Key groups include waterfowl, shorebirds, Anatidae (ducks, geese, swans), cranes, seabirds, landbirds, and raptors, each relying on specific habitats.

Waterfowl, which depend heavily on wetland ecosystems, are significantly affected by habitat loss. The EAAF alone supports over 50 million migratory waterbirds. Shorebirds within this group, such as the Spoon-billed Sandpiper, Far Eastern Curlew (Numenius madagascariensis), Great Knot, and Red Knot (Calidris canutus), critically depend on intertidal habitats, notably the YS. Around 88% of the shorebird species monitored in the YS exhibit declining population trends.

The Anatidae family, including species such as Baer's Pochard, Scaly-sided Merganser (Mergus squamatus), Swan Goose (Anser cygnoid), and Lesser White-fronted Goose (Anser erythropus), faces threats from wetland drainage, habitat destruction, and pollution. Cranes, symbolically and culturally significant, include the critically endangered Siberian Crane, and vulnerable species such as the White-naped Crane (Grus vipio), Red-crowned Crane, Hooded Crane, and Oriental Stork

(Ciconia boyciana). These cranes heavily rely on NEA wetlands for their breeding and wintering habitats.

Seabird species such as Saunders's Gull (Saundersilarus saundersi) and the Chinese Crested Tern (Sterna bernsteini) are threatened by coastal developments and disturbances. Landbirds, notably passerines like the critically endangered Yellow-breasted Bunting (Emberiza aureola), have suffered severe population reductions, primarily due to extensive hunting practices. Raptors also encounter various threats along their migratory routes, although comprehensive studies are relatively limited.

According to the International Union for Conservation of Nature (IUCN), several migratory bird species in NEA are categorized under different threat levels. Critically Endangered (CR) species include the Spoon-billed Sandpiper, Baer's Pochard, Siberian Crane, and Chinese Crested Tern. Endangered (EN) species encompass the Great Knot, Far Eastern Curlew, Scaly-sided Merganser, Oriental Stork, Black-faced Spoonbill, and Nordmann's Greenshank (Tringa guttifer). Vulnerable (VU) species include Swan Goose, Lesser White-fronted Goose (Anser erythropus), Red-crowned Crane, Hooded Crane, White-naped Crane, Relict Gull (Ichthyaetus relictus), and Long-tailed Duck (Clangula hyemalis). Near Threatened (NT) species include Curlew Sandpiper (Calidris ferruginea), Red Knot, Asian Dowitcher (Limnodromus semipalmatus), Whimbrel (Numenius phaeopus), Black-tailed Godwit (Limosa limosa), and Dalmatian Pelican (Pelecanus crispus).

Population trends indicate an overall decline across many waterbird populations in the EAAF. The EAAFP's 2022 Conservation Status Review reported that approximately 42% of monitored populations are decreasing, while 27% are increasing, and the rest show stable or fluctuating trends (Wetlands International 2022). Notably, the Spoon-billed Sandpiper experienced an 88% decline from 2002 to 2009, and Baer's Pochard populations have declined by over 99% in their mainland China wintering grounds (Zöckler et al. 2010). Similarly, the Far Eastern Curlew has declined significantly at a rate of approximately 4.68% annually in Australia from 1996 to 2014 (Convention on Migration Species 2017).

Despite widespread declines, there have been notable conservation successes. The Black-faced Spoonbill population, once fewer than 300 individuals in 1989, has recovered to approximately 7,000 individuals by 2024 due to targeted international conservation efforts (Kennerley 1989, Hong Kong Bird Watching Society 2024). Nevertheless, ongoing urban expansion and renewable energy infrastructure present continuous threats, highlighting the need for adaptive management and continuous conservation vigilance.

Significant data gaps persist, especially for landbird species and less-studied bird groups. For example, population trends remain unknown for about 43% of EAAF waterbird populations (Wetlands International 2022). This lack of comprehensive data obscures the full scope of the conservation crisis and poses challenges to effective conservation planning. Accurate population monitoring, detailed assessments, and establishing historical population baselines are crucial steps towards creating informed, effective conservation strategies that cater specifically to each bird group's ecological requirements and threats in NEA.

Table 1. Key Migratory Birds in NEA: IUCN Status, Population Trends, and Major Flyways

Common Name	Scientific Name	Major Northeast Asian Flyway	Key Northeast Asian Habitat Countries (Breeding, Stopover, Wintering)	Global IUCN Red List Status (Latest)	EAAF/Northeast Asia Population Trend (Period)	EAAF Estimated Population	Key Northeast Asian Threats
Shorebirds							
Spoon-billed Sandpiper	*Calidris pygmaea*	EAAF	RFE (breeding), YS (stopover), Southeast Asia (wintering)	CR	Decreasing (8% per year 2009-2016; 88% 2002-2009)	120-220 pairs (2009)	YS stopover site loss, threats at breeding & wintering grounds, hunting
Far Eastern Curlew	*Numenius madagascariensis*	EAAF	RFE, NE China (breeding), YS (stopover), Australia/SE Asia (wintering)	EN	Decreasing (Australia 4.68% per year 1996-2014; recent slowing of decline possible)	28,000-32,500	YS stopover site loss & degradation, coastal development, human disturbance
Great Knot	*Calidris tenuirostris*	EAAF	NE Siberia (breeding), YS (stopover), Australia/SE Asia (wintering)	EN	Decreasing (survival rate decline 2007-2012)	160,000-180,000	YS stopover site loss (especially ROK)
Bar-tailed Godwit	*Limosa lapponica*	EAAF	Arctic (breeding), YS (stopover), Australia/New Zealand (wintering)	NT (some subspecies higher threat)	*L. l. baueri* & *L. l. menzbieri* YS stopover populations decreasing		YS stopover site loss
Anatidae							
Baer's Pochard	*Aythya baeri*	EAAF	RFE, NE China (former breeding), now C & E China (breeding/wintering)	CR	Severe decline (>99% in China wintering grounds)	<1,000 mature individuals	Wetland drainage, overhunting, habitat destruction
Scaly-sided Merganser	*Mergus squamatus*	EAAF	RFW, NE China (breeding), C & S China,	EN	Decreasing (mixed stability/decrease)	2,400-4,500 mature individuals	Breeding site deforestation, wintering site damming &

			South Korea (wintering)				water pollution, human disturbance
Swan Goose	*Anser cygnoid*	EAAF, CAF	Mongolia, Russia, China (breeding), Yangtze River Basin, China (wintering)	VU	Decreasing (Yangtze Basin)	60,000-90,000 [EAAFP]	Wintering site habitat loss, hunting
Cranes							
Siberian Crane	*Leucogeranus leucogeranus*	EAAF (Eastern)	NE Siberia (breeding), Poyang Lake, China (wintering)	CR	Eastern population increasing/stable (2012-2018)	Approx. 3,600-4,000 (Eastern)	Wintering site hydrological changes (Three Gorges Dam, etc.), habitat degradation
Red-crowned Crane	*Grus japonensis*	EAAF	RFE, NE China, Hokkaido (Japan) (breeding), Korean DMZ, E China coast (wintering)	VU	Mixed (E China decreasing, Japan/Korea increasing/stable)	2,800-3,430	Wetland loss & degradation, agricultural changes, human disturbance
White-naped Crane	*Grus vipio*	EAAF	Mongolia, NE China, SE Russia (breeding), Korean DMZ, Izumi (Japan), Poyang Lake (China) (wintering)	VU	Mixed (China decreasing, Korea/Japan increasing)	5,500-6,500 [EAAFP]	Breeding & wintering site wetland loss, farmland changes
Hooded Crane	*Grus monacha*	EAAF	S Central Siberia, N China (breeding), Izumi (Japan) (main wintering), Korea, Yangtze Basin (China) (wintering)	VU	Korea/Japan wintering population stable (1996-2018)	Approx. 9,500-11,000	Wintering site concentration (Izumi) disease risk, China wintering site habitat degradation

Oriental Stork	*Ciconia boyciana*	EAAF	RFE, NE China (breeding), Yangtze River Basin (China) (wintering)	EN	Increasing (2012-2020)	Approx. 3,000-4,000 [EAAFP]	Wetland development, pesticide use, power line collision
Other Waterbirds							
Black-faced Spoonbill	*Platalea minor*	EAAF	W Coast Korean Peninsula, NE China (breeding), Taiwan, Hong Kong, Japan, Vietnam (wintering)	EN	Increasing (1994-2021)	Approx. 6,988 (2024)	Coastal development, habitat pollution, disease, low genetic diversity
Landbirds							
Yellow-breasted Bunting	*Emberiza aureola*	EAAF, CAF	Siberia to NEA (breeding), SE Asia/S Asia (wintering)	CR	Rapid decline [12]	Unknown (formerly very common)	Large-scale illegal trapping & trade (mainly China)

Note: Population trends and estimates may vary based on the latest data and sources. IUCN status is as of 2024 or most recent assessment.

1.2.1 The Black-faced Spoonbill (Platalea Minor): A Conservation Success Story Facing New Perils

The Black-faced Spoonbill represents one of the most remarkable, albeit fragile, conservation stories in the EAAF. Once on the brink of extinction with a global population of fewer than 300 individuals in the late 1980s, the species has rebounded significantly due to decades of coordinated international conservation efforts. The global population surpassed 6,988 individuals in the 2024 census, a testament to the success of habitat protection and collaborative management.Despite this recovery, the species remains listed as Endangered (EN) on the IUCN Red List, a status reflecting its restricted range, low genetic diversity, and a new suite of emerging threats.

Recent data indicate that the species' rapid population growth is now decelerating. The 2025 census recorded 7,081 individuals, a modest increase of just 1.3% from the previous year, marking the second-lowest growth rate in a decade.This slowdown suggests the population may be encountering new limiting factors or approaching the carrying capacity of its available habitats. This has fueled a debate regarding its conservation status; while the population increase is undeniable, proposals to downlist the species are met with caution from conservationists who point to the severity of new threats, particularly from coastal development and renewable energy infrastructure, as a reason to maintain its endangered classification.

The species' life cycle is concentrated in a few key locations within NEA. The primary breeding grounds are located on small, rocky, and often uninhabited islands off the west coast of the Korean Peninsula and in Liaoning Province, China.After the breeding season, the birds migrate south to their wintering grounds. The most critical wintering site is in Taiwan, which hosts well over half of the global population, particularly in the wetlands of the Tsengwen Estuary. Other vital wintering areas include the Deep Bay area of Hong Kong and Shenzhen, and sites in Japan and Vietnam. The Yellow Sea serves as a critical migratory corridor and stopover region, linking these breeding and wintering sites.

The Black-faced Spoonbill is a flagship species for both the North-East Asian Subregional Programme for Environmental Cooperation (NEASPEC) and the EAAFP. This status has galvanized international cooperation, culminating in the development of International Single Species Action Plans (ISSAPs). A new ISSAP for the period 2026-2036 is currently under revision, with a specific mandate to assess and formulate strategies to mitigate emerging threats, including the rapid expansion of offshore wind farms and other coastal energy infrastructure.

1.2.2 The White-naped Crane (Antigone Vipio): A Species of Contrasting Fates

The White-naped Crane, classified as Vulnerable (VU) by the IUCN, presents a starkly different conservation challenge characterized by a deep and concerning divergence in the fortunes of its two major populations. This dichotomy makes the species a compelling case study for understanding how regional pressures and conservation responses can lead to vastly different outcomes within a single species.

The species is broadly divided into a western and an eastern population, defined by their distinct migratory flyways. The western population, which breeds primarily in the grasslands and steppes of northeastern Mongolia, undertakes a long migration to wintering grounds centered around Poyang Lake in China's Yangtze River basin. This population is in a state of rapid and severe decline. Once numbering around 3,000 individuals, its population has plummeted by as much as two-thirds, with current estimates at only 1,000-1,500 birds. This decline is largely attributed to habitat degradation and hydrological changes in its wintering areas.

In sharp contrast, the eastern population is stable or increasing. These cranes breed in the Amur-Heilong River basin along the border of Russia and China and migrate south through the Korean Peninsula. Their primary wintering sites are the Cheorwon Basin within the Korean Demilitarized Zone (DMZ) and the Izumi Feeding Station in Kyushu, Japan. The number of cranes wintering in the Republic of Korea (ROK) has shown a phenomenal increase of over 2,300% between 2000 and 2024, highlighting the success of habitat management and protection efforts in this part of the flyway.

The species' habitat preferences underscore its close relationship with both natural and human-modified landscapes. Breeding occurs in shallow wetlands, wet meadows, and river valleys, while wintering cranes rely heavily on a mosaic of habitats, including coastal wetlands and agricultural areas, particularly rice paddies where they feed on waste grain. This reliance on agricultural landscapes places them in potential conflict with changing farming practices and rural development. Conservation efforts, led by organizations like the International Crane Foundation (ICF) and supported by frameworks like NEASPEC, are focused on securing these critical habitats, particularly through habitat restoration in the Korean DMZ and urgent research to understand and reverse the decline of the western population.

1.2.3 The Hooded Crane (Grus Monacha): A Population on A Knife's Edge

The Hooded Crane is classified as Vulnerable (VU), with a global population estimated between 11,600 and 19,000 individuals that is considered relatively stable. However, this seeming stability masks an extreme and precarious vulnerability that defines the species' conservation status: an overwhelming concentration of its population at a single wintering site.

The core of the Hooded Crane's conservation challenge lies in the fact that over 80% of its entire global population—and in some years, more than 90%—winters at one location: the artificial feeding station and surrounding agricultural lands in Izumi, southern Japan. This extreme aggregation, while a testament to successful local management that has supported the population, places the species on a knife's edge. A single localized catastrophic event, such as a highly pathogenic disease outbreak, severe weather, or significant habitat degradation from nearby development, could have a devastating impact on the entire global population.

The species' breeding grounds are located in the remote taiga forests and wetlands of south-central and southeastern Siberia, with some breeding suspected in northern China and Mongolia. From these areas, the vast majority migrates to Izumi. Much smaller flocks winter at a few other sites, including Yashiro in Japan, several locations in South Korea, and wetlands along the middle Yangtze River basin in China, such as at Chongming Dongtan.

The threats to the Hooded Crane are therefore twofold. First is the ever-present risk associated with the Izumi concentration. Second are the pressures on the smaller wintering populations and their habitats, particularly in the Yangtze basin, which are affected by habitat loss from land reclamation and the hydrological impacts of large-scale water management projects like the Three Gorges Dam. Conservation frameworks, including its listing on CITES Appendix I and CMS Appendices I & II, recognize these vulnerabilities. Management strategies are consequently focused not only on maintaining the integrity of the Izumi site but also on the critical need to identify, protect, and potentially restore alternative wintering sites to disperse the population and mitigate the profound risk of having all eggs in one basket.

1.3 Current Status of Movement Study in Migratory Birds in NEA

NEA, particularly the East Asian-Australasian Flyway (EAAF), faces severe threats, hosting the highest number of threatened migratory bird species globally. Effective conservation thus requires a detailed understanding of migratory patterns, connectivity, and ecological needs, especially given the rapid expansion of energy infrastructure such as OWFs.

Advancements in bird-tracking technologies have significantly enriched our knowledge. Satellite telemetry and GPS tracking are essential tools, particularly for larger birds such as cranes, geese, and raptors (Ram et al. 2024, McGinness et al. 2024). For instance, GPS studies on five goose species (Lesser White-fronted Geese (Anser erythropus), Greater White-fronted Geese (Anser albifrons), Bean Geese, Greylag Geese (Anser anser), and Swan Geese (Anser cygnoides)) highlighted critical stopover sites and revealed extensive reliance on agricultural landscapes, which account for approximately 63% of land used during migration (Guo et al. 2019). Similarly, satellite tracking of Mallards (Anas platyrhynchos) wintering in Japan has mapped their diverse migratory routes across Korea, Russia, and Japan, providing crucial insights for managing habitat use and monitoring potential disease transmission routes (Lee et al. 2020).

For smaller migratory birds, lightweight geolocators have revealed previously unknown patterns. Studies on White-shouldered Starlings (Sturnia sinensis) breeding in Hong Kong identified migrations to Vietnam, Cambodia, and southern China, demonstrating diverse migratory strategies within single populations (Dingle et al. 2025). Research using geolocators on Dunlin (Calidris alpina) subspecies has documented distinct spatial and temporal migration patterns (Lagassé et al. 2022), emphasizing the complexity of bird migration within even closely related groups.

Bird banding remains a foundational method, offering long-term data essential for understanding broad migratory routes and population dynamics. Despite its value, recovery rates of banded birds remain low, approximately 0.57% in Japan from 1961 to 2002, highlighting the need for complementary methods (https://www.yamashina.or.jp/hp/english/banding/birds_rings.html).

Bioacoustic monitoring, particularly nocturnal flight call (NFC) analysis, has become increasingly useful for studying nocturnal migration. For instance, a pioneering study in Beijing, China identified over 84,000 NFCs from at least 111 species, illustrating significant potential for monitoring migratory phenology and species composition, particularly in urban and less-accessible environments (Liu et al. 2024).

Radar ornithology has further contributed to understanding flock behavior, flight speeds, and migration altitudes. Stable isotope analysis (SIA) complements these methods by linking breeding, stopover, and wintering locations through chemical signatures in feathers, which retain isotopic information about the sites of feather growth (Gauthreaux and Belser 2003). This method is particularly beneficial when combined with geolocator data, refining location estimates for small birds.

Climate change significantly affects migration timing (phenology). In eastern Japan, the first arrival dates for 36 species advanced by an average of 7.3 days per decade, while last departure dates for 63 species delayed by 10.6 days per decade (Miyamoto and Kondoh 2025). Such shifts, driven by rising temperatures, pose severe risks of phenological mismatches, potentially impacting bird survival and breeding success. In ROK, peak arrival and departure dattes for wintering species were estimated by statistical model (Lee et al. 2022)

1.4 Current Status of Energy Infrastructure Development in NEA

NEA is characterized by significant and growing energy demands driven by rapid industrialization, urbanization, and dense populations. China, the world's largest energy consumer, produced and consumed substantial amounts of coal, oil, and natural gas in 2023. Despite China's commitment to peak emissions by 2030 and reach carbon neutrality by 2060, the nation continues expanding coal capacity, constructing 94.5 GW of new coal power in 2024, primarily for grid stability. Concurrently, China leads globally in renewable energy, with 890 GW of solar and 520 GW of wind capacity installed by 2024 (https://www.macrobusiness.com.au/2025/04/china-doubles-down-on-coal-use). These renewable expansions frequently occur in sensitive ecological areas, including deserts and coastal wetlands.

Japan, heavily reliant on energy imports, aims for carbon neutrality by 2050 under its 7th Strategic Energy Plan. Renewables are projected to constitute 40-50% of power generation by 2040, emphasizing offshore wind (targeting 10 GW by 2030 and up to 45 GW by 2040) (Coca 2025, DLA Piper 2024, Edelman 2025). These developments predominantly occur along ecologically significant marine and coastal areas. Japan continues to depend significantly on imported LNG, requiring coastal infrastructure potentially disruptive to migratory bird habitats.

ROK similarly relies on imported fossil fuels, with ambitious plans under its 11th Basic Plan for Long-Term Electricity Supply and Demand (BPLE) to achieve 70% clean energy by 2038 (Institute for Energy Economoics and Financial Analysis 2025). Offshore wind power expansion along the YS's western coast is a major initiative, despite potential ecological conflicts with critical bird habitats. coastal developments in ROK (Lee et al. 2023), including LNG terminals and renewable projects, frequently overlap with internationally recognized vital migratory bird sites.

Mongolia, heavily dependent on coal, aims to diversify with renewable energy targets set to 30% of installed capacity by 2030. Renewable projects such as the Salkhit Wind Farm are mainly in the Gobi Desert, impacting unique avian biodiversity (Join SDG Fund 2025, Government of Mongolia 2015). The nation's significant coal exports necessitate extensive infrastructure (power lines and transportation routes), which can fragment habitats and threaten avian species.

The RFE focuses on resource extraction and energy exports, notably oil, gas, coal, and hydropower (Interfax 2025). Expanding linear infrastructure and thermal power plants to support these activities significantly impact critical habitats for migratory birds, especially in sensitive Arctic and subarctic ecosystems.

Energy policies across the region increasingly prioritize renewable energy expansion to achieve decarbonization targets. China's Energy Law 2025 promotes renewables while managing energy security challenges (Cipher 2025). Japan's Strategic Energy Plan emphasizes offshore wind and hydrogen technology alongside continued nuclear and LNG use (Ashurst 2025). Energy strategy in ROK includes substantial LNG and nuclear expansions in parallel with renewable growth (Enerdata 2025). Mongolia's "Vision 2050" strategy prioritizes renewable energy growth and foreign investment for infrastructure (China Briffing 2023). The RFE emphasizes modernization and expansion of energy infrastructure to facilitate industrial growth (Specialeurasia 2025).

While each country adopts unique strategies, the regional expansion of energy infrastructure, especially renewable projects, poses significant ecological risks. Strategic planning, robust environmental assessments, and rigorous adherence to biodiversity conservation standards are crucial to mitigate these risks effectively, particularly for migratory birds whose habitats frequently overlap with energy development zones.

Table 2. Comparative overview of energy infrastructure development trends in NEA Countries (2020-2025 Focus)

Country	Primary Fossil Fuel Sources & Key Projects (2020-2025)	Key Renewable Energy Focus & Targets (GW/%)	Major grid Expansion Initiatives	Overarching Energy Policy Driver(s)
China	Coal (continued new plant construction, e.g., 94.5 GW started 2024); Natural Gas (increasing consumption, LNG terminal expansion in coastal areas)	Solar (world leader, ~890 GW total by 2024); Wind (~520 GW total by 2024); Non-fossil fuels 49% of installed capacity (2022)	Extensive Ultra-High Voltage (UHV) grid expansion to connect remote generation to eastern demand centers.	Energy security, "Dual-carbon" goals (peak by 2030, neutrality by 2060), economic development.

Japan	LNG (crucial for transition, new terminal studies/completions e.g., Sodegaura); Oil & Coal (significant import reliance, gradual reduction efforts)	Offshore Wind (10 GW by 2030, 30-45 GW by 2040); Solar (target 23-29% of power by 2040); Renewables 40-50% of power by 2040	Enhancement of grid capacity for offshore wind integration, inter-regional transmission lines.	Carbon neutrality by 2050, energy security (reducing import dependency), economic growth.
South Korea	LNG (capacity to rise to 69.2 GW by 2038); Coal (gradual reduction, some conversion to LNG); Oil (import reliant); East Sea gas field development	Offshore Wind (significant plans, esp. Yellow Sea); Solar; Renewables target 29% share by 2038 ; Clean power (renewables + nuclear) 70% by 2038	Grid modernization to support renewables and meet industrial demand.	Carbon neutrality goals, energy security, industrial competitiveness (e.g., RE100 for semiconductor industry).
Mongolia	Coal (dominant domestic source and export, e.g., Tavan Tolgoi expansion); Oil (small domestic production, import reliant for products)	Wind (e.g., Salkhit Wind Farm); Solar (Gobi desert projects); Renewables 30% of installed capacity by 2030	Expansion of transmission lines to support mining and new renewable projects, often in remote areas.	Energy diversification, improving infrastructure, attracting foreign investment, reducing air pollution ("Vision 2050").
Russian Far East	Oil & Gas (Arctic, Sakhalin export projects); Coal (regional use and export); Hydropower (Amur basin potential)	Very low renewable penetration (<1% wind/solar); Focus on large hydro. Some discussion of small modular reactors.	Modernization of isolated grids, new power plants (thermal, hydro) and transmission lines to support resource extraction and regional development.	Economic development of the Far East, resource export to Asia, energy security for remote regions.

1.5 Review Effects of Energy Infrastructure Development on Migratory Birds in NEA

Migratory birds rely on an interconnected network of critical habitats across their migratory routes, many formally recognized as Important Bird and Biodiversity Areas (IBAs), Key Biodiversity Areas (KBAs), and Flyway Network Sites (FNS). Despite these designations, legal protection is not guaranteed, leaving these sites vulnerable to infrastructure development.

Global data indicates significant overlaps between critical biodiversity areas and infrastructure: approximately 75% of KBAs contain roads, and 37% host power lines (Simkins et al. 2023). Planned expansions of energy plants, oil and gas facilities, and renewable energy installations further threaten these habitats, increasing risks of habitat fragmentation, loss, and bird mortality. To mitigate such impacts, integration of biodiversity considerations into regional and national development planning is essential.

Wetland ecosystems, notably the YS and Bohai Bay in China, provide vital stopover habitats within the EAAF. These areas have suffered dramatic habitat losses due to reclamation for industrial, agricultural, and urban use. Over 65% of tidal mudflats in the YS have been reclaimed since the mid-20th century, severely impacting critical species (e.g., Far Eastern Curlew, Great Knot, Spoon-billed Sandpiper). Similarly, Bohai Bay faces intense pressures from industrial expansions, aquaculture changes, and pollution, significantly reducing available feeding grounds essential for migratory shorebirds (MacKinnon et al. 2012, Murray et al. 2014).

Inland wetland habitats (e.g., Poyang Lake in China) face threats from hydropower and wind energy projects. These developments alter the hydrological regimes, impacting critical foraging areas for waterbirds including the Siberian Crane. Similarly, the transboundary Amur-Heilong Basin, spanning Russia, China, and Mongolia, faces habitat disruptions due to hydropower dams, agriculture intensification, and pollution (Hu et al. 2022, WWF, Shcheka 2005). These disturbances threaten significant migratory species like cranes and storks, highlighting the need for transboundary cooperation in habitat conservation.

Arid and steppe ecosystems, including the Gobi Desert and Daurian Steppe, also encounter substantial impacts from energy infrastructure. The Gobi Desert, shared by China and Mongolia, experiences habitat fragmentation from extensive mining operations, associated roads, railways, power transmission lines, and solar energy projects (Convention on Migratory Species 2024). These activities present collision and electrocution risks, especially to large raptors and ground-nesting species. The Daurian Steppe, a critical grassland habitat shared by Russia, Mongolia, and China, is similarly affected by infrastructure development, livestock overgrazing, wildfires, and poorly designed power lines, leading to significant declines in populations of globally threatened birds like the Great Bustard (*Otis tarda*) and Lesser Kestrel (*Falco naumanni*).

The Arctic and subarctic regions of the RFE, including Sakhalin Island, serve as essential breeding grounds for numerous migratory bird species utilizing the EAAF and CAF. Oil and gas developments, pipeline constructions, and other infrastructure projects disrupt these sensitive ecosystems, causing habitat loss and fragmentation. Climate change further exacerbates these issues, promoting tundra shrubification and permafrost thaw, altering habitats vital for species such as the Spoon-billed Sandpiper and Bar-tailed Godwit (*Limosa lapponica*) (Mekonnen et al. 2021, Mauclet et al. 2022, Myers-Smith et al. 2015)). The combined pressures from infrastructure development and climate-driven habitat changes pose significant threats to the ecological integrity of these northern breeding grounds.

Effectively mitigating the impacts of energy infrastructure on migratory birds requires comprehensive spatial planning that prioritizes bird conservation, rigorous environmental impact assessments, and strengthened international collaboration. Adopting biodiversity-friendly infrastructure design and ensuring strict regulatory compliance are crucial steps toward sustainable energy development. These measures collectively support the preservation and restoration of critical avian habitats, promoting the resilience of migratory bird populations across NEA.

Table 3. Critical Migratory Bird Habitats and IBAs/FNS in NEA Intersecting with Energy Development Zones

Site Name/Ecoregion	Country	Key migratory Bird Species Supported (Threatened/Congregatory Examples)	Designated Status (Examples)	Primary Energy Infrastructure Threats in/near Site
Yellow Sea Tidal Flats (various locations)	China, R. Korea	Spoon-billed Sandpiper (CR), Far Eastern Curlew (EN), Great Knot (EN), Nordmann's Greenshank (EN), Bar-tailed Godwit,	FNS (e.g., Yancheng, Chongming Dongtan [China]; Getbol, Suncheon Bay), Ramsar	Land reclamation for industry/ports/aquaculture, Offshore Wind Farms, Coastal Power Plants, LNG

		various shorebirds & waterfowl	Sites, UNESCO World Heritage (Getbol, Korea)	Terminals, Pollution from coastal development
Bohai Bay Coastal Wetlands (e.g., Luannan Coast)	China	Red Knot, Great Knot, Bar-tailed Godwit, various shorebirds	FNS (e.g., Yellow River Delta, Shuangtai Hekou), Provincial Wetland Park (Nanpu Zuidong)	Industrial development (steel works, ports on reclaimed land), Aquaculture changes (deepening ponds), Oil production (spill risk), Pollution
Amur-Heilong River Basin (various wetlands)	Russia, China, Mongolia	Oriental Stork (EN), Red-crowned Crane (EN), White-naped Crane (VU), Swan Goose (VU), various waterfowl	FNS (e.g., Khingansky, Lake Khanka; Sanjiang, Xingkai Hu [China]), Ramsar Sites, National Nature Reserves (Zhalong, Momoge)	Hydropower Dams (existing & planned), Pipelines, Mining, Agricultural encroachment, Pollution
Poyang Lake	China	Siberian Crane (CR) (98% of world pop.), White-naped Crane (VU), Oriental Stork (EN), various waterfowl	FNS (Poyang Hu NR), Ramsar Site, National Nature Reserve	Wind Farms (in "bottleneck" areas), Upstream Dams altering hydrology, Agricultural intensification
Daurian Steppe (various IBAs/protected areas)	Russia, Mongolia, China	Great Bustard (VU), White-naped Crane (VU), Swan Goose (VU), Lesser Kestrel (VU), Saker Falcon (EN), Steppe Eagle (EN)	FNS (Daursky NR; Mongol Daguur SPA [Mongolia]), IBAs	Power Lines (electrocution/collision), Mining infrastructure, Roads, Agricultural expansion
Gobi Desert Oases & Steppe (various locations)	Mongolia, China	Various migratory shorebirds (e.g., Pacific Golden Plover), Saker Falcon (EN), Henderson's Ground Jay, Houbara Bustard (VU)	IBAs, National Protected Areas (e.g., Ugtam NR)	Mining (coal, e.g., Tavan Tolgoi), Large-scale Solar Parks, Power Lines, Roads, Railways
Russian Far East Arctic Tundra (e.g., Lena Delta, Kytalyk, Chukotka)	Russia	Spoon-billed Sandpiper (CR), Bar-tailed Godwit, Red Knot, Dunlin, Emperor Goose, Brent Goose, Bewick's Swan	FNS (e.g., Lena Delta, Kytalyk NR), Zapovedniks	Oil & Gas Exploration/Extraction, Pipelines, Mining, Shipping routes (Northern Sea Route), Climate Change impacts
Sakhalin Island Coastal & Marine Areas	Russia	Steller's Sea Eagle (VU), White-tailed Eagle (NT), Spotted Greenshank (EN), Blakiston's Fish Owl (EN), various seabirds	Regional protected areas, IBAs	Offshore Oil & Gas Platforms, Subsea & Onshore Pipelines, LNG Plants, Shipping, Potential oil spills

Note that CR=Critically Endangered, EN=Endangered, VU=Vulnerable, NT=Near Threatened (IUCN Red List Categories often referenced in snippets)

1.5.1 Documented Impacts on the Black-faced Sponbill: the Barrier Effect of Offshore Wind

The most direct and alarming evidence of the impact of new energy infrastructure on a flagship species comes from recent research on the Black-faced Spoonbill. The rapid, large-scale deployment of offshore wind farms (OWFs) in the Yellow Sea, a critical migratory corridor for the species, has been shown to create a significant "barrier effect" that alters migration, imposes severe energetic costs, and can lead to indirect mortality.

A groundbreaking study by Lai et al. (2025) used high-resolution GPS tracking to document the behavior of two young Black-faced Spoonbills encountering the dense cluster of OWFs off the coast of Jiangsu, China. The case of an individual bird, M03, is particularly illustrative. On its first southward migration, M03 flew into a series of massive wind farms. After passing through two of them, it altered its course, and upon encountering a third, it reversed its direction entirely, flying 376.8 km back towards the Korean Peninsula. This return journey was one of the longest continuous flights recorded in the study, and upon landing, the bird remained stationary for over 29 hours, a clear sign of extreme exhaustion. M03 never re-attempted the migration and was found dead a month later, suggesting that the energetic cost and stress of navigating the OWF barrier led to migration failure and, ultimately, its death.

The second tracked bird, Y70, also exhibited a profound response. It made two unsuccessful attempts to cross the same OWF-dense region, turning back each time. It ultimately delayed its final, successful departure by more than two weeks, making its migration the latest of all tracked birds. The study noted that in many instances, the birds were flying at altitudes that put them directly within the rotor-swept zone of the turbines.

These findings reveal a critical dimension of impact that extends beyond the conventional focus on direct collision mortality. Standard Environmental Impact Assessments (EIAs) for wind farms typically rely on Collision Risk Models (CRMs) to estimate the number of birds that will physically strike a turbine. However, the experience of the Black-faced Spoonbill demonstrates that the cumulative barrier effect of large-scale developments may be a more insidious and potentially more significant threat. The population-level consequences are not just the sum of collision fatalities but also include the reduced fitness, reproductive success, and survival of birds that are energetically compromised or fail to reach their destinations.

Furthermore, the vulnerability of young, inexperienced birds to these barriers appears to be particularly high. Both M03 and Y70 were young birds navigating the flyway for the first or second time. Experienced adults may have developed strategies or possess the physiological reserves to better cope with such obstacles. This suggests that a single, species-wide "avoidance rate" used in many models is likely an oversimplification. The disproportionate impact on juvenile survival could have severe demographic consequences by impeding the recruitment of new individuals into the breeding population, thereby undermining the long-term recovery of the species.

1.5.2 Inferred and Documented Impacts on Cranes: Collision, Electrocution and Displacement

For the White-naped and Hooded Cranes, the threats from energy infrastructure are primarily associated with terrestrial developments, including power lines, onshore wind farms, and the landscape-altering effects of large dams. While direct studies on these specific crane species' reactions to wind farms in Asia are scarce, a combination of documented incidents and powerful proxy evidence from closely related species allows for a robust assessment of the risks.

Power line collision and electrocution are well-documented and significant sources of mortality for large-bodied, low-maneuverability birds like cranes. This risk is a function of several interacting factors. Cranes are susceptible due to their physiology and behavior; their high wing loading (heavy bodies relative to wing size) results in higher flight speeds and reduced agility, making it difficult to avoid obstacles discovered at close range. Their flight behavior, which often involves large flocks traveling between foraging and roosting sites in low-light conditions at dawn and dusk, further increases the risk. The risk is not uniform across a power line; the thinner, uppermost earth wires (or ground wires) are less visible and are thought to be responsible for the majority of collisions, as birds may successfully avoid the thicker conductor bundles below only to strike the nearly invisible wire above. Problematic areas are often predictable, occurring where power lines intersect with daily flight paths, migratory corridors, or key habitats like wetlands and agricultural fields that attract large numbers of birds. In the vast, open landscapes of the Russian Far East and the Daurian Steppe, the lack of natural perches makes power infrastructure attractive for raptors, but also poses a significant collision threat to cranes and other large birds that traverse these habitats.

The expansion of electricity grids to connect new energy sources and serve growing demand across the open landscapes of the Mongolian steppe, the agricultural plains of China, and the coastal regions of the Korean Peninsula directly increases this threat. As cranes fly between foraging and roosting sites, often in low-light conditions, they are highly susceptible to colliding with these barely visible wires.

The impact of wind turbines on cranes is best understood through the lens of displacement, or avoidance behavior. While direct data for White-naped or Hooded Cranes is limited, extensive research on the similarly sized and endangered Whooping Crane (Grus americana) in North America provides a compelling proxy. These studies have demonstrated that Whooping Cranes exhibit a significant "zone of influence," actively avoiding areas within a 5-kilometer radius of wind turbines. This avoidance behavior constitutes a form of functional habitat loss; even if the habitat remains physically intact, it becomes unavailable to the cranes. Applying this 5 km buffer to key crane stopover and wintering sites in NEA reveals a substantial potential for habitat loss from onshore wind development.

This displacement creates a second-order impact that can be described as "economic displacement." As energy infrastructure renders certain habitats unusable, cranes are forced to concentrate in the remaining suitable areas. This increased density can lead to greater competition for resources, elevated social stress, and, critically, a heightened risk of disease transmission. This is a particularly grave concern for the Hooded Crane, whose population is already dangerously concentrated at the Izumi wintering site. Infrastructure development hundreds of kilometers away could indirectly exacerbate this risk by forcing the few birds that winter elsewhere to relocate, further consolidating the population at its most vulnerable point.

Finally, the reliance of both crane species on agricultural landscapes, such as the rice paddies of Korea and Japan, creates a complex nexus of conflict. These open, flat, and often extensive areas are not only critical foraging habitats for cranes feeding on waste grain but are also ideal locations for developing large-scale wind and solar farms and the transmission lines needed to connect them. This direct spatial competition means that conservation strategies cannot focus solely on protecting "natural" wetlands. They must also engage with land-use planning in agricultural mosaics, where the conflict between energy development and crane survival is often most acute. This is compounded by the impacts of large hydropower dams, such as the Three Gorges Dam, which have altered the hydrology of the Yangtze River basin, degrading the wetland habitats crucial for the wintering western population of White-naped Cranes and the small flocks of Hooded Cranes that rely on the area.

The following table synthesizes the primary threats posed by different types of energy infrastructure to the three flagship species.

Table 4. Matrix of energy infrastructure threats to flagship species

	Flagship Species		
	Black-faced Spoonbill	White-naped Crane	Hooded Crane
Offshore Wind Farms	**High Risk**. Documented barrier effect causing migration alteration, exhaustion, and indirect mortality in the Yellow Sea. High collision risk in coastal zones.	**Low Risk**. Primarily an inland/coastal wetland species; limited direct exposure.	**Low Risk.** Primarily an inland/coastal wetland species; limited direct exposure.
Onshore Wind Farms	**Medium Risk**. Potential collision risk and displacement from foraging areas if sited near coastal wetlands.	**High Risk**. Inferred major habitat loss due to a ~5 km displacement zone, based on Whooping Crane data. Collision risk.	**High Risk**. Inferred displacement and habitat loss. High potential impact if developed near the concentrated Izumi wintering site.
Power Lines (Transmission/Distribution)	**Low-Medium Risk**. Collision risk, particularly in coastal areas near breeding or wintering sites.	**High Risk**. Well-documented threat of collision for large, low-maneuverability cranes.	**High Risk**. Documented threat of collision.
Large-Scale Solar Parks	**Medium Risk**. Habitat loss if sited on coastal wetlands/salt pans (e.g., in Taiwan).	**Medium Risk**. Loss of open grassland or agricultural foraging habitat.	**Medium Risk**. Loss of open agricultural foraging habitat, especially near wintering sites.
Hydropower Dams	**Low Risk**. Indirect impacts via alteration of estuarine foraging habitats.	**High Risk**. Major degradation of wintering habitat for the western population in the Yangtze basin (Poyang Lake).	**High Risk**. Degradation of wintering habitat for the small population in the Yangtze basin.

1.6 Review of the Methodology for Assessing the Effects of Energy Infrastructure on Migratory Birds

The global imperative to transition towards sustainable energy systems is accelerating, driven by the unprecedented challenge of climate change. Offshore wind energy has emerged as a pivotal solution for nations striving to meet ambitious climate goals. However, a growing concern arises from the increasing colocation of these developments within coastal and marine zones of critical ecological significance for migratory birds. This issue is particularly salient within the EAAF, where the YS region functions as an indispensable stopover site for millions of migratory waterbirds (Figure 1).

Migratory birds exhibit a profound reliance on interconnected networks of staging, breeding, and wintering sites spanning vast distances. Their survival is intricately linked not only to habitat integrity at these discrete locations but also to the cumulative anthropogenic pressures encountered throughout their migratory journeys. The deployment of offshore wind farms within key coastal and marine habitats has instigated concerns regarding potential adverse impacts on bird populations, encompassing direct mortality from turbine collisions, displacement from vital foraging grounds, and the degradation of essential habitat.

In light of these ecological challenges, the imperative for scientifically robust methodologies capable of accurately assessing the risks posed by energy infrastructure to migratory birds has intensified. This report provides a critical review of the current state of these methodologies, drawing upon established national and international best practices, including insights gleaned from recent Korean studies focusing on spatial analysis and bird utilization patterns in relation to offshore wind energy projects (see 2.7).

1.6.1 Current Assessment Methodologies

A cornerstone of current assessment practices involves the spatial analysis of bird distribution and habitat utilization. This approach integrates species-specific datasets encompassing seasonal abundance, movement ecology, and habitat preferences to delineate areas of high conservation importance. For instance, in the ROK, recent research initiatives have mapped the spatial distribution of species such as Black-tailed Gull (*Larus crassirostris*), Black-faced spoonbill, Fat Eastern Curlew through the analysis of multi-year GPS tracking data (Lee and Lee 2024; see also 2.7). These spatial outputs serve to identify critical foraging and roosting areas, thereby informing strategic spatial planning and turbine siting decisions. Analogous methodologies have been implemented internationally. Similarly, in Europe, studies on Northern Gannets (*Morus bassanus*) have employed Utilization Distribution (UD) models to delineate core foraging zones and evaluate their spatial overlap with planned wind farm developments (Peschko et al. 2021, Garthe et al. 2017). Such spatial analyses are fundamental for identifying geographical areas where avian species exhibit an elevated risk of interaction with wind turbines.

Collision Risk Models (CRMs) represent another essential analytical tool employed to estimate the probability of avian collisions with turbine rotor blades. These models synthesize information pertaining to i) bird flight height distributions, ii) turbine dimensions and operational rotational velocities, and iii) bird passage rates through wind farm areas. For example, Brabant et al. (2015) conducted in the Belgian North Sea utilized CRMs to estimate the annual mortality risk for Lesser Black-backed Gulls (*Larus fuscus*), revealing that even seemingly low collision rates can translate to significant population-level consequences when extrapolated across multiple offshore wind installations. In Korea, nascent modeling efforts are incorporating flight height data derived from GPS telemetry and direct observational studies, offering a more refined assessment of collision risk for species such as the Black-tailed Gull (Park et al. 2024, Mikami et al. 2022).

While spatial analysis and CRMs provide critical insights into site-level and project-specific risks, the study didn't inherently assess the long-term demographic ramifications of increased mortality or habitat displacement at the population level. This is where Population Viability Analysis (PVA) assumes a pivotal role. PVA models simulate the future population dynamics of avian species under various impact scenarios, accounting for i) baseline demographic parameters such as survival and reproductive rates, ii) stochastic environmental variability, and iii) additive mortality resulting from turbine collisions or displacement pressures (see Chapter 3 for more details). For instance, applying a PVA framework to the Far Eastern Curlew, a species already classified as endangered, could elucidate whether the predicted mortality rates associated with an offshore wind project would push the population beyond sustainable demographic thresholds. Such analyses provide a robust scientific foundation for regulatory decision-making, including the establishment of mortality limits or the mandating of specific mitigation measures.

1.6.2 Limitations and Implications

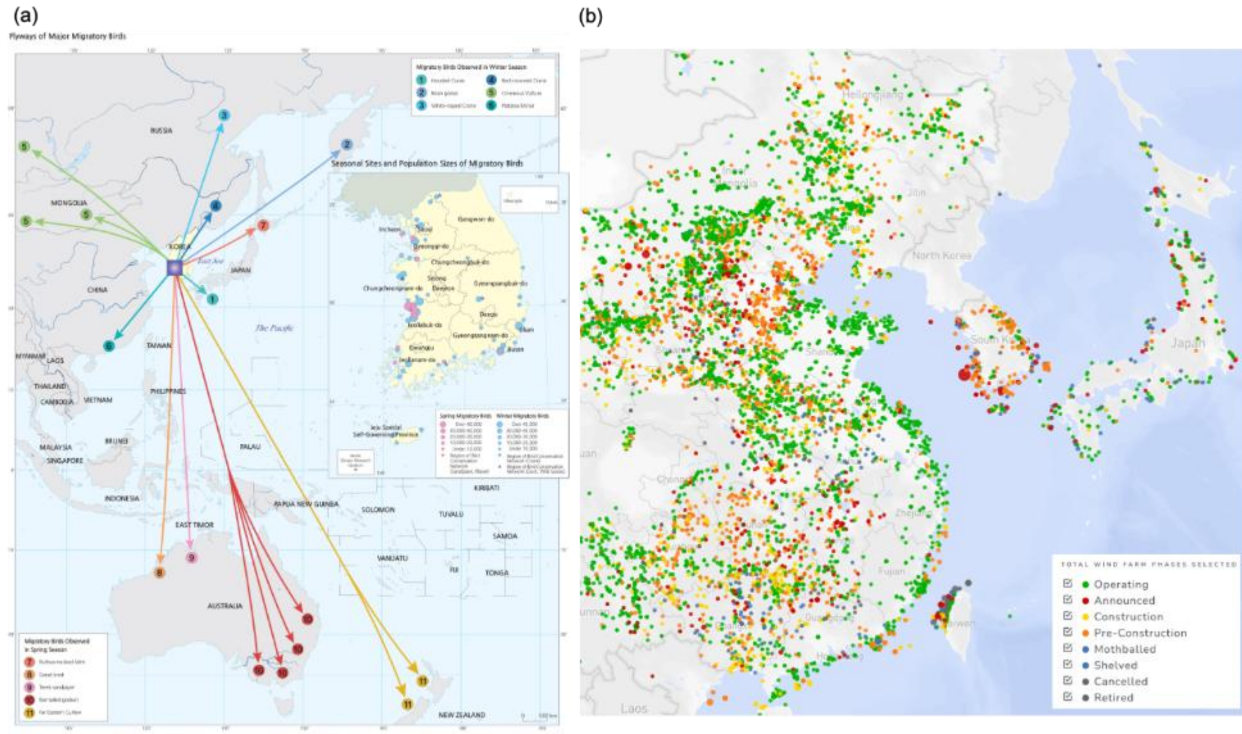
Despite the availability of these sophisticated methodologies, several lacunae and limitations persist in their practical application. Firstly, a significant proportion of assessments maintain a narrow focus on individual project footprints, failing to adequately account for the cumulative ecological impacts arising from multiple developments along shared migratory pathways. Secondly, data deficiencies concerning long-term avian behavior, survival probabilities, and population trends within the East Asian context constrain the precision and predictive power of many models. Thirdly, cross-jurisdictional coordination remains often inadequate, despite the inherent reliance of migratory birds on habitat networks that transcend national boundaries. Lastly, the ecological consequences of displacement and habitat degradation are frequently less comprehensively studied and more challenging to quantify compared to direct collision mortality.

1.6.3 Recommendations for Methodological Improvement

Building on current practice and recognizing the serious ecological risks facing migratory birds in NEA, five priority actions are recommended to strengthen science and policy for managing the impacts of energy infrastructure. First, it is critical to expand spatial data collection and cross-border data sharing. Developing a regional avian tracking platform - integrating satellite and GPS telemetry, and systematic surveys including citizen science - will provide the foundation for understanding bird movements across flyway nations in NEA. This shared knowledge is essential for cumulative impact assessment and coordinated flyway-scale planning. Second, all energy projects, especially offshore wind farms, must be assessed for their cumulative and transboundary impacts on migratory bird populations. Current project-level assessments are not enough. Effective cumulative assessment requires integrating data across national borders to evaluate the combined pressures of multiple projects along migration routes, breeding habitats, and staging areas (see Masden 2010 for more details). Third, regulatory frameworks should mandate the use of PVA in Environmental Impact Assessments. PVA provides a population-level perspective on how added mortality or habitat loss may affect long-term species survival. Requiring PVA will improve the scientific credibility of decision-making and help define acceptable risk thresholds for vulnerable species. Fourth, project approvals must include enforceable mitigation and monitoring requirements. Measures such as seasonal turbine shutdowns during peak migration, buffer zones protecting key habitats, and long-term post-construction monitoring must be mandatory. These steps ensure that predicted impacts are verified and that adaptive management can be applied to prevent unexpected harm. Finally, proactive regional collaboration is essential. Engagement through mechanisms like the EAAF Partnership can align national policies with flyway-scale conservation goals. Shared research, joint policy frameworks, and coordinated management actions will help ensure that energy development proceeds without undermining population in migratory birds.

While tools like spatial analysis, collision risk modeling, and PVA are advancing rapidly, their effectiveness depends on comprehensive, coordinated application across projects, sectors, and borders. By moving from isolated project assessments to integrated flyway-scale planning, NEA countries can deliver both renewable energy expansion and bird conservation. A future where wind energy and migratory birds thrive together is possible - but only with science-based, collaborative action across the region.

Figure 1. (a) Flyway of major migration birds in NEA, (b) Status of energy infrastructure (wind power) around NEA



Source: (a) National Institute of Biological Resource(2015), http://nationalatlas.ngii.go.kr/pages/page_1302.php and (b) Global Energy Monitor, https://globalenergymonitor.org/projects/global-wind-power-tracker/tracker-map/

1.7 Case Study: Analysis of the Space Use of Marine Birds to OWFs in ROK

1.7.1 Introduction

The Ministry of Environment (MoE) in ROK and the Korea Environment Institute (KEI) have spearheaded an initiative to develop comprehensive spatial utilization maps for marine bird populations in the Korean peninsula (Lee et al. 2024, Lee et al. 2023). This undertaking is strategically designed to bolster the environmental review processes associated with the burgeoning offshore wind power sector in the nation. The primary focus of this initiative has been the Black-tailed Gull, a numerically dominant and ecologically significant seabird species within the marine ecosystems spanning around the Korean Peninsula including the YS.

The proactive development of these spatial utilization maps by key governmental and research institutions signifies a crucial step towards integrating robust ecological data into national renewable energy planning frameworks. Note that the map represents where/how marine birds around the Korean Peninsular distributed and occupied as both breeding and non-breeding. This approach reflects a growing recognition of the potential conflicts between energy infrastructure development and wildlife conservation, and it underscores a commitment to evidence-based decision-making for mitigating such conflicts. The selection of a dominant species like Black-tailed Gulls is intended to provide insights that may also serve as an indicator for broader ecosystem responses to environmental change and development pressures. This foundational research is particularly timely, given the accelerated legislative and developmental push for offshore wind energy in ROK, highlighting the necessity for systematic environmental considerations.

Black-tailed Gulls serves as the focal species for this study due to its ecological prominence and widespread distribution. It is a representative seabird that breeds extensively around the Korean Peninsula and is classified as a resident species, commonly observed along all national coastlines and in offshore marine areas throughout the year.

These gulls exhibit colonial breeding behavior, typically establishing breeding sites on uninhabited islands. During the non-breeding season, particularly in winter, they disperse to nearby coastal areas, harbors, and river estuaries to overwinter. Several key breeding colonies of the Black-tailed Gull in ROK are designated as Natural Monuments, underscoring their conservation significance. These include i) Hongdo Island, Tongyeong City, Gyeongsangnam-do Province (Natural Monument No. 335), ii) Chilsando Island, Yeonggwang-gun County, Jeollanam-do Province (Natural Monument No. 389), and iii) Nando Island, Taean-gun County, Chungcheongnam-do Province (officially recognized as "Breeding Ground of Black-tailed Gulls on Nando Island, Taean"). A group of islands in Ongjin-gun County, Incheon Metropolitan City, collectively designated as Natural Monument No. 360, which includes Sindo Island, Dongmando Island, Seomando Island, Gujido Island, and Baengnyeongdo Island. Baengnyeongdo Island, in particular, is noted for its importance as a seabird breeding site (Lee and Lee, 2023, Lee et al. 2005).

The reproductive biology of Black-tailed Gulls is characterized by a typical clutch size of 1-3 eggs. The incubation period lasts approximately 25 days, and chicks fledge, or become capable of flight, around 37-43 days after hatching. Individuals generally reach sexual maturity at the age of three years. The average lifespan of a Black-tailed Gull is approximately 30 years, although some individuals have been recorded to survive for over 60 years (Kwon 2004).

As a common, widespread species with numerous legally protected breeding sites, its population dynamics and spatial ecology can serve as an important indicator for the health of coastal and marine ecosystems. Potential impacts on this species from offshore developments could signal broader ecological disturbances. Furthermore, its relatively long lifespan and delayed sexual maturity mean that adult survival rates are critical for maintaining stable populations; thus, any new sources of anthropogenic mortality, such as collision with wind turbines, are of particular concern. The preference for uninhabited islands as breeding sites also renders these colonies sensitive to human disturbances, including those stemming from the construction and operational phases of nearby marine infrastructure

1.7.2 Methods

(a) Methodology for GPS-based Tracking

This research commenced in June 2021, involving the deployment of GPS-based tracking devices on a total of 159 adult Black-tailed Gulls. The tagging operations were conducted across eight distinct breeding islands distributed nationwide, providing a comprehensive geographical scope for the study (Lee et al. 2023).

To minimize disturbance and potential stress to the birds, particularly during the sensitive breeding season when external stressors can lead to nest abandonment (Yorio and Boersma 1992), individuals were captured using clap traps. The handling protocol was designed to be efficient, with the entire process of weighing, measuring, and attaching the GPS device completed within 30 minutes for each bird. Throughout this process, birds were kept in specialized bird bags, which covered their eyes to reduce visual stimuli and help maintain a calm state.

Considerable attention was given to the potential impact of the tracking devices on the birds. It is well-documented that the additional weight of GPS trackers can increase a bird's energy expenditure and impose a physical burden (Pennycuick et al. 1989, Kenward 2000, Vandenabeele et al. 2012). This factor is especially critical for breeding seabirds like the Black-tailed Gull, which undertake numerous foraging trips between their breeding colonies and marine feeding areas to provision their chicks. Any reduction in flight efficiency or increase in energy consumption due to the trackers could potentially compromise their breeding success. While general ornithological guidelines often suggest that the weight of tracking devices should not exceed 3-5% of the bird's body mass, this study adhered to a more conservative threshold, ensuring that the devices used were within 2-3% of the individual's body weight, thereby minimizing potential adverse effects.
The GPS tracking devices were programmed with specific data acquisition protocols. The default setting recorded location coordinates (latitude and longitude), altitude, and flight speed at 30-minute intervals. To capture finer-scale movement details during active flight, a "booster mode" was implemented. This mode was automatically activated when the device's sensors detected flight, increasing the frequency of location coordinate acquisition to every 10 seconds. This dual-mode approach optimizes battery life while ensuring high-resolution data capture during periods of significant movement.

As of December 2023, data from 55 individuals were still being reliably received, with these birds confirmed to be alive and their trackers functioning stably. This represents an overall tracker retention and device operational success rate of 34.6% over a 2.5-year period. While this rate may appear modest, it is a significant achievement for long-term seabird tracking studies, which often face challenges related to device durability, battery longevity, feather molt leading to device loss, and natural mortality of the tracked individuals. The resulting dataset, even from this subset of the initially tagged cohort, provides an invaluable long-term perspective on the species' spatial ecology. The substantial initial sample size (159 birds) and the extended tracking duration (2.5 years) contribute to the robustness of this dataset for understanding year-round habitat utilization and inter-annual variations in movement patterns (Lee et al. 2024). The explicit measures taken to minimize stress and device weight reflect a commitment to ethical animal research practices.

Table 5. Summary of GPS-Tagged Black-tailed Gulls and Data Retention

Parameter	Value
Number of Breeding Islands Surveyed	8
Total Individuals Tagged	159
Individuals with Transmitting Trackers (Dec 2023)	55
Overall Tracker Retention/Operational Rate	34.6%
Study Duration for Retention Calculation	2.5 years

(b) Analytical Approach: Kernel Density Estimation (KDE)

The substantial volume of location coordinate data collected from the GPS trackers was subjected to spatial analysis using Geographic Information System (GIS) software to perform Kernel Density Estimation (KDE). The KDE method, first introduced into the field of ecology by Worton (1989), has since become one of the most widely adopted and robust techniques for estimating the home range and spatial utilization patterns of animals (Péron 2019).

KDE is a non-parametric statistical method used to estimate the probability density function of a random variable. In the context of animal movement ecology, it analyzes the distribution of recorded location data points to identify areas of concentrated use. The output of KDE quantifies the intensity of an animal's space use, illustrating how frequently specific areas are visited or occupied by the target species (Liu et al. 2018, Moskat et al. 2019, Campion et al. 2020).
The primary output generated from KDE is a Utilization Distribution (UD). The UD is a probability surface that represents the likelihood of finding an animal at any given point within its range. This continuous surface is typically visualized and summarized using contour lines, also known as isopleths, which delineate areas encompassing specific percentages of the animal's activity. For this study, UD isopleths were generated at 99%, 95%, and 50% probability levels. These specific percentages are commonly used in ecological research to define different scales of habitat use (Lee and Lee, 2022).

Based on these UD isopleths, habitat areas were classified as core and general habitat areas. The Core area enclosed by the 1-50% UD isopleth is generally classified as the core habitat or core use area. This represents the region where the animal concentrates a significant majority of its time and activities. The General habitat area between the 51% and 99% (or often 95%) UD isopleths is classified as the general habitat area, representing regions used less intensively but still forming part of the animal's overall home range.

The selection of KDE as the analytical method, along with the specific UD isopleth percentages (99%, 95%, and 50%), signifies a methodological intent to move beyond simply mapping the maximum extent of an animal's movements. Instead, it aims to identify and differentiate areas based on the intensity of their use. This distinction between core and general habitat areas is of paramount importance for developing targeted and effective conservation and management strategies, particularly when evaluating the potential impacts of fixed-location infrastructure, such as offshore wind turbines. The identification of core habitats is critical because these areas are likely essential for survival and reproductive success, encompassing key foraging grounds, roosting sites, and areas adjacent to breeding colonies.

Table 6. Classification of Habitat Use Based on Kernel Density Estimation (KDE) Isopleths

KDE Isopleth Percentage	Classification	Description of Significance
1-50%	Core Habitat Area	Represents areas of highest use intensity, critical for daily survival and key activities.
51-95%	General Habitat Area	Represents areas regularly used but with less intensity than core areas; part of home range.
95-99%	Extended Range	Represents the outer limits of space use, including occasional excursions.

1.7.3 Results

(a) Comprehensive Tracking Data and Regional Movement Patterns

The complete dataset of GPS tracking records, as illustrated in Figure 2, reveals that Black-tailed Gulls originating from breeding colonies dispersed across the Korean Peninsula exhibit extensive utilization of the broader marine region in NEA. This area serves them for critical life-history functions including breeding, foraging, and wintering.

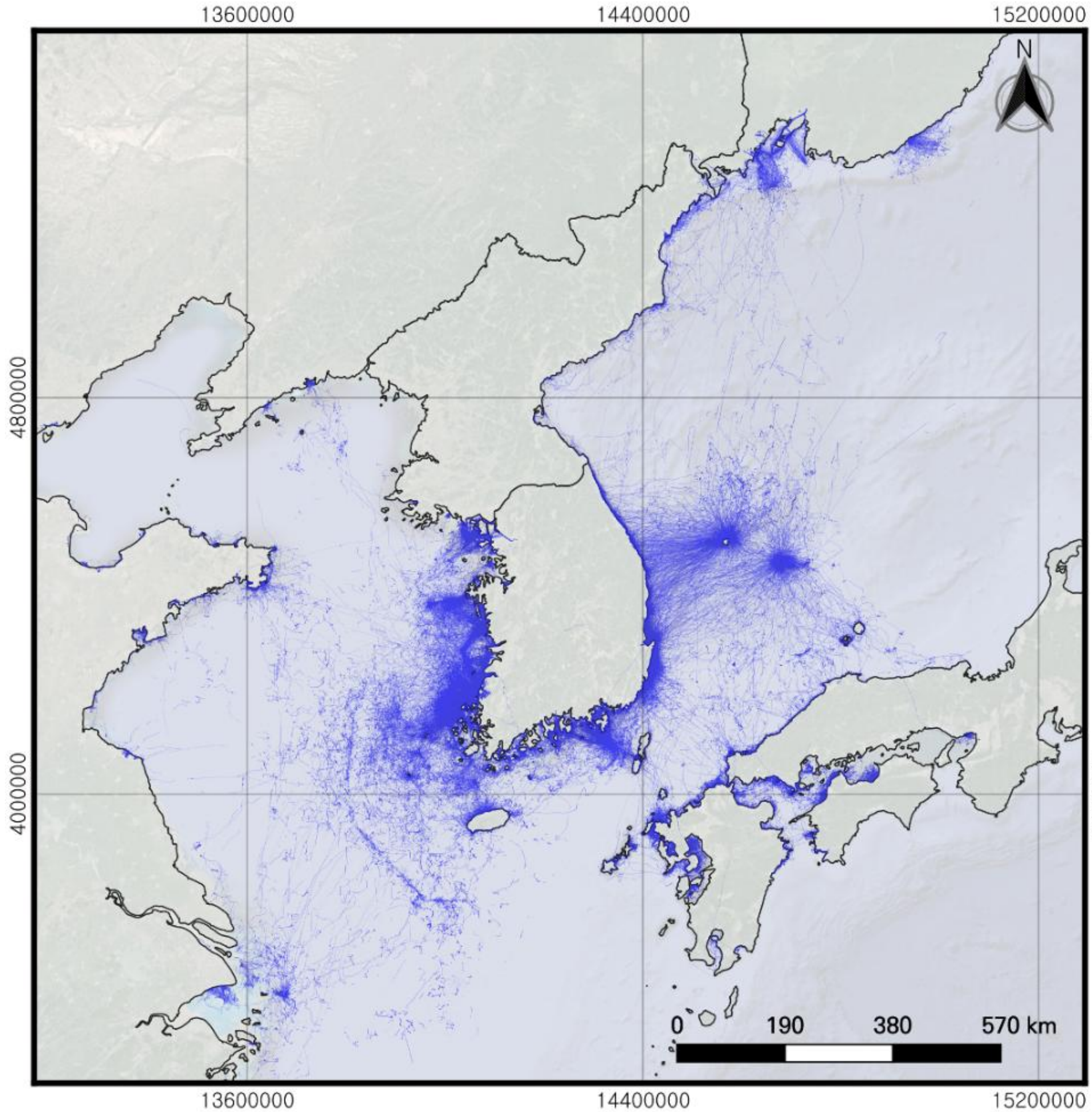
Black-tailed Gulls breeding on Ulleungdo and Dokdo, islands situated in the East Sea, demonstrated a consistent pattern of using the eastern coastline of the Korean Peninsula, from Sokcho in the north to Ulsan in the south, as their primary foraging grounds during the breeding season. As winter approaches, these populations undertake migrations, moving towards the South Sea of Korea and extending to the southern regions of Japan to overwinter.

The gulls breeding on Hongdo Island, located in the South Sea, were found to utilize the entire South Sea coastal region of Korea. Post-analytical review of the tracking data indicated that some individuals from this population also made excursions to Japanese waters, suggesting a degree of international connectivity.

The YS as the West Sea is characterized by a high density of islands serving as breeding sites for Black-tailed Gulls. The tracking data showed that these gulls consistently utilize their island breeding colonies and the adjacent rich intertidal flats and estuarine ecosystems. These coastal wetlands serve as crucial foraging areas throughout the year and also as important wintering grounds for local populations. Following the breeding season, gulls from colonies in the YS were observed migrating to nearby tidal flats for overwintering, with some individuals undertaking longer-distance movements to coastal regions of China and Taiwan.

A noteworthy pattern emerged from the tracking data - a high concentration of Black-tailed Gulls along the maritime boundary demarcating the Exclusive Economic Zones (EEZs) of the ROK and China. This spatial clustering is strongly presumed to be linked to the activities of fishing fleets in the area, with gulls likely attracted to readily available food sources such as fishery discards. This opportunistic foraging behavior, where gulls follow fishing vessels, has been documented in other studies of Larus species and highlights an important anthropogenic influence on their distribution.
In terms of overall marine space utilization, Black-tailed Gulls in the YS region displayed a pattern of broad and relatively even use of the available marine habitats. In contrast, populations breeding on Ulleungdo and Dokdo in the East Sea exhibited a more constrained spatial distribution, primarily focusing their foraging and other activities along the Korean coast. These populations in East Sea showed limited tendencies for long-distance flights into the open sea towards Hokkaido, Japan.

Figure 2. GPS tracking points of Black-tailed Gulls for 2021-2023 in ROK



Source: Lee et al. (2024)

These results indicate distinct regional strategies in habitat utilization among Black-tailed Gull populations. Gulls from East Sea colonies appear to be more coastally restricted in their post-breeding dispersal compared to their counterparts in the YS, which engage in more extensive international movements. The observed congregations near EEZ boundaries underscore the significant influence of anthropogenic food subsidies derived from fisheries on gull distribution. This reliance may alter natural foraging behaviors and create zones of heightened interaction and potential conflict with human maritime activities. Such areas of high gull density, driven by fishing activities, could also coincide with locations considered for offshore infrastructure development, thereby increasing the potential for interactions. The movements of some Hongdo, South Sea individuals to Japan further highlight a level of international connectivity that might not be apparent from traditional, non-tracking-based observational methods.

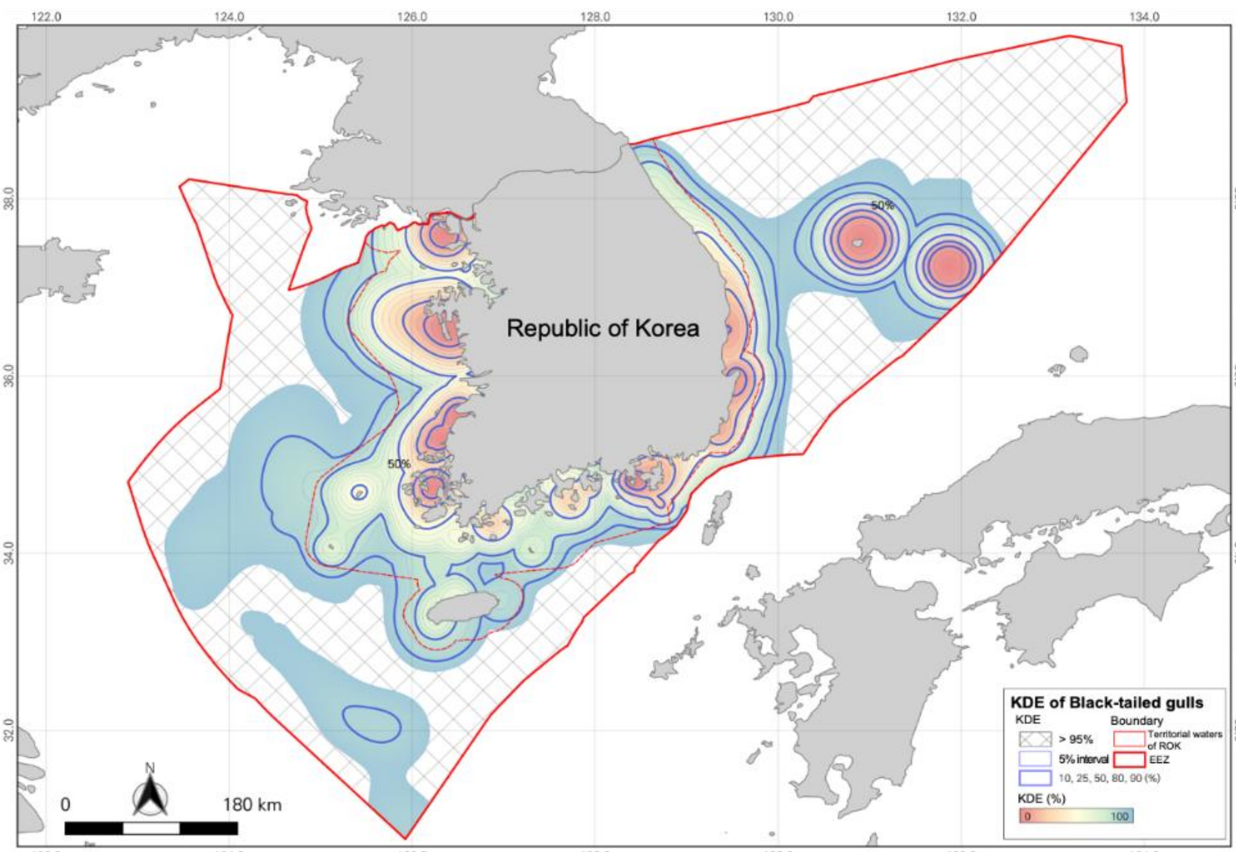
Table 7. Overview of Endangered Avian Species with Spatial Overlap with Black-tailed Gull Core Habitats

Common Name	Scientific Name	Nature of Overlap with Black-tailed Gull Core Habitats (KDE 50%)
Black-faced Spoonbill	Platalea minor	Shares colonial breeding sites; shared foraging areas
Chinese Egret	Egretta eulophotes	Shares colonial breeding sites; shared foraging areas
Far Eastern Curlew	Numenius madagascariensis	Utilizes shared foraging areas (e.g., tidal flats) as stopover sites
Bar-tailed Godwit	Limosa lapponica	Utilizes shared foraging areas (e.g., tidal flats) as stopover sites
Grey Plover	Pluvialis squatarola	Utilizes shared foraging areas (e.g., tidal flats) as stopover sites

(b) Habitat Utilization Patterns from KDE Analysis

KDE analysis, with results depicted in Figure 3, provided a quantitative assessment of habitat utilization intensity, confirming and refining the general movement patterns. The KDE results clearly indicate that Black-tailed Gulls primarily concentrate their activities in and around tidal flats, coastal zones, and the immediate vicinities of their major breeding islands.

Figure 3. Results of Kernel Density Estimation (KDE) of Black-tailed gulls in ROK for 2021-2023



Source: Lee et al. (2024)

In coastal regions where extensive natural tidal flats are absent, the gulls exhibited a tendency to congregate in and around port areas. This behavior is likely driven by the availability of anthropogenic food sources, such as discards from fishing activities within harbors and refuse from human settlements, demonstrating their adaptability to resource availability.

An example of extended marine habitat use was observed for the population breeding on Nando Island in Chungcheongnam-do Province. For these gulls, the calculated home range, based on KDE, extended significantly far into the open sea, indicating that even populations breeding on relatively coastal islands can have substantial offshore marine footprints.

Regarding the extent of home ranges relative to national maritime boundaries, distinct patterns were observed in NEA including YS, South Sea and East Sea aroung the Korean Peninsular. In the YS and South Sea, the KDE results revealed that the vast majority of the 90% UD home range for Black-tailed Gulls was contained within the territorial waters of the ROK. A notable exception was observed in the waters near Heuksando Island (Jeollanam-do Province), where the home range extended more prominently into international waters. In contrast, the home range (presumably the 90% UD) of Black-tailed Gulls breeding in the East Sea encompassed a considerably larger area that extended more significantly beyond Korean territorial waters compared to the patterns observed in the YS or South Sea.

The KDE results effectively translate the raw tracking data into probabilistic maps of space use, highlighting areas of differential importance. The finding that most activity for populations in the YS and South Sea occur within Korean territorial waters (with the specific exception near Heuksando) has direct implications for national-level environmental management and the geographical focus of Environmental Impact Assessments (EIAs). Developments proposed within these national waters are more likely to interact with these specific gull populations. The Heuksando exception suggests this area may function as a critical international corridor, a significant transboundary foraging zone, or an area with unique oceanographic features attracting gulls. The more extensive international range of the gulls in the East Sea reinforces their broader marine habitat utilization, necessitating considerations for transboundary cooperation if offshore developments are planned near maritime borders. The Nando Island in the YS case, with its far-reaching offshore movements, serves as a caution that even populations breeding relatively close to the mainland can exploit distant marine resources, complicating simple assumptions about their spatial limitations.

(c) Spatial Overlap with Endangered and Target Species in Birds

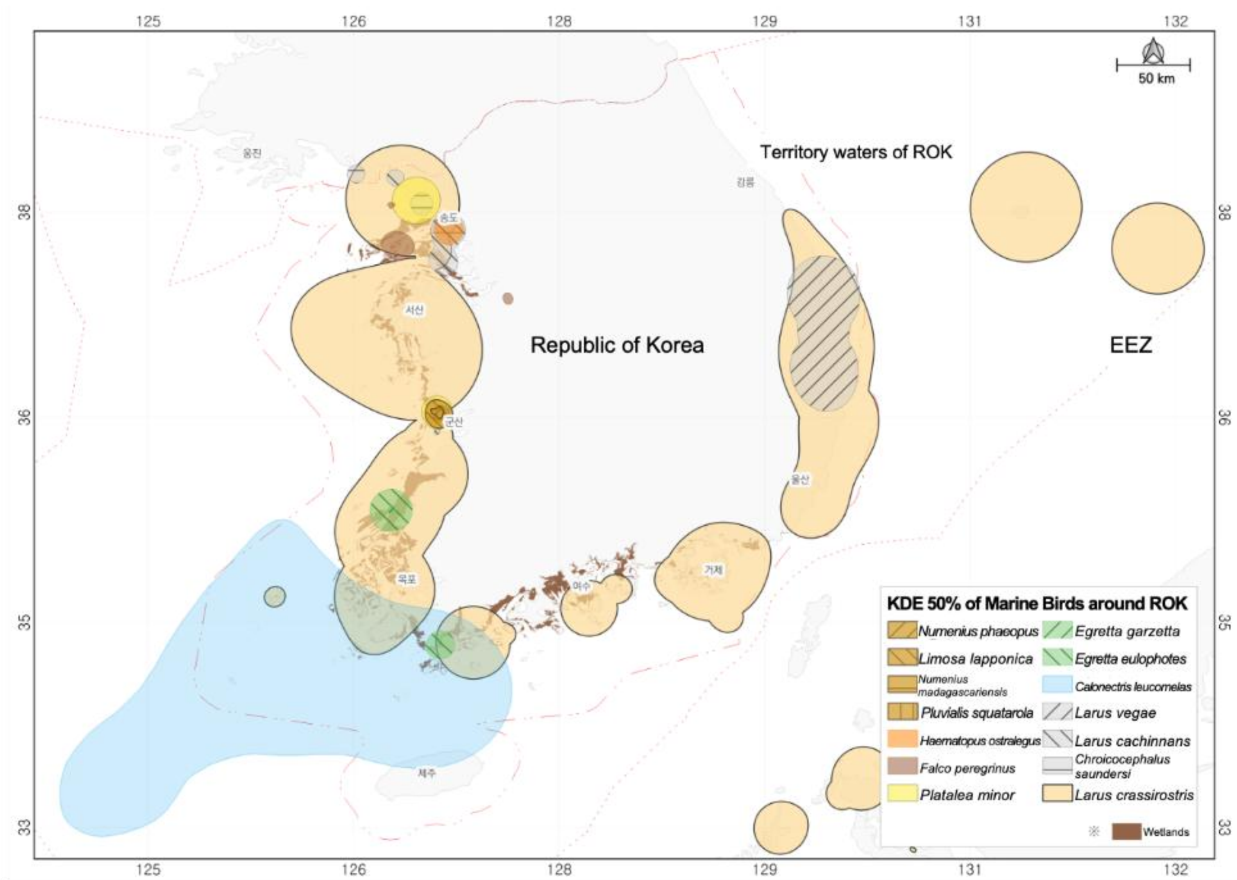
Fig. 4 presents the results of KDE analyses performed for several endangered species in birds whose habitats are known to share with those of Black-tailed Gulls. This comparative spatial analysis yields significant insights for multi-species conservation planning.

The study identified two categories of endangered species exhibiting spatial congruence with Black-tailed Gulls. Firstly, Black-faced Spoonbills and/or Chinese Egrets (*Egretta eulophotes*) breed with Black-tailed gulls colonially to share the same breeding habitats forming mixed-species colonies. Second, many migratory birds including Far Eastern Curlew, Bar-tailed godwit and Grey Plover (*Pluvialis squatarola*) share primary foraging areas as stopover sites. These species rely on the same coastal foraging grounds, particularly tidal flats, that are frequented by Black-tailed Gulls during their migratory journeys.

A key finding from this comparative KDE analysis is that the core habitat areas (defined by the KDE 50% isopleth) of these aforementioned endangered species were found to be entirely encompassed within the KDE 50% core habitat areas identified for Black-tailed Gulls.

Overall, this high degree of spatial overlap in core habitat use carries substantial implications for conservation. It strongly suggests that the home range data derived from tracking Black-tailed Gulls can serve as a reliable proxy for identifying critically important habitats for these co-occurring endangered species. This finding elevates the conservation value of Black-tailed Gull tracking data beyond a single-species focus. It implies that measures taken to protect or mitigate impacts within the core habitats of Black-tailed Gulls are likely to confer significant conservation benefits to a suite of other species of conservation concern. Such spatial congruence points towards

Figure 4. Spatial Overlap (KDE 50%) with Endangered and Target Species in Birds



Source: Lee et al. (2024)

1.7.4 Discussion

(a) Considerations for Environmental Impact Assessment (EIA) of Offshore Wind Farms

The findings of this study carry significant implications for the methodologies employed in EIAs concerning OWF developments and their effects on marine birds. The EIA process, encompassing baseline ecological surveys, impact prediction, and mitigation strategy formulation, must exhibit inherent adaptability to the unique ecological characteristics of each proposed site. This is particularly crucial for offshore wind projects, which encounter a far broader spectrum of spatial and ecological variability compared to their terrestrial counterparts. This variability necessitates context-specific baseline surveys and impact analyses, moving beyond standardized approaches. A clear, ecologically relevant categorization of OWF projects based on their spatial attributes is therefore essential for effective environmental management.

Based on spatial characteristics, OWF projects can be broadly categorized as: coastal proximity projects, island-based projects, and true offshore projects. The potential impacts on populations in marine birds vary accordingly. Nearshore or island projects are more likely to directly affect critical foraging and resting habitats, potentially causing displacement or resource access loss. Offshore projects, conversely, may primarily interact with migratory pathways or pelagic foraging and dispersal areas, posing risks like barrier effects or collision mortality during transit. These distinct spatial impact profiles demand meticulous consideration within the EIA process, influencing target species selection, monitoring program design, and impact severity prediction.

A critical point highlighted is the inadequacy of certain current practices for predicting impacts on highly mobile species like birds. Migratory bird route data, often aimed at understanding long-distance migration, may suffer from infrequent location data collection due to GPS device limitations, resulting in linearized flight path representations (see Schaub et al. 2023 for more details). Simple overlap analysis between these generalized routes and wind farm footprints is an oversimplification, failing to capture the three-dimensional space use and fine-scale interactions of birds with their environment.

This study advocates for a more ecologically robust impact assessment approach, shifting from linearized pathways to analyzing actual habitat space use derived from comprehensive tracking data. This involves generating probabilistic space use models, such as KDE-derived home ranges, and evaluating spatial overlap with identified core habitat areas (e.g., the KDE 50% isopleth). This area-based, probabilistic approach is particularly relevant in the relatively featureless open marine environment, where large artificial structures like wind turbines can create significant anthropogenic barriers or collision hazards, profoundly affecting seabird habitat use and movement patterns. This represents a move towards more scientifically defensible and ecologically meaningful EIA practices, challenging less rigorous methodologies and promoting data-intensive approaches for a more accurate reflection of potential environmental risks.

(b) Contribution to Policy and Conservation

This study was explicitly designed to contribute substantively to environmental policy and marine bird conservation in ROK. Key objectives included acquiring high-resolution spatial data for Black-tailed Gulls and other potentially affected, including endangered, avian species. This involved tracking bird movements and surveying populations within known core habitats. The ultimate goal is to establish a scientifically robust siting information map for strategic OWF placement and a comprehensive spatial database for marine birds. Such a database is envisioned as a critical tool for resolving conflicts arising from the environmental impacts of offshore wind power, a vital sector for national carbon neutrality, and for informing national renewable energy environmental policy development.

Preliminary analyses of other tracked avian groups, such as shorebirds and falcons, revealed high site fidelity to breeding or stopover locations within ROK, suggesting energy conservation strategies during migration. This site fidelity underscores the vulnerability of these locations to localized disturbances.

Despite the study's advancements, significant knowledge gaps remain regarding migration routes, critical stopover sites, and core habitat areas for many endangered marine bird species in the area of sea around ROK. This data deficit highlights the urgent need for continued, long-term research investment in marine bird spatial ecology and migration studies to ensure effective protection amidst accelerating OWF development. Future research should leverage detailed data (spatial coordinates, flight altitudes, fine-scale movements) for sophisticated impact assessments, including refined collision risk models and barrier effect analyses, to inform complementary solutions for wind farm siting that balance renewable energy targets with biodiversity conservation. This pragmatic approach aims for coexistence through data-driven site selection, operational mitigation, and potentially strategic compensatory measures, positioning the research as a direct contributor to sustainable development objectives.

(c) Methodological Strengths and Limitations of the Current Study

This study is part of a larger, ongoing, multi-year project addressing data deficiencies regarding spatial utilization patterns in marine birds relevant to wind energy development. Previous monitoring efforts in ROK usually focused primarily on terrestrial and nearshore environments, creating a knowledge gap in offshore areas targeted for new wind projects. This study, initiated in 2021, directly addresses this gap by tracking marine bird species with potential habitat and movement corridor overlap with planned or operational offshore wind farms.

The findings presented are interim, based on ongoing monitoring within a two-year data collection window for many individuals. While providing valuable insights, they should not be considered definitive. Comprehensive outputs will be developed upon full dataset incorporation and analysis in subsequent project phases.

Despite its interim status, the study's methodological foundations are robust, utilizing GPS tracking technology and standard spatial ecology analytical techniques like the KDE. A significant strength lies in its ambitious scale, involving large-scale, simultaneous tracking across numerous breeding islands and stopover sites, a relatively uncommon undertaking even internationally, highlighting the pioneering nature of this Korean initiative.

Internationally, marine bird monitoring related to offshore wind has a longer history, evolving from ship-based visual surveys to increasingly incorporating GPS tracking for detailed individual movement data (Quéroué et al. 2024). Given the anticipated extensive offshore wind development around the Korean Peninsula, GPS tracking is a pertinent and efficient methodology for studying bird distribution and movement from key breeding and stopover areas, offering relatively rapid analyses of marine spatial use over large geographical areas, which can be challenging with ship-based surveys alone.

The large-scale, simultaneous tracking effort, despite current limitations in analyzed species and tracking duration for some individuals, holds considerable national and international significance, providing a valuable baseline and methodological template for future work. Subsequent research phases must build upon this foundation by incorporating advanced assessment techniques, particularly sophisticated collision risk modeling, to translate spatial data into actionable guidance for wind farm planning and mitigation. Transparency regarding the study's ongoing nature and limitations is crucial for appropriate interpretation of current results and for setting the stage for more comprehensive future outputs.

(d) Robustness of Findings: Inter-annual Consistency

A critical component of this research involved analyzing inter-annual variability to assess the reliability of observed spatial use patterns. Comparing spatial use metrics from the first and second years of tracking data for the same individuals or cohorts revealed no statistically significant differences in the utilization of important, high-use areas by Black-tailed Gulls.

This inter-annual consistency in key habitat use lends considerable robustness to the study's conclusions, even at this interim stage, suggesting that identified core areas are persistently important for the species. This consistency enhances confidence in using these spatial data for long-term environmental planning and EIA. However, while core area use demonstrates robustness, the authors acknowledge a limitation in the broader interpretation due to the lack of a comprehensive nationwide survey detailing the scale, population sizes, and geographical attributes of all marine bird breeding islands along the coast of the ROK. This absence of a complete baseline inventory tempers the full interpretative potential of the tracking data, as knowing exact population sizes per colony would allow for more nuanced analyses, such as weighting foraging area importance based on supported bird numbers or exploring source-sink dynamics.

Overall, the results consistently demonstrate the critical importance of colonial breeding sites and associated primary foraging areas for Black-tailed Gulls, aligning with the widespread colonial breeding strategy in marine birds offering benefits like information exchange and collective defense. The KDE 50% core habitat areas identified predominantly correspond to these essential locations: breeding islands, key foraging zones (tidal flats, productive coastal waters), and connecting marine corridors. While the importance of these breeding-season core areas remained statistically consistent between years, the study noted changes in the spatial distribution and significance of areas utilized during the post-breeding dispersal phase, an expected ecological pattern as birds disperse more widely after the constraints of central-place foraging.

2 Scenario Analysis

2.1 Review of the Methodology for Analysis of Bird Population from Energy Development

As global energy demands rise alongside climate mitigation imperatives, energy developments have expanded rapidly across terrestrial and marine landscapes. These changes present new and complex conservation challenges for migratory birds, which rely on extensive networks of habitats across their annual cycles (Torstenson et al. 2024). To accurately assess the ecological consequences of these developments, a range of scientific methodologies have been developed, encompassing individual movement tracking, population-level impact quantification, rigorous impact assessment designs, predictive modeling, and cumulative effects evaluations.

2.1.1 Tracking and Monitoring Individual Movements: Revealing Exposure and Behavior

Advances in tracking technologies have revolutionized the study of migratory birds, moving beyond traditional banding methods that offered limited spatial and temporal data. Satellite telemetry, using Platform Transmitting Terminals (PTTs), has long facilitated real-time tracking of large-bodied species over continental scales (Gould et al. 2024, Hardin et al. 2024). These devices provide critical insights into migratory connectivity, flight routes, and mortality locations. However, their size and cost restrict their use to larger species capable of carrying the additional weight without compromising survival or behavior.

GPS tracking has provided a transformative leap in accuracy and resolution, allowing for the documentation of fine-scale movements. The miniaturization of these devices now enables tracking of medium-sized species, with data transmitted via cellular or satellite networks. Meanwhile, for smaller species, light-level geolocators have enabled researchers to estimate broad-scale movements based on daylight cycles. While these devices require recapture to retrieve data and have lower spatial precision, they have significantly expanded knowledge of small passerine migrations.

Automated radio telemetry networks, such as the Motus Wildlife Tracking System, further support regional-scale monitoring by detecting tagged birds as they pass receiving stations (Bird Canada 2022, Motus Docs 2023). These systems are particularly effective for tracking smaller birds over large areas. Radar technologies, including repurposed weather surveillance systems, provide additional capacity to monitor the scale, speed, and altitude of nocturnal migrations, offering landscape-level perspectives on movement patterns.

Combining these technologies allows researchers to map migratory routes, identify critical habitats, and assess bird exposure to energy infrastructure. Analytical methods such as home range analysis, resource selection functions, and step-selection models are employed to quantify habitat use and behavioral responses. Trajectory analyses help detect flight deviations, informing assessments of barrier effects and collision risks. The integration of multiple data sources enhances the ecological relevance and spatial resolution of impact assessments, moving towards a comprehensive understanding of species-specific and flyway-scale risks.

2.1.2 Population-Level Assessments: Abundance, Mortality, and Displacement

While tracking provides insights into individual exposure, assessing population-level consequences requires robust data on abundance, survival, and habitat use. Long-term monitoring programs (e.g., the North American Breeding Bird Survey) offer valuable baselines for detecting trends and contextualizing localized impacts. Field methods including point counts, transect surveys, and distance sampling are widely used to estimate densities and detect changes in bird communities in response to development.

Mortality estimation, particularly from collisions with wind turbines and power lines, is a critical component of impact assessment. Carcass searches are standard practice, but raw counts underestimate true mortality due to searcher detection inefficiency, carcass scavenging, and limitations in search area coverage (e.g., Ponce et al. 2010. Bias correction trials are therefore essential, involving controlled experiments to quantify detection probabilities and carcass persistence. Without these corrections, mortality estimates risk severe underestimation, misleading conservation and management decisions.

Displacement, or the avoidance of habitats near infrastructure, represents a more subtle but potentially more extensive impact. Occupancy modeling helps quantify shifts in habitat use by comparing pre- and post-construction presence or absence data. Habitat suitability models further assess changes in the availability and quality of suitable habitats. Studies have demonstrated significant displacement effects, such as marked reductions in bird abundance within operational wind farms, underscoring the need to consider both direct and indirect impacts in population-level assessments.

2.1.3 Rigorous Impact Assessment Designs: Enhancing Scientific Validity

Reliable impact assessments require well-designed studies that isolate the effects of energy developments from natural environmental variability. The Before-After-Control-Impact (BACI) design is recognized as one of the most robust methodologies for this purpose. By comparing ecological conditions before and after development at both impact and control sites, BACI helps distinguish project-specific effects from broader environmental fluctuations (Smith et al. 1993, Downes 2010). Multiple years of pre-impact data collection are recommended to establish reliable baselines.

Gradient-based designs, such as Before-After-Gradient (BAG) and Impact-Gradient (IG), offer alternative frameworks for assessing spatial responses to development (Methratta 2020, Smith and Dwyer 2016, Methratta 2021). These designs analyze bird responses along distance gradients from infrastructure, providing spatially explicit insights into impact zones.

However, implementing these designs poses challenges, including logistical complexity, cost, and the difficulty of identifying suitable control sites. Variability in environmental conditions across regions can confound results, highlighting the importance of careful site selection and statistical rigor. Nonetheless, these designs remain essential for scientifically defensible impact assessments.

2.1.4 Predictive Modeling and Analytical Integration: Linking Impacts to Population Dynamics

Mathematical modeling plays a critical role in translating observed impacts into population-level forecasts. Integrated Population Models (IPMs) combine multiple data sources, such as abundance surveys, survival estimates, and reproductive data, into cohesive demographic frameworks (Schaub and Abadi 2011, Besbeas et al. 2002, Abadi et al. 2010). These models improve parameter estimates and allow researchers to assess the relative contributions of different vital rates to population trends. By simulating how changes in survival or reproduction affect overall population trajectories, IPMs provide powerful tools for understanding the ecological significance of observed impacts.

Population Viability Analysis (PVA) is another widely used approach for projecting future population trends under different impact scenarios (Boyce 1992, Beissinger and McCullough 2002, Morris and Doak 2002, IUCN SSC Standards and Petitions Committee 2022). PVAs incorporate demographic data, environmental variability, and stochastic events to estimate extinction probabilities and population growth rates. These models are particularly useful for evaluating the sustainability of additional mortality or habitat loss, guiding regulatory decisions on acceptable impact thresholds. However, the reliability of PVAs depends on the quality of input data and should be interpreted as providing relative, rather than absolute, forecasts.

The Avian-Impact Offset Method (AIOM) offers a habitat-based framework for translating displacement impacts into compensatory mitigation requirements (Shaffer et al. 2019). By quantifying the number of displaced bird pairs and converting this into offset habitat needs, AIOM provides a standardized approach to habitat compensation. This method has been applied in various contexts, including wind and solar energy developments, supporting the implementation of ecological offsets as part of impact mitigation strategies.

2.1.5 Cumulative Effects Assessment: Moving Beyond Project-Specific Evaluations

Migratory birds experience cumulative pressures across their entire life cycles, including habitat loss, pollution, climate change, and multiple infrastructure developments. Recognizing this, cumulative effects assessment (CEA) seeks to evaluate the combined impacts of multiple projects and stressors at regional or flyway scales (Therivel and Ross 2007, King et al. 2020, United States Council on Environmental Quality 1997, EAAFP 2022, Bond and Morrison-Saunders 2016).

CEA methodologies include spatial analyses that overlay species distributions with development footprints, identifying areas of concentrated risk (Masden and Cook 2016, Tulloch et al. 2018, Seitz et al. 2011). Modeling approaches link landscape change projections with species distribution and population models, enabling scenario-based forecasting of cumulative impacts. Extrapolation methods, using site-specific data to estimate broader regional effects, are also commonly employed, though they rely on assumptions about representativeness and transferability.

Despite methodological advancements, CEA faces significant challenges. Data gaps, scale mismatches, and uncertainties about interaction effects complicate assessments. Nonetheless, moving towards strategic, landscape-scale evaluations is essential for safeguarding migratory bird populations. Integrating CEAs into national and transboundary planning frameworks can help reconcile energy development with biodiversity conservation, ensuring that cumulative impacts are adequately considered in decision-making processes. The following Table 8 provides a comparative overview of key research methodologies discussed in this section.

Table 8. Comparative Overview of Key Research Methodologies for Assessing Energy Impacts on Migratory Birds

Methodology	Brief Description	Key Applications in Energy-Avian Impact Assessment	Strengths	Limitations/ Challenges
GPS/Satellite Tracking (PTTs, GPS tags)	Attaching electronic devices to birds to record or transmit precise location data over time.	Identifying migration routes, stopover sites, flight altitudes near infrastructure; assessing avoidance/attraction, habitat use changes; determining mortality locations.	High accuracy (GPS); near real-time data (transmitting tags); can track long distances and full annual cycles for appropriately sized species. Miniaturization expanding use.	Cost; tag size/weight limits use on smaller species; battery life; potential effects of tag on bird behavior/survival; data retrieval for archival tags.
Light-Level Geolocators	Small archival tags recording ambient light levels to estimate geographic location based on day length/solar noon.	Tracking broad-scale migration routes and wintering locations of small birds, especially songbirds, over full annual cycle.	Very small and lightweight, suitable for smallest migrants; relatively inexpensive.	Lower accuracy than GPS; requires tag recapture to retrieve data; data processing can be complex.
Motus Wildlife Tracking System	Network of automated radio telemetry stations detecting small, digitally-coded tags on passing animals.	Tracking regional to continental movements, passage rates, stopover duration, and survival along migration routes for small tagged birds.	Enables tracking of very small species; collaborative network infrastructure; relatively low tag cost allows larger sample sizes.	Detection range limited (few km per station); requires birds to pass near a receiver; infrastructure dependent.
Radar Monitoring (Weather, Specialized)	Using radar systems to detect and quantify bird movements in the airspace.	Assessing large-scale migration patterns (timing, intensity, altitude, direction); monitoring bird activity around energy facilities for collision risk assessment.	Can monitor large volumes of airspace; detects nocturnal migrants; non-invasive.	Difficulty in species identification; ground clutter can interfere; weather effects; specialized radar can be expensive.
Standardized Population Surveys (e.g., BBS)	Systematic, repeated bird counts over large areas using standardized protocols.	Providing baseline population trend and distribution data; contextualizing local impacts; use in BACI control data.	Long-term datasets; broad geographic coverage; standardized methodology allows trend analysis.	Primarily focused on breeding season for many surveys; may not detect all species well; observer variability.
Carcass Searches & Mortality Estimation	Systematic searches for bird fatalities around energy infrastructure, with adjustments for biases.	Estimating direct collision mortality rates at wind turbines, power lines, solar facilities.	Provides direct evidence of mortality; established protocols for bias correction.	Labor-intensive; accuracy highly dependent on rigorous, site-specific bias trials (searcher efficiency, scavenger removal); small carcasses easily missed; some fatalities may fall outside search plots.
Before-After-Control-Impact (BACI) Design	Comparing ecological parameters at impact and control sites,	Isolating project-specific impacts (e.g., displacement,	Considered a robust design for impact	Requires adequate pre-impact data (often years); finding

	before and after a development.	abundance changes) from natural variability for various energy types.	assessment; helps establish causality.	suitable control sites can be difficult; long-term commitment and cost; confounding factors can still occur.
Gradient Designs (BAG, IG)	Assessing ecological changes along a gradient of influence from an impact source (e.g., distance from turbines).	Quantifying extent of displacement or other effects at varying distances from infrastructure.	Can reveal spatial patterns of impact; BAG (with 'Before' data) is robust.	IG (without 'Before' data) relies on spatial comparison assumptions; defining the true gradient of impact can be challenging.
Occupancy Modeling	Statistical methods to estimate site occupancy probability while accounting for imperfect detection.	Assessing changes in habitat use/distribution by species in response to energy infrastructure.	Accounts for detection probability, leading to more accurate estimates of presence/use; flexible modeling framework.	Requires repeated surveys to estimate detection; model assumptions need to be met.
Integrated Population Models (IPMs)	Statistical models combining multiple data sources (e.g., counts, survival, reproduction) to estimate demography.	Assessing how energy-related impacts on specific vital rates (e.g., survival, recruitment) affect overall population dynamics and trends.	Improves precision of demographic estimates; can estimate latent parameters; provides holistic view of population drivers.	Data-intensive; complex to develop and implement; requires good understanding of population ecology and different data types.
Population Viability Analysis (PVA)	Modeling population persistence over time under various scenarios, incorporating demographic rates and stochasticity.	Projecting future population trajectories under different energy development scenarios (e.g., varying mortality/habitat loss levels) and assessing extinction risk.	Allows exploration of future scenarios and mitigation effectiveness; incorporates uncertainty.	Highly dependent on quality of input demographic data ("rubbish in, rubbish out"); predictions are relative, not absolute; can be complex; results sensitive to assumptions.
Avian-Impact Offset Method (AIOM)	Tool to quantify habitat-based impacts (displacement) and determine compensatory mitigation needs.	Calculating the amount of offset habitat needed to compensate for bird pairs displaced by energy/transportation infrastructure.	Provides a standardized, biologically-based method for calculating offsets; converts biological loss to land units.	Relies on accurate estimates of displacement from underlying studies (e.g., BACI); effectiveness of offset habitat needs verification.
Cumulative Effects Assessment (CEA)	Analyzing combined, incremental effects of multiple human activities on species/ecosystems over time/space.	Assessing the total impact of multiple energy projects (and other stressors) on regional bird populations or along flyways.	Addresses the bigger picture beyond single project impacts; essential for landscape-scale planning.	Complex; data scarcity; defining appropriate scales; understanding interaction effects; attributing specific impacts within multi-stressor environments. Methodologies still evolving.

2.2 Understanding Population Viability Analysis (PVA) and Its Application to Evaluate Effects of Energy Infrastructure on Bird Population

2.2.1 Background

Bird populations worldwide are increasingly exposed to a range of threats posed by expanding energy infrastructure. Various energy technologies (particularly, wind turbines, solar farms, and extensive networks of power lines) are recognized for their potential to negatively affect bird populations through both direct and indirect mechanisms. Direct mortality is often the most visible impact, resulting from collisions with turbine blades, solar structures, or overhead transmission lines, as well as electrocution at poorly designed power poles. Indirect effects include displacement from critical breeding or foraging habitats due to disturbance or avoidance behavior, functional habitat loss caused by land conversion, and barrier effects that disrupt traditional migratory pathways (Leung and Yang 2012, Drewitt and Langston 2006, Loss et al. 2014, Erickson et al. 2005, Bernardino et al. 2018, Lovich and Ennen 2011). These pressures interact with existing stressors such as climate change, habitat loss, and unsustainable resource use, amplifying the challenges faced by many avian species, particularly those already experiencing population declines.

Here, it is no longer sufficient to rely solely on the documentation of individual fatalities or local habitat changes when evaluating the environmental consequences of energy development. Instead, there is a growing recognition of the need to assess impacts at the population level, quantifying how various threats influence long-term viability and extinction risk. Population Viability Analysis (PVA) has emerged as a scientifically robust tool to meet this need (Brook et al. 2000). As a quantitative method grounded in demographic theory and ecological modeling, PVA provides a structured approach to project future population trajectories, estimate extinction probabilities, and evaluate the potential effects of management interventions.

The purpose of this section is to explain how PVA operates as a population-level assessment framework, with particular focus on its relevance to the evaluation of energy infrastructure impacts on birds. This includes an exploration of the theoretical underpinnings, model structures, data requirements, and practical applications of PVA. Specific attention is given to how PVA can be used to model the demographic consequences of collision mortality, electrocution, displacement, and habitat loss (Hunt 2002, Schaub and Pradel 2004, Bureau of Land Management 2012, Wade 2000, Oro et al. 2014). The section further examines the integration of mitigation measures into PVA and highlights the utility of the method in both single-project and cumulative impact assessments. Finally, the strengths and limitations of PVA as a decision-support tool are critically evaluated.

2.2.2 Understanding Population Viability Analysis (PVA)

PVA is a method designed to assess the likelihood of a species' population persisting over a defined period, typically in the face of identified threats. Central to PVA is the use of mathematical models that simulate population dynamics based on key biological parameters such as survival, reproduction, age structure, and environmental variability (Morris and Doak 2002, Caswell 2001). By projecting these dynamics forward in time, PVA allows scientists and managers to estimate extinction probabilities, forecast population trends, and identify the life stages or ecological processes most influential to persistence.

The foundation of PVA lies in its capacity to incorporate stochasticity, random variation that reflects real world unpredictability (Morris and Doak 2002). This includes demographic stochasticity, which arises from chance events in individual survival and reproduction, and environmental stochasticity, representing year-to-year variability in habitat conditions, food availability, or weather. Many PVAs also include the potential for catastrophic events, such as disease outbreaks or severe storms, which, although rare, can cause population crashes (Caswell 2001, Lande 1993, Melbourne and Hastings 2008). The inclusion of stochasticity ensures that no PVA simply produces a single deterministic outcome, but instead generates a distribution of possible futures, reflecting the uncertainty inherent in ecological systems.

The types of models used in PVA range from relatively simple matrix models, such as Leslie or Lefkovitch matrices, which divide populations into discrete age or stage classes, to highly detailed individual-based models (IBMs) that simulate the fates of individual organisms (Grimm and Railsback 2005, Lacy 1993). Matrix models are often favored for their ability to identify key demographic parameters influencing population growth. IBMs, by contrast, offer greater ecological realism by allowing for variability among individuals and spatially explicit movement across landscapes.

Incorporating density dependence where population growth slows as density increases due to resource limitation is another important feature of advanced PVAs. Some models also consider Allee effects, where very small populations experience reduced growth due to difficulties in mate finding or cooperative behaviors (Courchamp et al. 1999, Dennis 2002, Berec et al. 2007). Regardless of the model type, PVA requires robust input data (Beissinger and Westphal 1998). Key parameters include age- or stage-specific survival and fecundity rates, current population size and structure, habitat carrying capacity, and measures of demographic and environmental variability. The reliability of PVA outcomes depends on the quality of these data. Where data are limited, models can still provide valuable insights through sensitivity analyses that highlight which parameters most influence model outcomes, guiding future research and monitoring priorities.

Table 9. Comparison of Common PVA Model Types

Feature	**Unstructured/Time Series**	**Structured (Age/Stage)**	**Metapopulation**	**Spatially Explicit Individual-Based (SE-IBM)**
Key Characteristics	Models overall population size/trend; Stochastic exponential growth	Tracks numbers in age/stage classes; Matrix models common	Models dynamics of linked subpopulations; Focus on extinction/colonization	Simulates individual fates & movements on detailed landscape maps
Primary Outputs	Overall stochastic growth rate (λ); Extinction probability based on trend variance	Age/stage-specific contributions; λ; Extinction probability; Sensitivity/Elasticity analysis	Metapopulation persistence probability; Occupancy dynamics; Influence of connectivity	Individual trajectories; Patch occupancy; Population persistence; Detailed spatial pattern effects
Core Data Needs	Time series of population	Stage-specific survival & fecundity;	No. of subpopulations;	Patch-specific demography;

	counts/indices; Current size; Variance in growth rate	Initial stage structure; Variance in vital rates	Extinction & colonization rates; Dispersal rates/patterns	Individual movement rules; Habitat map (size, quality, location)
Strengths	Least data demanding; Useful for initial assessment	Analyzes life-stage effects; More biologically detailed than unstructured	Explicitly models spatial subdivision & connectivity; Relevant for fragmented habitats	Highest biological realism; Can model complex behaviors & landscape interactions
Limitations	Ignores age structure, density dependence, spatial effects; Sensitive to data quality	Assumes homogeneity within stages; Data needs higher than unstructured; Often assumes closed population	Often simplifies within-patch dynamics; Dispersal data hard to obtain	Most data demanding; Computationally intensive; Complex to build and validate
Suitability for Energy Impacts	Limited; Best for assessing overall trend impacts if data are sparse	Good for collision/electrocutio n (affects survival); Can model impacts on fecundity	Good for fragmentation effects (habitat loss, barriers); Assessing connectivity impacts	Best for detailed habitat loss/fragmentation, barrier effects, displacement, fine-scale mitigation analysis

2.2.3 Applying PVA to Assess Energy Infrastructure Impacts on Birds

(a) Modeling Direct Mortality from Collisions and Electrocutions

One of the most straightforward applications of PVA is to assess the population-level consequences of direct mortality resulting from energy infrastructure. For example, wind turbines pose a significant collision risk to migration birds such as large soaring birds and seabirds (Drewitt and Langston 2006, Marques et al. 2014, Bernardino et al. 2018). Similarly, power lines can cause both collisions and electrocutions, particularly affecting raptors and other large-bodied species (Lehman et al. 2007, de Lucas et al. 2012). These mortality events, while observable, require population-level modeling to assess whether they are significant enough to influence long-term viability.

In practice, additional mortality is incorporated into PVA by adjusting the survival parameters of the affected age or stage classes. For instance, if monitoring data indicate that OWFs cause the death of an estimated 50 adult birds per year, this number is translated into a reduction in the annual survival probability used in the model. This adjustment allows the model to project how this increased mortality may affect future population trajectories compared to a baseline scenario without the development.

Accurately estimating mortality rates is a critical step. This typically involves data from collision risk models, such as the Band model, which integrate bird flight behavior, turbine specifications, and avoidance rates to predict annual fatalities (Band 2012, Cook and Robinson 2017, Masden 2015, Johnston et al. 2014). Alternatively, empirical data from carcass searches around existing infrastructure can be used, provided that appropriate bias correction factors are applied to account for scavenger removal and searcher detection efficiency.

Notable applications include the use of PVA to assess the impacts of OWFs on kittiwake populations, where predicted collision fatalities were modeled as reductions in adult survival (Cook et al. 2014, Searle et al. 2018). Similar approaches have been applied to assess electrocution risks for species such as Bonelli's Eagles (*Aquila fasciata*) and the Great Indian Bustard (*Ardeotis nigriceps*), demonstrating the utility of PVA in evaluating direct mortality impacts(Dutta et al. 2011, Collar et al. 2017).

(b) Modeling Indirect Effects of Displacement and Habitat Loss

Indirect impacts, such as displacement from foraging or breeding habitats and habitat loss due to land conversion, are more challenging to quantify but can have equally significant population-level consequences (Drewitt and Langston 2006, Pearce-Higgins et al. 2012, Perrow and Skeate 2019, Kiessecker et al. 2011). These impacts may reduce reproductive success, lower survival rates by forcing birds into suboptimal habitats, or reduce the overall carrying capacity of the environment.

In PVA, these effects are typically modeled by adjusting fecundity or survival parameters, or by reducing the carrying capacity (K) in density-dependent models. For example, if displacement reduces the number of breeding pairs in a colony, this can be modeled as a reduction in fecundity. If habitat loss reduces the area available for foraging, K can be lowered to reflect the decreased capacity of the environment to support the population.

While these approaches are conceptually straightforward, they require detailed ecological data to quantify the demographic consequences of displacement or habitat alteration. Such data are often lacking, making these applications of PVA more uncertain than those based on direct mortality.

2.2.4 Evaluating Cumulative Impacts Using PVA

As the development of energy infrastructure intensifies, cumulative impacts (i.e., those arising from multiple projects across a landscape or flyway) become a major concern. PVA is increasingly used within the CEA frameworks to evaluate the combined population-level consequences of multiple developments.

This process involves identifying all relevant projects, estimating their individual impacts, summing these impacts to derive a total cumulative effect, and incorporating this cumulative effect into a PVA model. This allows for the projection of long-term population trajectories under combined pressures, supporting strategic planning and mitigation at the landscape or flyway scale.

However, CEAs face significant methodological challenges. Defining the appropriate spatial and temporal scales, obtaining consistent data across projects, and accurately apportioning impacts to specific populations require sophisticated approaches. Furthermore, simple additive models may overlook synergistic effects or ecological thresholds. Advanced spatially explicit or individual-based PVAs offer potential solutions but require substantial data and computational resources. A key strength of PVA is also its ability to evaluate the potential effectiveness of mitigation measures.

2.2.5 Integrating Mitigation and Conservation into PVA

A key strength of PVA is its ability to evaluate the potential effectiveness of mitigation measures (Fox et al. 2006). This includes siting and design measures to avoid high-risk areas, operational curtailment of wind turbines during peak migration, habitat restoration to offset habitat loss, and collision reduction technologies such as bird flight diverters.

PVA allows practitioners to compare population trajectories under scenarios with and without these mitigation measures, providing a quantitative basis for evaluating their effectiveness. This supports evidence-based decision-making and adaptive management, where monitoring data from implemented projects are used to refine model parameters and improve future predictions (Beissinger and McGullough 2002, Morris and Doak 2002, Williams et al. 2009). Importantly, PVA should be viewed as an iterative tool that evolves as new data become available. Integrating PVA into adaptive management frameworks ensures that conservation actions remain effective in the face of changing conditions and improved scientific understanding.

In summary, while PVA provides a robust framework for assessing the population-level impacts of energy infrastructure on birds, its reliability depends on the quality of input data and the appropriateness of model structures. Ongoing research, monitoring, and methodological development are essential to fully realize the potential of PVA in supporting sustainable energy development and avian conservation.

2.3 Review the target species avaiable for scenario analysis

2.3.1 Migratory Birds in NEA: Suitability for PVA

NEA serves as one of the most ecologically significant regions in the EAAF, providing essential breeding, staging, and wintering habitats for a wide diversity of migratory bird species. Among these, cranes, shorebirds, waterfowl, seabirds, and coastal waterbirds represent key ecological groups of high conservation concern. These species face mounting pressures not only from traditional threats such as habitat loss, land reclamation, and hunting but also from emerging drivers including climate change and large-scale renewable energy infrastructure, particularly offshore wind energy (MacKinnon et al. 2012, Kiesecker et al. 2011). Understanding their population-level responses to these threats through Population Viability Analysis (PVA) is increasingly recognized as a conservation and management priority (Beissinger and McCullough 2002).

Several species or groups stand out as candidates for scenario-based PVA due to the availability of baseline data and their ecological or conservation significance. For instance, Red-crowned Cranes is among the most iconic wetland-dependent species in NEA. Both its continental and island populations have been the focus of demographic and spatial studies, with preliminary PVA efforts undertaken, particularly for the island population in Hokkaido, Japan (Masatomi and Kitagawa 2011, Masatomi 2000, Ueta and Masatomi 2000, Higuchi et al. 1992, Harris and Mirande 2013). Similarly, White-naped Cranes and Hooded Cranes are of interest due to their declining western populations and habitat reliance on fragile wetlands (Harris and Mirande 2013, Qian et al. 2009, Chong et al. 2020). While data on their full life-cycle demographics are limited, satellite tracking and migratory behavior analyses offer a starting point for future modeling efforts (Higuchi et al. 1999).

Among globally threatened shorebirds, Spoon-billed Sandpipers represents one of the most intensively studied species in the EAAF. With fewer than 1,000 mature individuals, it is the subject of international conservation action plans, head-starting programs, and intensive monitoring (Zöckler et al. 2010, BirdLife International 2023a). This makes it an excellent candidate for PVA, although its small population size poses modeling challenges. Similarly, species like Great Knots, Far Eastern Curlews, and Bar-tailed Godwits have been the focus of flyway-scale population trend analyses, with annual decline rates of 4-8% strongly linked to habitat loss in the YS (Studds et al. 2017). While demographic data gaps remain, their ecological importance and population trajectories make them high-priority targets for scenario-based PVA.

Black-faced Spoonbills offers another promising case. Benefiting from sustained international conservation efforts, its global population has increased from fewer than 300 individuals in the 1980s to over 7,000 today (Yu and Swennen 2004, Sung et al. 2017). A recent PVA study has already projected potential long-term declines driven by cumulative habitat loss and climate change impacts on wintering grounds. This makes it a leading candidate for integrating additional stressors such as offshore wind energy into updated PVA models.

Waterfowl species like Baikal Teals (*Sibirionetta formosa*), which have recovered from historical lows to populations exceeding one million, provide a contrasting case (BirdLife International 2023b). While currently listed as Least Concern, their wintering concentration in ROS and exposure to emerging threats such as pesticide use and habitat modification warrant attention, though their suitability for detailed PVA may be secondary to more acutely threatened species.

Despite these promising candidates, the feasibility of robust PVA is frequently constrained by gaps in demographic data, particularly survival and fecundity rates across the full migratory range. For many species, particularly those with broad distributions or data-poor breeding grounds in remote areas of Russia and Mongolia, key population parameters remain poorly quantified. This limits the precision of population forecasts and underscores the need for expanded demographic research.

Table 10. PVA Feasibility and Data Status for Migratory Birds Breeding in Northeast Asia

Species	Breeding Area in North-East Asia	IUCN Status (EAAF Population)	Key Demographic Data Availability (Pop. Size/Trend, Survival, Fecundity, Dispersal/Connectivity - with quality/source notes)	Existing PVA Studies	PVA Feasibility
Red-crowned Crane (Grus japonensis)	Amur River Basin (Russia), Northeast China	EN	Pop. Size/Trend: Continental ~1,400 (stable/decreasing), Japan ~1,600 (increasing). Survival: Continental adult/subadult mortality suggested high. Fecundity: Continental juvenile ratio 10-25%, Hokkaido 11.6%. Dispersal/Connectivity: Continental-Korean Peninsula/China migration, dispersal within Japan.	Yes (Hokkaido)	High (Hokkaido), Medium (Continental)
White-naped Crane (Antigone vipio)	Daurian Steppe (Russia), Mongolia, Northeast China	VU	Pop. Size/Trend: ~4,900-5,300, western population (Yangtze wintering) sharply declined (4,000 -> 1,000-1,500). Survival: Limited info. Fecundity: Limited info. Dispersal/Connectivity: Satellite tracking data, migratory route changes observed.	No	Medium
Hooded Crane (Grus monacha)	Taiga region (Russia)	VU	Pop. Size/Trend: ~11,500-11,600, decreasing trend. >80% winter in Izumi, Japan. Survival: Limited info. Fecundity: Limited info. Dispersal/Connectivity: Concentration at key wintering site.	No	Medium-Low
Black-faced Spoonbill	Northeast China, some	EN	Pop. Size/Trend: Increased from <300 in 1989 to ~7,000 in 2024. Survival: Data used in	Yes	High

(Platalea minor)	islands off west coast of Korean Peninsula		modeling exist. Fecundity: Data used in modeling exist. Dispersal/Connectivity: Key breeding-wintering site connectivity studies ongoing.		
Spoon-billed Sandpiper (Calidris pygmaea)	Chukotka Peninsula, Kamchatka Peninsula (Russian Far East)	CR	Pop. Size/Trend: 240-456 adults, continuous decline (5-8%/year). Survival: Modeling studies exist. Fecundity: Some data from headstarting programs. Dispersal/Connectivity: Satellite tracking, high dependence on key stopover sites (Yellow Sea).	Yes (population estimation models)	High
Great Knot (Calidris tenuirostris)	Mountain slopes in Siberian tundra	EN (EAAF)	Pop. Size/Trend: EAAF ~425,000, Yellow Sea dependent groups declining -5.1%/year. Survival: Survival change studies linked to Yellow Sea dependence. Fecundity: Limited info. Dispersal/Connectivity: Key stopover in Yellow Sea.	No (trend analysis)	Medium-High
Far Eastern Curlew (Numenius madagasca riensis)	Wetlands, grasslands in Russian Far East	EN (EAAF)	Pop. Size/Trend: EAAF ~35,000, Yellow Sea dependent groups declining -5.8%/year. Survival: Survival change studies linked to Yellow Sea dependence. Fecundity: Limited info. Dispersal/Connectivity: Key stopover in Yellow Sea.	No (trend analyssi)	Medium-High
Baikal Teal (Sibirionett a formosa)	Forest zone of Eastern Siberia	LC	Pop. Size/Trend: Recovered from tens of thousands in 1980s to >1 million around 2010. Survival: Limited info. Fecundity: Limited info. Dispersal/Connectivity: Concentration at key wintering sites (Korea, Japan, China).	No	Medium

Note: IUCN status is global unless specified for EAAF population. Data availability is relative and depends on the complexity level of the PVA model. Demographic data requirements vary accordingly.

2.3.2 Current Status of Population Prediction Studies in NEA

Existing population prediction studies in NEA have largely focused on high-profile or critically endangered species. Red-crowned Cranes have been modeled for both island and continental populations, with studies suggesting that climate change may shift breeding grounds northward into Russian territories (Ueta and Masatomi 2000). Black-faced Spoonbills have benefited from detailed PVA, which forecasts a potential shift from short-term population growth to long-term decline due to habitat loss in wintering areas (Sung et al. 2017). Spoon-billed Sandpipers have been the focus of non-breeding distribution models identifying critical YS stopover sites, though comprehensive PVA efforts remain limited (Zöckler et al. 2010).

For shorebirds dependent on the YS, population trend analyses using Bayesian N-mixture models have revealed steep declines across multiple species, highlighting the urgency of integrating these data into population models that can assess future risks under various management and development scenarios (Studds et al. 2017, Cohen et al. 2018). Population surveys in Baikal Teals have shown remarkable recovery, but detailed demographic modeling is lacking.

In ROK, studies using occupancy modeling for common landbirds have identified general population declines, particularly among long-distance migrants. Similarly, research on Poyang Lake, China waterbirds has modeled the impacts of hydrological changes and habitat degradation, showing the sensitivity of wetland-dependent species to environmental variability. However, existing models often focus on isolated stressors such as habitat loss or climate change, with few integrating the cumulative effects of multiple pressures. Moreover, these models frequently rely on limited life-stage data or single-site studies, restricting their applicability to flyway-scale conservation planning.

Table 11. Summary of Existing Population Change Prediction Studies for Selected Migratory Birds in NEA

Species	Study Reference (Author, Year, Source ID)	Geographic Scope	Methodology (PVA, Trend Analysis, Occupancy Model, etc)	Key Prediction Results	Major Threats Considered in Model
Red-crowned Crane	Masatomi 2008 ; Kong et al. 2020	Hokkaido, Eurasian Continent	Simple PVA, MaxEnt habitat modeling	Hokkaido stable, continental breeding grounds shifting north, increasing importance of Russia	Habitat loss, climate change
White-naped Crane	Jia et al. 2021	EAAF Western Route	Satellite tracking, migration route modeling	Migration route changes, sharp decline in western wintering population	Wetland loss
Black-faced Spoonbill	Sung et al. 2017	EAAF-wide	Trend analysis, PVA	Short-term increase followed by decline around 2050	Habitat loss, climate change, human disturbance
Spoon-billed Sandpiper	Zöckler et al. 2010 ; Chowdhury et al. 2022	EAAF-wide	Population estimation, distribution modeling	Continuous decline (5-8%/year), importance of key stopover sites	Habitat loss, hunting
Bar-tailed Godwit (menzbieri)	Studds et al. 2017	EAAF	Bayesian N-mixture model, trend analysis	-6.1% decline/year	Yellow Sea tidal flat loss
Far Eastern Curlew	Studds et al. 2017	EAAF	Bayesian N-mixture model, trend analysis	-5.8% decline/year	Yellow Sea tidal flat loss
Red-necked Stint	Studds et al. 2017	EAAF	Bayesian N-mixture model, trend analysis	-7.5% decline/year	Yellow Sea tidal flat loss
Great Knot	Studds et al. 2017	EAAF	Bayesian N-mixture model, trend analysis	-5.1% decline/year	Yellow Sea tidal flat loss
Korean Landbirds (52 spp.)	Kim et al. 2021	South Korea	Occupancy modeling	38% species declining, especially long-distance migrants & common species	Climate change (some spp.), land cover change (some spp.)
Poyang Lake Waterbirds	Han et al. 2025	Poyang Lake, China	Habitat quality assessment, hydrological modeling	Overall habitat quality decline, extreme hydrological conditions exacerbate fragmentation	Water level fluctuations, habitat change

2.3.3 Impacts of Energy Infrastructure on Migratory Bird Populations

While the global shift toward renewable energy is a critical strategy for mitigating climate change, the rapid expansion of OWFs presents new ecological risks for migratory birds, particularly in coastal and marine environments like the YS. Potential impacts include direct collision mortality, displacement from key habitats, barrier effects on migration pathways, and habitat loss or alteration from infrastructure development.

Empirical studies in the EAAF region have begun to document these impacts. In ROK, bird surveys at the South-West Sea demonstration complex reported low collision risk due to flight altitude and turbine spacing, although other assessments have highlighted gaps in legal and ecological impact standards (Lim et al. 2023). In China, studies near Yancheng and Poyang Lake have documented collision fatalities and displacement effects, particularly for large waterbirds like the Oriental Stork (Zhang et al. 2022). Japanese research has identified high-risk areas for geese, swans, and seabirds near coastal cliffs and offshore development zones (e.g., Japan's National daily 2019).

European studies provide additional insights, demonstrating species-specific responses ranging from high avoidance and displacement distances to low collision risk in well-designed wind farms. For example, radar tracking in Denmark showed that geese and ducks generally avoided turbine arrays (Desholm and Kahlert 2005), while UK studies reported unexpectedly high avoidance rates among seabirds (Cook et al. 2014). These findings collectively suggest that avian responses to OWFs are highly variable, dependent on species behavior, turbine design, and site-specific ecological conditions (Krijgsveld et al. 2011). Therefore, robust site- and species-specific impact assessments are essential, particularly in data-poor regions like the EAAF.

2.3.4 Integrating Energy Infrastructure and Climate Change into Scenario-Based PVA

Given the complexity of cumulative impacts from OWFs and climate change, scenario-based PVA offers a promising approach for evaluating future population trajectories under different management and development scenarios. This requires integrating spatially explicit data on habitat distribution, energy infrastructure locations, and climate change projections into demographic models.

Developing such models involves translating predicted collision and displacement impacts, derived from collision risk models and field studies, into changes in survival and fecundity rates within PVA frameworks. Recent methodological advancements, such as those proposed by Horswill et al. (2022), emphasize the need to integrate temporal trends in demographic rates into PVA for more accurate impact forecasting.

Incorporating pathway contribution metrics, as demonstrated by Smith et al. (2022) and Sample et al. (2020), allows for the assessment of how specific migratory route disturbances affect overall population dynamics. This is particularly relevant for EAAF species that traverse multiple jurisdictions and face regionally variable threats. A major challenge lies in quantifying synergistic effects, such as climate-driven shifts in migration routes intersecting with high-density OWF zones or reduced resilience due to compounded stressors. Addressing these complexities requires comprehensive data on species-specific demographic responses to multiple stressors, including avoidance rates, displacement distances, energetic costs, and habitat dependency. Despite these data gaps, scenario-based PVA can provide valuable insights by exploring "what-if" scenarios, conducting sensitivity analyses to prioritize research needs, and comparing the relative risks of different development strategies. This approach enables proactive conservation planning even under uncertainty.

Focusing initial efforts on high-priority species such as the Red-crowned Crane, Black-faced Spoonbill, Spoon-billed Sandpiper, and shorebirds in the YS offers the greatest potential for generating actionable conservation insights. These species are not only globally threatened but also heavily reliant on habitats likely to overlap with OWF development, making them ideal candidates for scenario-based PVA. To support this, coordinated long-term monitoring programs across the EAAF are essential, integrating demographic research, wildlife tracking, habitat assessment, and impact monitoring at energy development sites. Such efforts must extend beyond project-specific EIAs to address the cumulative and flyway-scale impacts of energy infrastructure and climate change. By adopting this integrated, scenario-based approach, stakeholders can better understand and manage the complex trade-offs between renewable energy development and the conservation of NEA populations in migration birds.

Table 12. Key Data Requirements for PVA of Migratory Birds in the EAAF Under Cumulative Stressors (Offshore Wind and Climate Change)

Parameter Type	Data Source/Methodology	Current Availability for Key EAAF Species (Specific Examples, High/Medium/Low)	Key Gaps and Research Priorities
Change in Adult Survival Rate due to OWF Collision	Telemetry, long-term banding, collision monitoring, CRM	Low (EAAF-specific data very scarce)	Quantify EAAF species-specific, OWF design-specific collision & avoidance rates; obtain data for nocturnal migrants.
Change in Fecundity due to Climate Change-induced Habitat Degradation	Long-term breeding site monitoring, climate-habitat modeling	Medium-Low (Predictions exist for some species, but direct link to fecundity often lacking)	Predict changes in key breeding/wintering sites under climate scenarios & link to reproductive success.
Impact of OWF Displacement-related Energy Costs on Survival Rate	Physiological studies, behavioral observation, individual-based models	Low (Almost no studies for EAAF species)	Measure increased energy expenditure from OWF avoidance behavior in key species & model survival impacts.
Change in Stopover Site Carrying Capacity due to Sea Level Rise	GIS analysis, sea-level rise models, bird distribution data	Medium (Some studies for key areas like Yellow Sea exist)	High-resolution topographic change predictions for key EAAF stopover sites & model species-specific carrying capacity changes.
Displacement Levels & Habitat Use Change with OWF Setback Distance	GPS tracking, radar surveys, behavioral observation	Low-Medium (Some European examples, EAAF data scarce)	Quantify behavioral responses & habitat use changes of key EAAF species to varying setback distances & OWF layouts.
Mismatch between Climate Change-induced Migration Timing Shift & Fecundity	Long-term migration timing monitoring, food resource availability surveys	Medium (Observed in some species, but causal link to fecundity often lacking)	Simultaneously monitor migration timing shifts & key food resource phenology for major species & assess reproductive impacts.
Overall Vital Rates under Cumulative Stress (OWF+Climate Change+Other)	Integrated long-term monitoring, complex stressor experiments/modeling	Very Low	Estimate demographic parameter changes reflecting interactions & synergistic effects of major threats.

2.4 Case study: Potential impact of energy infrastructure on the trend of bird population in East Asia

2.4.1 Species Overview and Conservation Context

Black-tailed Gulls are a widespread coastal seabird in NEA, with breeding populations distributed across Japan, Korea, eastern China, and parts of the RFE. It occupies a significant ecological niche as a generalist forager, preying on fish, invertebrates, and discards from fishing vessels, thereby influencing nearshore trophic dynamics. Beyond its ecological role, the species bears cultural significance, such as its spiritual association with the Kabushima Shrine in Japan and its symbolic presence on Dokdo in ROK, which further complicates its conservation status by intertwining biological concerns with sociopolitical narratives.

Despite being categorized globally as “Least Concern” by the IUCN, regional population trends show disparities. Notably, long-term declines in Japanese colonies, with populations reduced to 3–35% of their former size over three decades, highlight potential inconsistencies in global status assessments and the necessity for regionally grounded conservation evaluations (e.g., Oka et al. 2006, Watanuki 2016). Given the increasing development of coastal and offshore infrastructure across NEA including wind farms, harbors, and aquaculture installations, the need to forecast population dynamics under various threat scenarios becomes pressing. PVA serves as a critical tool for integrating demographic data and projecting long-term outcomes under both status quo and altered environmental conditions.

2.4.2 Demographic and Ecological Profile for PVA Development

Black-tailed Gulls breed across a range of insular and coastal habitats, forming large colonies in Japan (e.g., Kabushima, Teuri Island, Rishiri Island; approximately 10,000-100,000 breeding pairs; concerning declines have been reported in this region), Korea (e.g., Dokdo, Hongdo, Chilsando; approximately 10,000-100,000 breeding pairs; the wintering population in Korea was estimated at around 55,000 individuals in 2021-2022; an informal source estimates over 300,000 individuals in Korea), and China (Yellow Sea islands; approximately 100-100,000 breeding pairs and 50-10,000 wintering individuals). Note that population in RFE is approximately 10,000-100,000 breeding pairs and 1,000-10,000 migrating individuals. These breeding colonies vary in size from a few hundred to over 50,000 individuals, often situated in areas exposed to varying degrees of anthropogenic influence (BirdLife International 2023c). The species’ adaptability to diverse nesting substrates (e.g., rocky cliffs, grassy slopes, and artificial structures) contributes to its resilience, yet also exposes it to novel risks.

Lifespan of Black-tailed Gulls is relatively long, with banding data indicating individuals can survive over 30-40 years. However, critical demographic parameters essential for robust PVA modeling such as age-specific survival rates, reproductive output, and recruitment, remain incomplete or vary considerably among colonies and across years (Oka 2004, Ministry of the Environment, Japan 2020). Adult annual survival is estimated at ~0.90 based on proxy data from congeneric species, though direct longitudinal studies on Black-tailed gulls remain limited (but see Lebreton and Clobert 1991). Subadult and juvenile survival rates are even less certain; fledgling resighting data from Rishiri Island, Japan suggest low local recruitment (≤24%), likely confounded by natal dispersal (Oro and Furness 2002, Watanuki 2016).

Reproductive parameters show high temporal and spatial variability. Clutch sizes typically range between 1.5-2.2 eggs per nest, with hatching success of ~70-77% and fledging success highly site-dependent (as low as 0.01 fledglings per egg laid in some years at Kabushima, Japan). Environmental conditions, parental condition (e.g., mercury burdens), and intraspecific aggression contribute to interannual fluctuations (Watanuki 1986, Watanuki 2016, Kurosawa and Chiba 2005). Furthermore, early breeding has been observed in some individuals as young as two years old, challenging traditional assumptions of maturity age and necessitating a flexible fecundity schedule in modeling efforts (Oka 1994).

The generation length is estimated at approximately 14 years, based on a first breeding age of four and adult annual survival of 90%, aligning with demographic profiles of long-lived seabirds. However, skewed sex ratios what observed in other Laridae but unconfirmed in this species, may influence long-term population structure and should be incorporated into more advanced models when data allow (BirdLife International 2023c, Caswell 2001, IUCN Standards and Petitions Committee 2022).

Table 13. Key Demographic Parameters of Black-tailed Gulls in NEA for PVA

Parameter	Value/Range	Key Sources	Notes/Caveats
Maximum Lifespan	>32 years		KNPS study: >17 years
Adult Annual Survival Rate	0.90 (estimate)	(proxy)	Based on *Larus ridibundus*, *Larus crassirostris* data lacking. Rishiri Island return rates 76.4%-94.7% not directly equivalent to survival.
Subadult Annual Survival Rate	Data lacking		Generally assumed to be intermediate between juvenile and adult.
Juvenile/Fledgling (First-Year) Annual Survival Rate	Data lacking		76% not resighted at natal colony on Rishiri (includes dispersal). Highly uncertain.
Age of First Breeding	2-5 years, avg. approx. 3-4 years		Breeding at 2 years observed on Rishiri Island.
Clutch Size	1.57-2.16 eggs/nest (avg.), typically 2-3		High habitat and annual variability.
Hatching Success	Approx. 69.6%-76.9% (Hongdo, South Korea)		Varies by year, habitat. Not significantly related to mercury exposure at Kabushima.
Fledging Success (per hatched chick)	Approx. 71.3%-75.3% (Hongdo, based on 15-day survival post-hatch)		Varies by year, habitat.
Fledging Success (per pair/nest)	0.01-0.29 chicks/egg (Kabushima, based on eggs laid)		Very high annual variability. 90% in 2018 vs. 40% in 2019 (Kabushima, based on nests with eggs). Bentenjima 21.7% (based on eggs laid).
Sex Ratio at Hatching (M/F)	Data lacking		Other Larus species suggest potential deviation from 1:1.
Adult Sex Ratio (M/F)	Data lacking	(sample)	Culled sample from Rishiri was 1.42 M/F, but unlikely representative of breeding population. Female bias observed in other gull species.
Generation Length	Approx. 14 years (estimate)	Calculated	Assumes age of first breeding 4 yrs, adult mortality 0.10.

2.4.3 Methodological Framework for PVA

A stage-based matrix model, particularly the Leslie matrix, offers a structured method to simulate population trajectories under variable scenarios. Key model inputs include annual survival rates for juveniles (S_0), subadults ($S_{1\text{-}3}$), and adults (S_{4+}), age-specific fecundity, and initial population size. Given the uncertainty of certain parameters, especially juvenile survival, a scenario-based modeling approach will allow exploration of plausible trajectories and critical thresholds.

Density dependence and environmental stochasticity must be incorporated to reflect ecological realism. Although empirical data on density feedbacks in Black-tailed Gulls in NEA are lacking, density dependence in reproduction and survival is common among colonial seabirds. Therefore, logistic functions or soft ceiling approaches may be applied to constrain growth when the population approaches historical carrying capacity.

Environmental stochasticity will be modeled using annual variability in reproductive rates, based on historical productivity ranges (e.g., 0.01–0.29 fledglings/egg). Catastrophic events (e.g., oil spills, heatwaves) are not included explicitly but can be modeled as probabilistic shocks in future iterations. Sensitivity analyses will identify the parameters most influential on population growth rate (l), extinction risk, and quasi-extinction thresholds. Given the uncertainty of future environmental changes and management actions, a scenario-based approach is effective. This allows exploration of how the population responds under various potential future conditions.

Table 14. Model Scenarios

Scenario	Description
Baseline Scenario	Predicts population trends assuming current demographic rates and environmental conditions persist, and no additional major threats (e.g., construction of new large-scale wind farms) are introduced. Reflecting the conflicting current population trends discussed in Section 2.3 (stable vs. declining), multiple baseline scenarios can be established (e.g., stable baseline, baseline reflecting declining trend in Japan)
Collision Risk Scenarios	
Low collision risk	A scenario where additional mortality due to collision with offshore wind farms and other structures is set low. This could assume effective avoidance behavior or mitigation measures are implemented
Medium collision risk	A scenario applying collision rates reported for similar species or model-based estimates
High collision risk	A worst-case scenario simulating low avoidance rates and concentrated construction of wind farms in high-risk areas

Note that each collision risk scenario can apply differential collision mortality rates to specific age groups (e.g., adult foraging individuals) or specific breeding colony populations, linked to distance from breeding sites and foraging habitat use patterns. For example, reflecting the high collision risk in areas near breeding sites/harbors presented in the Hokkaido study, the survival rate of populations using those areas can be adjusted

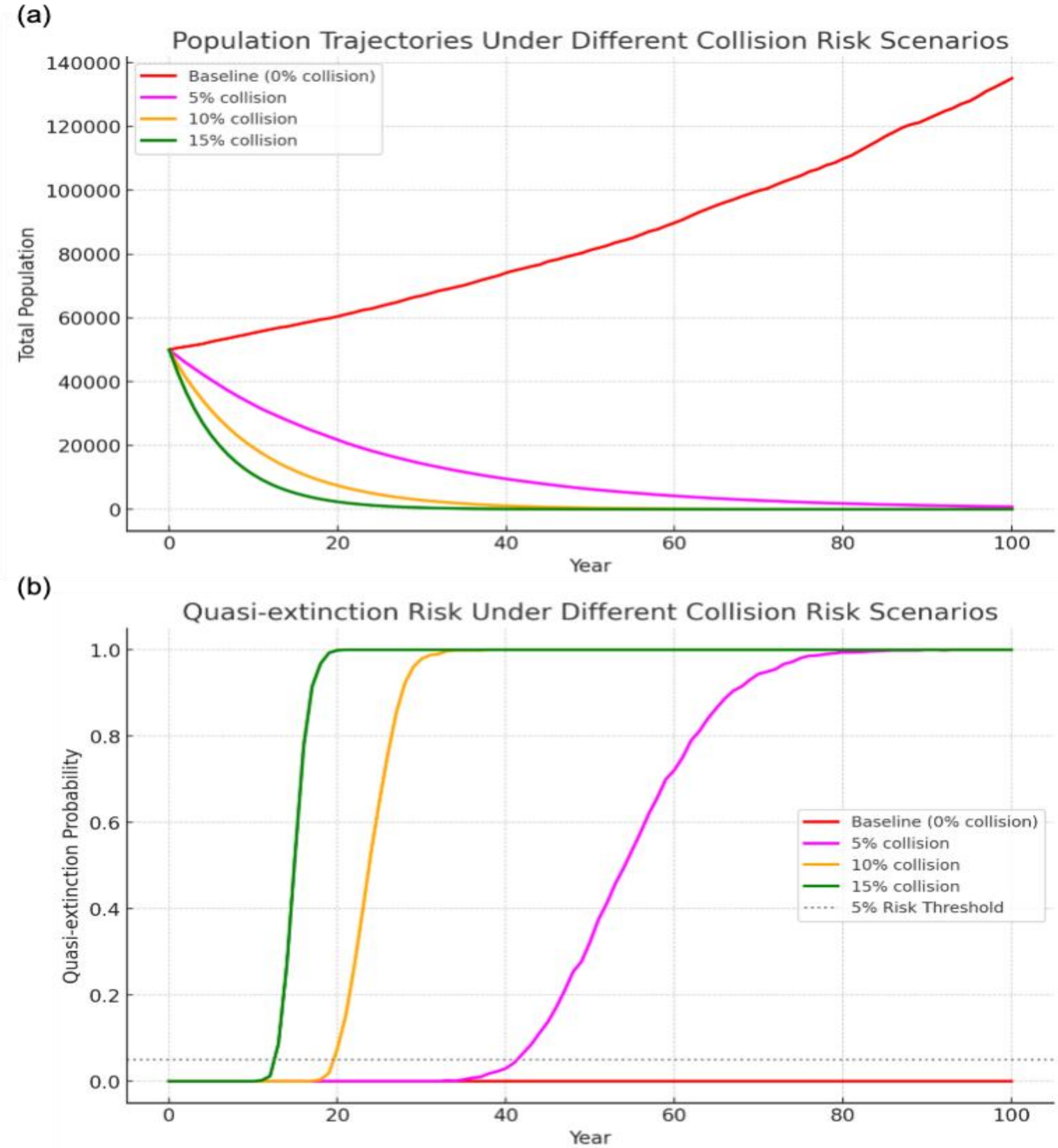
2.4.4 Threat Scenarios and Population Projections

Three main threat scenarios are explored alongside a baseline trajectory (Figure 5).

(a) Baseline (Stable vs. Declining)

Under stable demographic conditions (l»1), population size is predicted to remain near current levels, with fluctuations due to stochastic events. However, if recent declines in Japan reflect a broader trend (l<1), PVA will project long-term decline, even absent new threats. This divergence necessitates dual baseline models reflecting regional uncertainties.

Figure 5. (a) Prediction of population in Black-tailed gulls for next 100 yrs based on Scenarios, (b) Predicted Quasi-extinction Risk under Scenarios



(b) Collision Mortality Scenarios

Increasing offshore wind development poses direct mortality risks. Three sub-scenarios simulate increasing annual mortality: (i) Low Risk - Mortality of <0.1% added annually, reflecting effective avoidance or mitigation, (ii) Medium Risk - Mortality aligned with empirical studies from other seabirds (e.g., 0.5-1% adult mortality/year), (iii) High Risk - Worst-case estimates (~2% adult mortality/year), especially in regions with high turbine density and poor spatial planning. Adult survival is the most elastic parameter in seabird PVA. Thus, even small decreases can push l below unity, triggering population decline. In the high-risk scenario, simulations predict accelerated decline toward quasi-extinction thresholds within 50-60 years, particularly if compounded by low juvenile survival.

For spatial exposure and subpopulation sensitivity, not all colonies face equal risk. For example, birds nesting at coastal cliffs in Hokkaido in Japan, which overlap turbine rotor-swept zones, may exhibit higher mortality than island colonies with broader foraging ranges. Incorporating colony-specific exposure weights refines projections, highlighting subpopulation vulnerability even if overall population decline appears modest.

2.4.5 Sensitivity Analysis and Model Robustness

Sensitivity testing confirms that adult survival (S_4+) exerts the greatest control over l. Variation in juvenile survival (S_0) produces moderate changes, especially under high recruitment assumptions. Reproductive parameters, though variable, are less influential individually due to their relatively low contribution to l in long-lived species. Inclusion of earlier breeding onset (e.g., age 2) marginally increases growth rates but does not offset the effects of high adult mortality. Similarly, improved fledging success alone cannot fully mitigate decline under high-collision scenarios. This suggests that management efforts must prioritize adult survival-either by preventing direct mortality (e.g., collision avoidance) or improving adult condition (e.g., reducing pollutant loads).

The robustness of the PVA is limited by data uncertainties, particularly regarding: (i) Age-specific survival rates (especially S_0 and S_{1-3}), (ii) Colony-specific foraging ranges and spatial overlap with OWFs, (iii) Actual collision mortality rates under current and future turbine layouts, (iv) Long-term environmental trends affecting prey availability and breeding habitat quality.

2.4.6 Implications for Monitoring and Management

The PVA highlights the urgent need for targeted data collection: (i) banding and telemetry studies to estimate true survival and dispersal, (ii) standardized productivity monitoring across representative colonies, (iii) tracking of foraging behavior and airspace use relative to OWFs, (iv) quantification of avoidance behavior and barrier effects, (v) evaluation of cumulative impacts.

By modeling both deterministic and stochastic processes, and incorporating multiple plausible futures, the PVA framework enables identification of critical demographic thresholds and spatial hotspots for management intervention. For Black-tailed Gulls, this includes prioritizing mitigation near high-density colonies, adopting turbine spacing strategies that reduce collision risk, and integrating ecological insights into marine spatial planning.

2.5 Case study: Scenario-based PVA for flagship species

The feasibility and robustness of a Population Viability Analysis (PVA) are fundamentally dependent on the quality and availability of demographic data for the target species. For the three flagship species considered in this study, the data landscape is varied, offering opportunities for detailed modeling in some cases, while also revealing critical gaps that highlight priorities for future research. However, due to the overall lack of comprehensive and species-specific data for these flagship species, only a highly limited analysis was possible, and we acknowledge that the results presented here have clear limitations.

2.5.1 Data Availability and Gaps for the Black-faced Spoonbill

The Black-faced Spoonbill is a good candidate among the target species for a detailed PVA. There is a wealth of high-quality population trend data from the annual international winter census, which has tracked the species' recovery for decades. This provides a solid baseline for overall population size and growth rate. Previous modeling work, such as the trend analysis by Sung et al. (2017), has already laid a foundation for demographic assessment, and genetic studies have provided insights into its historical population size, confirming a severe past bottleneck. However, significant data gaps persist. Precise age-specific survival rates, particularly for juvenile and sub-adult birds, are not well-documented and are often inferred. Most critically, the direct demographic consequences of the newly identified threat from OWFs—that is, the quantitative reduction in survival or fecundity caused by the barrier effect and migration alteration—are unknown. This impact must therefore be modeled through a scenario-based approach, exploring a range of plausible mortality or fitness reduction values to understand the potential population-level effects.

2.5.2 Data Availability and Gaps for the White-naped Crane

The White-naped Crane also presents a viable, though more complex, case for PVA. Excellent population trend data exist, clearly delineating the divergent trajectories of the increasing eastern population and the declining western population. This allows for separate, comparative modeling. Satellite tracking studies have provided valuable information on migratory connectivity and habitat use. Crucially, at least one study has estimated an adult annual survival rate of approximately 84%, which can serve as a key parameter for modeling. While other parameters like fledging success and age of first breeding are less certain, they can be reasonably estimated using data from closely related crane species. The most significant data gap is the lack of specific demographic data (survival and fecundity rates) for the critically declining western population. Understanding the vital rates of this specific population is paramount for diagnosing the cause of its decline and modeling its future. Additionally, the precise mortality rate attributable to power line collisions across the flyway remains unquantified and must be included as a variable in scenario analyses.

2.5.3 Data Availability and Gaps for the Hooded Crane

The Hooded Crane is the most data-deficient of the three flagship species for the purposes of a traditional PVA. While there are excellent and reliable population counts, particularly from the concentrated wintering grounds at Izumi, Japan, there is very limited published data on its core demographic parameters in the wild, such as annual survival rates for different age classes and fecundity. Some life history information, such as fledging period (55-60 days), is known, but this is insufficient for a detailed demographic model. Consequently, a PVA for the Hooded Crane must be more conceptual in nature. It will rely on borrowing demographic parameters from better-studied congeners, such as the Sandhill or Whooping Crane, not to predict precise future population numbers, but to explore the relative sensitivity of the population to different types of threats. The primary value of a PVA for this species is to quantitatively demonstrate the immense risk posed by its population concentration, by modeling the disproportionate impact of a single catastrophic event at Izumi on the entire global population.

The following table summarizes the available demographic data and identifies key gaps for the three species, providing the foundation for the scenario analyses that follow (Table 15).

Table 15. Comparative demographic parameters for PVA of flagship species

Parameter	Black-faced Spoonbill	White-naped Crane	Hooded Crane
Adult Annual Survival	Medium Confidence. Estimated from population trends and congeners. No direct, long-term mark-recapture study.	Medium Confidence. Estimated at ~0.84 from one study. Lower than other stable crane populations (~0.94).	Data Gap / Low Confidence. No direct studies found. Must be inferred from congeners (e.g., 0.94 for Sandhill Crane).
Juvenile (1st yr) Survival	Data Gap / Low Confidence. Highly uncertain. Must be estimated or modeled as a variable.	Data Gap / Low Confidence. Highly uncertain. Must be inferred from congeners or modeled.	Data Gap / Low Confidence. Highly uncertain. Must be inferred from congeners or modeled.
Age at First Breeding	High Confidence. 3-4 years.	Medium Confidence. 2-3 years.	Low Confidence. Likely 3-5 years, inferred from other cranes.
Annual Fecundity (fledglings/pair)	Medium Confidence. Clutch size 2-3. Fledging success is highly variable and site-dependent. Can be estimated from census data (juvenile ratios).	Low Confidence. Clutch size 2. Fledging success (70-75 days to fledge) is known, but annual rate per pair is uncertain.	Low Confidence. Fledging period 55-60 days. Overall rate per pair is uncertain.
Population Trend Data	High Confidence. Excellent long-term data from annual international winter census.	High Confidence. Good data differentiating eastern (increasing) and western (decreasing) populations.	High Confidence. Excellent data from the concentrated Izumi wintering site.
Key Data Gaps for PVA	True age-specific survival rates; quantitative demographic impact of OWF barrier effect.	Demographic parameters (survival, fecundity) for the declining western population; power line mortality rates.	All core demographic parameters (survival, fecundity) for wild populations.

2.5.4 Scenario-based PVA for flagship species

This section translates the theoretical principles of PVA into a practical application, using the available data and identified threats for the three flagship species to project their potential future population trajectories under a range of plausible scenarios.

3.5.4.1 Scenario Design

To explore the potential impacts of energy infrastructure, three primary types of scenarios were designed for each species, tailored to their specific vulnerabilities:

1) Baseline Scenario

This scenario projects the population forward using the best available current demographic estimates, assuming no major new impacts from energy infrastructure. It serves as the reference against which other scenarios are compared. For the White-naped Crane, two distinct baselines were modeled to reflect the divergent trends of the increasing eastern population and the declining western population.

2) Energy Infrastructure Impact Scenario

This scenario incorporates additional, persistent pressures from energy development by modifying key demographic parameters. First, for the Black-faced Spoonbill, this scenario models the impact of the Yellow Sea OWF barrier effect by introducing a small, additional annual mortality rate (e.g., 0.5%, 1%, and 2%) to juvenile and adult survival probabilities to simulate the combined risk of collision and migration failure. Second, for the White-naped and Hooded Cranes, this scenario models two concurrent impacts: a small additional mortality from power line collisions and a reduction in the habitat's carrying capacity (K) to simulate the functional habitat loss caused by a 5 km displacement zone around new wind farms in their core wintering or stopover areas.

3) Catastrophic Risk Scenario (for Hooded Crane only)

Given its extreme concentration, a specific scenario was designed for the Hooded Crane to model the impact of a single, low-probability, high-consequence event. This was simulated as a one-time mortality event at the Izumi wintering site, removing 25% or 50% of the population in a single year to mimic a severe disease outbreak or other catastrophe.

3.5.4.2 Population projections for the Black-faced Spoonbill under Offshore Wind Expansion

The PVA projections for the Black-faced Spoonbill reveal the fragility of its recent conservation success. Under the Baseline Scenario, the population continues its trend of slow growth or stabilization, hovering near its current level, which is consistent with recent census data showing a plateauing population.

However, the introduction of even minor additional mortality in the Energy Infrastructure Impact Scenario dramatically alters this trajectory. A persistent, additional annual mortality of just 0.5~1%, a plausible outcome from the combined collision and barrier effect of the massive Yellow Sea OWF build-out, is sufficient to halt population growth and initiate a gradual decline. In the high-risk simulation, with an additional 2% annual mortality, the population is projected to decline steeply, potentially erasing the conservation gains of the past three decades and setting the species on a path toward quasi-extinction thresholds within 50 to 60 years. These results underscore a critical principle for long-lived species: their populations are highly sensitive to small, chronic changes in adult and juvenile survival. The PVA demonstrates that the seemingly "green" transition to offshore wind power could, if not managed with extreme care, inadvertently reverse one of the EAAF's most celebrated conservation achievements.

3.5.4.3 Comparative Analysis: Modeling Vulnerabilities of White-naped and Hooded Cranes

The PVA for the two crane species highlights distinctly different, yet equally concerning, types of vulnerability.

For the White-naped Crane, the analysis focused on the imperiled western population. The Baseline Scenario for this population, using current estimates of its decline, already projects a high probability of extirpation within the next century. The Energy Infrastructure Impact Scenario, which adds the pressure of further habitat loss from wind farm displacement and increased mortality from power lines in its remaining habitats, significantly accelerates this decline. The model shows that even modest additional pressures on this already-stressed population drastically shorten its time to extinction, emphasizing that for populations already in decline, there is virtually no tolerance for new anthropogenic threats.

For the Hooded Crane, the PVA illustrates the profound risk of its population structure. Under the Baseline and standard Energy Infrastructure Impact Scenarios, the population remains relatively stable, as the small, diffuse impacts are buffered by the large size of the overall population. However, the Catastrophic Risk Scenario reveals its true vulnerability. A simulated disease outbreak at Izumi that causes 25% mortality in a single year results in a population crash from which recovery takes decades. A 50% mortality event pushes the population into a state of immediate, critical endangerment, with a high probability of entering an extinction vortex. This analysis quantitatively confirms that the Hooded Crane's primary threat is not gradual decline, but the potential for a sudden, massive, and irreversible collapse due to its reliance on a single wintering location.

3.5.5 Species-specific Scenario analyses

The scenario-based simulations reveal critical differences in population trajectories across the three flagship species in response to chronic and catastrophic threats. These differences underscore the need for species-specific conservation strategies (Table 16).

Table 16. Model assumption and parameters

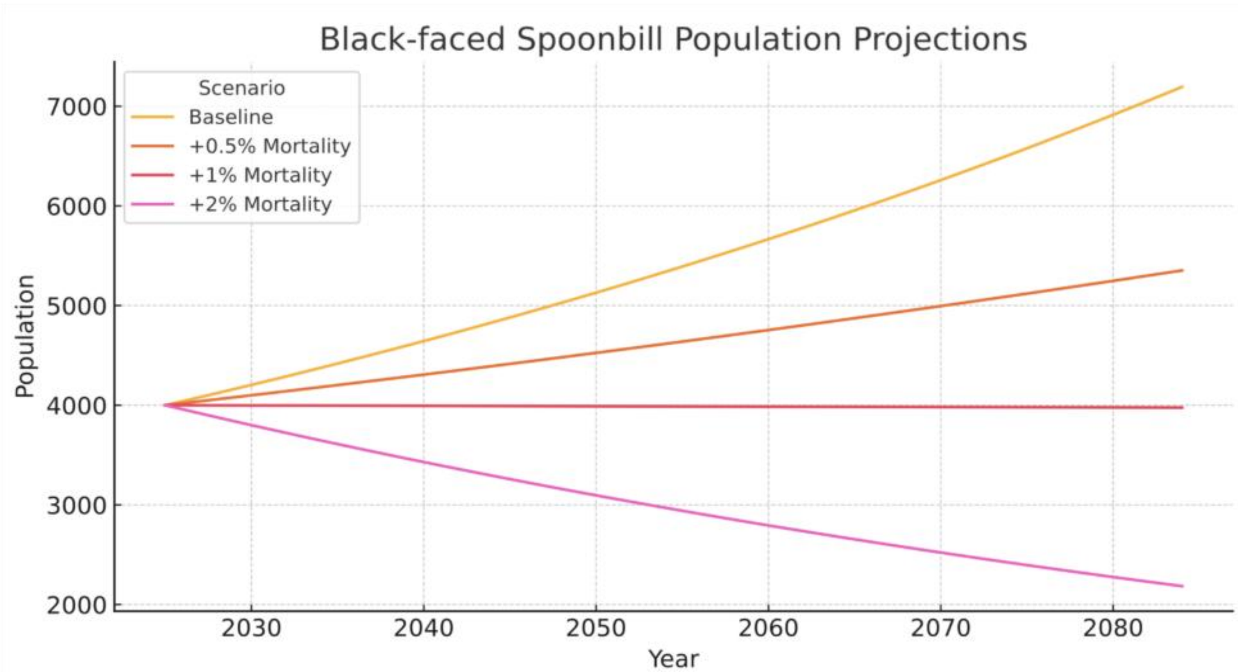
Parameter	Black-faced Spoonbill	White-naped Crane	Hooded Crane
Initial population	4,000	1,800 (west)	17,000
Baseline growth rate	+1.0%/year	-2.0%/year	+5.0%/year
Additional mortality	0.5%, 1%, 2%	0.5%, 1%	0.5%, 1%
Habitat capacity loss (K)	0%, 5%, 10%	0%, 5%, 10%	0%, 5%, 10%
Catastrophe year	-	-	2035
Catastrophe scale	-	-	25%, 50%
Simulation horizon	60 years (2025-2085)	60 years (2025-2085)	60 years (2025-2085)

Note: These values reflect conservative demographic assumptions based on published data and expert inference. The models are deterministic and do not inforporate stochastic variation but serve to highlight relative vulnerabilities.

(a) Black-faced spoonbill

The Black-faced Spoonbill, currently numbering around 4,000 individuals, demonstrates a narrow demographic buffer against additional mortality. Under baseline conditions with a modest annual growth rate of 1%, the population is projected to increase to approximately 7,200 individuals by 2085. However, when subjected to a 0.5% annual increase in mortality due to offshore wind farms (OWFs), the population reaches only around 5,400. With a 1% increase, growth is halted, and numbers decline to approximately 4,000. In the worst-case scenario of a 2% increase in mortality, the population plummets to 2,200 individuals by 2085, suggesting a trajectory toward quasi-extinction. This demonstrates the extreme sensitivity of long-lived species to chronic, small-scale mortality sources.

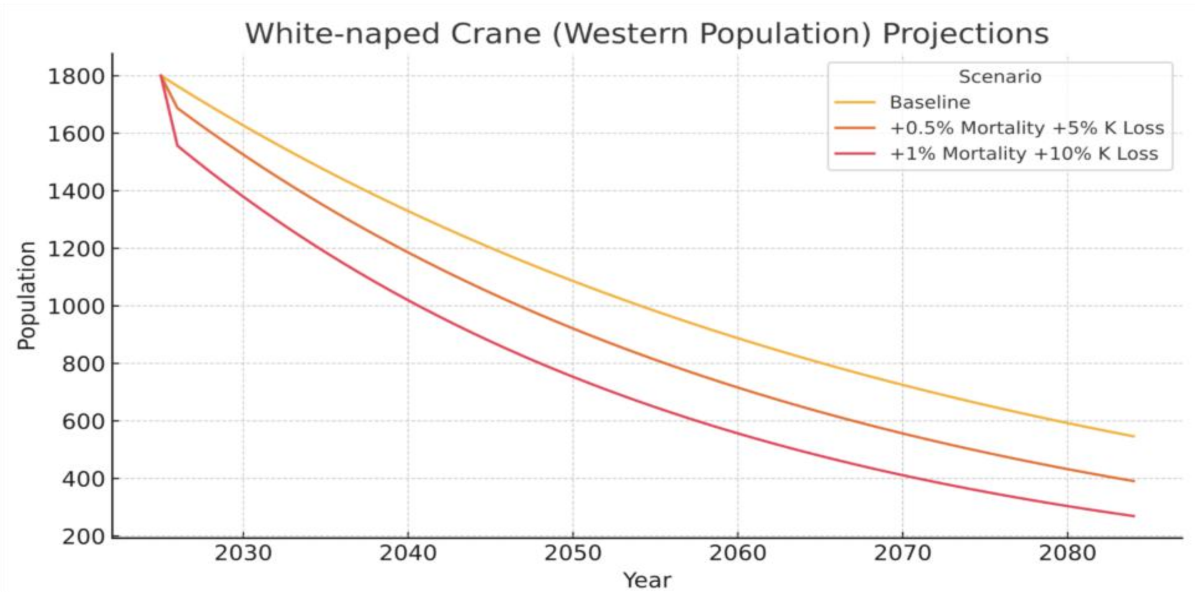
Figure 6. Prediction of population in Black-faced Spoonbill for next 60 yrs (2025~2085) based on Scenarios



(b) White-naped Crane (Western population)

The western population of the White-naped Crane, estimated at 1,800 individuals, is already undergoing a 2% annual decline. Under this baseline, the population drops to about 547 individuals by 2085. Additional threats from energy infrastructure exacerbate the decline. With an added 0.5% mortality and 5% reduction in carrying capacity (K), the population falls to 374. With a 1% added mortality and 10% K loss, the number drops further to 272. These projections indicate that the western subpopulation has virtually no tolerance for additional anthropogenic pressures, with even minor impacts accelerating its trajectory toward extirpation.

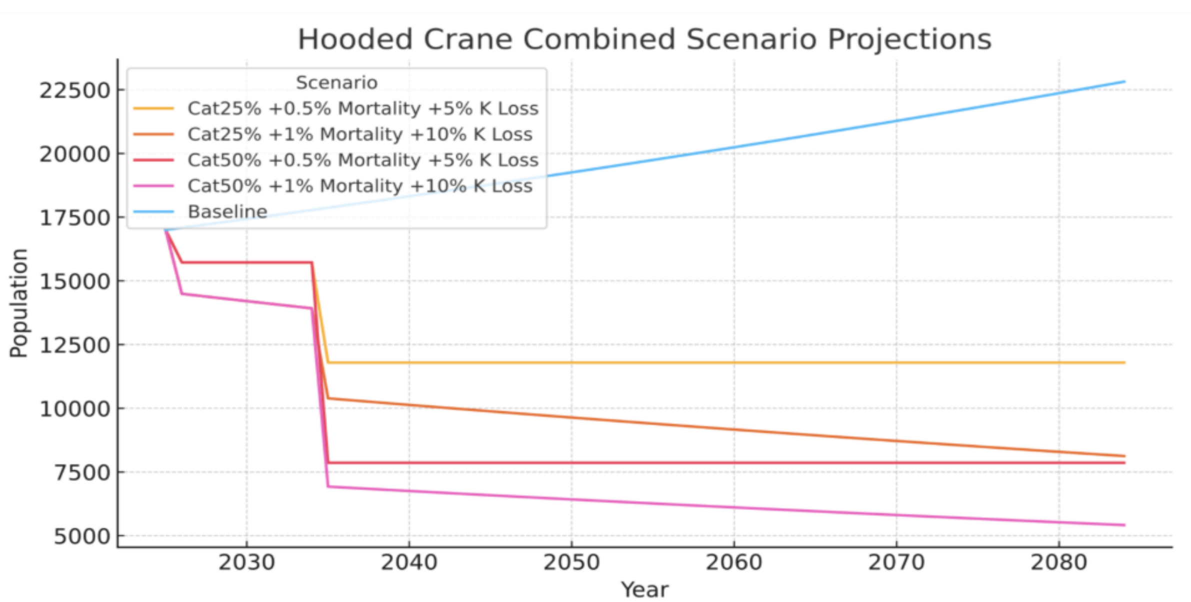
Figure 7. Prediction of population in White-naped Crane (western population) for next 60 yrs (2025~2085) based on Scenarios



(c) Hooded Crane

The Hooded Crane, with a global population of approximately 17,000 individuals, shows relative stability under baseline growth (0.5% annually), projecting to 22,600 individuals by 2085. However, the species' dependence on a single wintering site at Izumi renders it highly vulnerable to catastrophic events. Simulations combining a 25% one-time population loss in 2035 with additional infrastructure pressures (+0.5% mortality and 5% K loss) result in a 2085 population of 11,800. A similar event coupled with 1% mortality and 10% K loss reduces the population to 8,100. The 50% catastrophe scenarios yield even more severe outcomes: 7,900 and 5,300 respectively. These results highlight the compounded risk of rare but severe events when layered onto chronic environmental stressors.

Figure 8. Prediction of population in Hooded Crane for next 60 yrs (2025~2085) based on combined Scenarios



(d) Cross-species vulnerability synthesis

The simulation results clearly distinguish each species' demographic vulnerabilities. First, the Black-faced Spoonbill is highly sensitive to incremental mortality, particularly from OWFs along its migratory corridor. Second, the Western White-naped Crane population is at imminent risk, with no demographic resilience to additional pressures. Third, the Hooded Crane, while stable under baseline conditions, faces extreme collapse potential in the event of localized catastrophic mortality due to its wintering site concentration. Overall, these profiles emphasize that conservation responses must be tailored. Uniform mitigation strategies would fail to adequately protect species facing such divergent demographic risks.

3.5.6 Synthesis of Scenario Outcomes and Key Vulnerabilities

The scenario-based PVA reveals that while all three flagship species are threatened by energy infrastructure, the nature of their vulnerability differs fundamentally. The analysis provides a nuanced understanding of risk that can guide targeted conservation strategies.

(a) Black-faced Spoonbill

The primary vulnerability is to new, cumulative, and persistent threats within its core migratory corridor. Its population, having recovered from a bottleneck, is now facing a novel and large-scale threat (OWFs) that impacts survival across its entire annual cycle. Its conservation status is therefore precarious, balanced between past successes and future risks.

(b) White-naped Crane

The vulnerability is defined by population fragmentation and divergent fates. The western population is critically vulnerable to the compounding of existing and new pressures on its limited wintering grounds. Its trajectory is one of accelerated decline. The eastern population, while currently stable, is not immune to future risks if its key sites (e.g., the DMZ) face new development pressures.

(c) Hooded Crane

The vulnerability is one of extreme concentration and sensitivity to catastrophic events. The population is relatively robust to small, widespread impacts but is exceptionally fragile to a single, low-probability, high-impact "black swan" event at its primary wintering site. Its risk profile is one of stability punctuated by the potential for sudden collapse.

These distinct vulnerability profiles demonstrate that a one-size-fits-all approach to assessing or mitigating the impacts of energy infrastructure is insufficient. Conservation planning must be tailored to the specific demographic structure and threat landscape of each species.

3 Discussion

3.1 Assessed Impacts of Energy Infrastructure on Migratory Birds in NEA

Energy infrastructure expansion in NEA represents a growing environmental challenge, particularly for migratory bird populations dependent on coastal, wetland, and inland ecosystems across the region. The construction of renewable and conventional energy facilities (e.g., offshore wind farms, solar arrays to power plants, pipelines, and electricity grids) alters the landscape at multiple scales, directly and indirectly affecting birds through habitat loss, collision risk, behavioral disturbance, environmental contamination, and cumulative ecological pressures.

3.1.1 Habitat Loss, Degradation, and Fragmentation from Infrastructure Development

Habitat loss is the most immediate and irreversible impact of energy infrastructure development. Large-scale projects, including fossil fuel power stations, LNG terminals, solar photovoltaic (PV) farms, and wind farms, consume vast areas of coastal and inland landscapes. These developments displace or eliminate critical habitats used by migratory species for breeding, staging, or wintering. For instance, tidal flats along the YS, vital for shorebirds such as the Great Knot and Far Eastern Curlew, have been reduced dramatically by coastal reclamation supporting industrial zones and port expansions (Murry et al. 2015, Ma et al. 2014). Such losses, often permanent, remove essential ecological functions that cannot easily be restored elsewhere.

Infrastructure footprints extend beyond the core facilities themselves. Roads, pipelines, service corridors, and transmission lines fragment previously connected habitats, creating edge effects that alter vegetation structure and microhabitats. Fragmentation is particularly harmful to species sensitive to edge environments or requiring large continuous territories, such as cranes and raptors. In Mongolia and the Daurian steppe region, extensive mining and energy projects have introduced roads and linear structures into remote grasslands, potentially disrupting movements of species like the White-naped Crane (Levise 2024, World Wildlife Fund Mongolia 2016).

Solar PV farms present unique concerns. While marketed as low-impact developments, their installation in arid and semi-arid zones such as Mongolia's desert-steppe may alter surface albedo, soil moisture, and local vegetation composition (Levise 2024). While some studies report new microhabitats developing beneath panels, the long-term ecological consequences for native bird species remain poorly understood. Effective siting and pre-development ecological assessment are essential to ensure that no development degrades key habitats for grassland or desert-adapted species.

Mitigation for habitat loss must prioritize strategic avoidance, steering projects away from high ecological value areas. Where avoidance is not possible, on-site minimization measures and off-site habitat compensation become critical, although replicating lost functions, particularly of intertidal wetlands or large, connected landscapes, is challenging and rarely fully effective.

3.1.2 4.1.2 Direct Mortality from Collisions and Electrocution

Collisions with wind turbines and power lines pose a well-documented threat to migratory birds. Birds traveling across coastal or inland energy corridors may collide with turbine blades, especially in poor weather or low light conditions. OWFs, now rapidly expanding in the YS and around Japan and ROK, present particular risks to seabirds such as gulls, terns, and cormorants, which often fly at rotor-swept heights. Studies in ROK have identified overlapping flight altitudes between birds and turbine blades, highlighting potential collision zones.

Onshore wind farms also impact large birds like raptors and cranes. The installation of turbines near stopover or wintering areas, such as Poyang Lake in China, may expose large numbers of waterbirds to collision risk during daily foraging flights (Zhao et al. 2012). Wind farm design, turbine height, blade visibility, and turbine spacing all influence collision rates. However, empirical mortality data from operational offshore wind farms in NEA remain scarce, making impact prediction difficult.

Power lines pose additional threats. Collisions are particularly problematic for large-bodied, low-maneuverability species such as cranes, bustards, and waterfowl. New transmission corridors across the Mongolian steppe or coastal plains of China and ROK increase exposure, especially during migration or in poor visibility conditions (Bernardino et al. 2018, Xu et al. 2019). Electrocution on power poles disproportionately affects large perching birds such as eagles, owls, and storks, particularly on medium-voltage lines with hazardous designs. In open landscapes, where trees are scarce, birds may use power poles as perches or nesting sites, increasing electrocution risk. Mitigation requires adapting infrastructure design, such as marking power lines to improve visibility or insulating dangerous components on poles. For wind energy, careful siting away from major migratory routes, flyways, and high-use bird areas is critical. However, in practice, mitigation effectiveness is often uncertain without post-construction monitoring, which is inconsistently implemented across the region.

3.1.3 4.1.3 Disturbance and Behavioral Displacement

While less visible than direct mortality, displacement due to disturbance from energy infrastructure can result in significant habitat loss. Birds may avoid areas with operational turbines, power plants, or construction activity, reducing the availability of suitable foraging or roosting habitats. OWFs have been shown to displace seabirds such as divers, which may avoid turbine arrays by distances of several kilometers, effectively shrinking usable habitat. In terrestrial settings, cranes and waterfowl have been observed to avoid areas with high human activity or noise, including near airports, roads, or energy facilities.

Barrier effects from linear infrastructure such as extensive wind farm rows, pipelines, and transmission lines may also disrupt migration patterns (Lippemeier et al. 2018). Birds may be forced to alter flight paths, increasing energy expenditure and potentially delaying arrival at key breeding or staging sites. OWFs along narrow migration corridors or in coastal bottlenecks may redirect bird movements, with poorly understood long-term consequences. Artificial lighting from energy facilities may attract or disorient nocturnal migrants, leading to altered flight paths or increased collision risk. Chronic noise from turbines, pumps, or machinery can disturb breeding birds, potentially reducing reproductive success.

Effective assessment of disturbance impacts requires behavioral studies and tracking data to quantify avoidance distances, changes in habitat use, and energetic costs. Site-specific mitigation, such as turbine shutdowns during peak migration or reduced lighting, can reduce disturbance but requires careful operational planning and verification.

3.1.4 4.1.4 Pollution from Fossil Fuel-Based Infrastructure

Fossil fuel operations pose significant pollution risks through both acute and chronic pathways. Oil spills from offshore platforms, pipelines, or tankers can devastate coastal and marine ecosystems, directly affecting seabirds through oiling and poisoning. Past oil spills in regions like Bohai Bay, China have demonstrated these risks, with long-term ecological damage to shorebird habitats (Wang and Wang 2012, Zhang et al. 2014).

Coal-fired power plants emit airborne pollutants such as mercury, which can bioaccumulate in aquatic food webs, ultimately affecting fish-eating birds like gulls and terns. Mercury contamination in Black-tailed Gulls at Kabushima, Japan, illustrates how industrial emissions can reach top marine predators, potentially impairing reproduction and survival. Discharges from LNG terminals and wastewater from fossil fuel plants may further degrade water quality, affecting invertebrate and fish populations that birds depend on (Evers et al. 2007, Kurosawa and Chiba 2005, Choi and Lee 2012). While renewable energy reduces some pollution risks, energy sector transitions must consider legacy impacts from fossil fuel operations and ensure that new infrastructure minimizes chemical and noise pollution. Improved regulatory enforcement, pollution monitoring, and emergency spill response capacity are critical across the region.

3.1.5 4.1.5 Cumulative and Synergistic Impacts in Intensively Developed Regions

The combined impact of multiple energy projects, alongside other land uses such as agriculture, aquaculture, and urbanization, creates a cumulative burden on migratory bird populations. In regions like the YS and Bohai Bay, the layering of industrial development, port expansions, reclamation projects, and energy infrastructure has led to severe habitat loss and fragmentation (Murray et al. 2015, Melville et al. 2016, Studds et al. 2017, Seitz et al. 2011, King et al. 2020)). Even if individual projects appear manageable in isolation, their combined footprint can exceed ecological thresholds, particularly for species dependent on networks of stopover and wintering sites.

Synergistic effects, where multiple stressors interact to produce greater-than-expected impacts, are poorly understood but likely significant. For example, habitat loss forcing birds into smaller areas may increase their exposure to disturbance, collisions, or predation. Climate change adds an additional layer of complexity, potentially shifting bird distributions into new areas where they may face novel infrastructure risks.

Addressing cumulative impacts requires moving beyond project-by-project impact assessments. Strategic Environmental Assessment (SEA) and regional planning are essential to evaluate the combined effects of energy policies and infrastructure development at landscape and flyway scales (Therivel and Ross 2007, Partidário and Fischer 2004, Runge et al. 2015). Coordinated data sharing, cross-sectoral governance, and long-term ecological monitoring are necessary to manage cumulative risks and ensure the resilience of migratory bird populations across NEA.

Table 17. Matrix of Energy Infrastructure Types and Documented/Potential Impacts on Migratory Bird Guilds in NEA

Energy Infrastructure Type	Shorebirds/ Waders	Waterfowl (Ducks, Geese, Swans)	Cranes & Storks	Seabirds (Gulls, Terns, Albatrosses, etc.)	Raptors (Eagles, Hawks, Falcons, Owls)	Passerines (Songbirds)
Coal Mining & Power Plants	Habitat loss (coastal/wetland sites for plants), Pollution (water, air, ash affecting foraging areas)	Habitat loss (wetlands), Pollution (water contamination, acid rain)	Habitat loss (wetlands, e.g., Poyang), Pollution	Pollution (coastal power plants affecting marine food webs)	Bioaccumulation of pollutants (e.g., mercury from coal burning)	Habitat loss, Air pollution impacts
Oil & Gas Extraction/Pipelines	Habitat loss/degradation (coastal, Arctic breeding grounds), Pollution (oil spills), Disturbance	Habitat loss/degradation (Arctic/wetland breeding/staging), Pollution (oil spills), Disturbance	Habitat loss (wetlands, riverine systems due to pipeline crossings), Disturbance	High risk from oil spills, Disturbance from offshore platforms/pipelines, Habitat degradation (Sakhalin)	Disturbance, Potential prey contamination	Habitat fragmentation from pipelines/roads, Disturbance
LNG Terminals	Habitat loss (coastal reclamation for terminals), Disturbance, Pollution (operational, shipping)	Habitat loss (coastal sites), Disturbance from shipping and operations	Disturbance at coastal staging sites	Disturbance from increased shipping, Potential pollution impacting coastal foraging	Potential prey contamination from coastal pollution	Disturbance in coastal areas
Onshore Wind Farms	Collision risk (less data, but potential in coastal/wetland sites), Habitat loss/fragmentation, Disturbance/ Displacement	Collision risk, Habitat loss/fragmentation (e.g., Poyang Lake), Disturbance/Displacement	High collision risk (e.g., Poyang Lake cranes), Disturbance, Barrier effect	Collision risk (coastal sites)	High collision risk, Disturbance, Displacement	Collision risk, Habitat loss/ fragmentation, Disturbance
Offshore Wind Farms	Potential collision/displacement for coastal species, Barrier effect during migration	Collision risk, Displacement, Barrier effect	Potential collision/displacement for coastal migrating cranes/storks	High collision risk, Displacement, Barrier effect, Habitat alteration	Collision risk for coastal/migrating raptors	Collision risk for nocturnal migrants over sea
Large-Scale Solar Parks	Habitat alteration/loss (esp. in arid/semi-arid staging areas if oases affected)	Habitat alteration/loss if sited near wetlands	Potential habitat alteration if sited in open foraging areas	N/A (typically not marine/coastal)	Potential loss of hunting grounds, Collision with associated infrastructure (fences, power lines)	Habitat alteration/loss, Microclimate changes, Potential "lake effect" collisions
Hydropower Dams	Loss/alteration of downstream/reservoir edge foraging habitats	Major habitat loss/alteration (flooding of riverine wetlands, changes to downstream flow regimes)	Significant habitat loss/alteration (breeding/staging wetlands, e.g., Amur Basin)	Indirect impacts via changes to estuarine ecosystems	Loss of riparian hunting habitat	Loss of riparian habitat
Electricity Transmission/ Distribution Lines	Collision risk, Electrocution (less common), Habitat fragmentation by corridors	Collision risk (especially large waterfowl), Electrocution (less common)	High collision risk, Electrocution risk for perching	Collision risk (coastal lines)	High electrocution risk, Collision risk	Collision risk, Habitat fragmentation by corridors

3.2 Synthesizing the Threat Landscape for Flagship Species

The preceding analyses of population status, habitat use, energy infrastructure impacts, and scenario-based projections converge to paint a detailed and nuanced picture of the threat landscape for the three flagship species. Each species faces a unique combination of pressures that defines its conservation challenge and dictates the most urgent priorities for action.

3.2.1 The Black-faced Spoonbill: Balancing Conservation Gains with Renewable Energy Risks

The case of the Black-faced Spoonbill embodies a modern conservation paradox: a species brought back from the brink of extinction by decades of dedicated international effort now finds its recovery threatened by the global transition to renewable energy. The very coastal zones that are indispensable for its survival, particularly the shallow waters and tidal flats of the Yellow Sea, are also prime locations for the massive offshore wind farms being developed by China and the ROK. This creates a direct and acute conflict between biodiversity conservation and climate mitigation goals.

The species' recovery, while remarkable, is fragile. It is predicated on the continued protection of a small number of key breeding and wintering sites and the integrity of the migratory corridor that connects them. The PVA results demonstrate that this hard-won stability could be easily undone by the new, chronic pressure imposed by OWFs. The documented barrier effect, which leads to migration failure and indirect mortality, represents a threat that current EIA practices may not be adequately capturing. The conservation of the Black-faced Spoonbill is therefore no longer just a matter of protecting specific sites from traditional threats like reclamation and pollution; it now requires a fundamental rethinking of how to manage the seascape of its entire flyway in the face of large-scale industrialization for green energy.

3.2.2 The White-naped Crane: Addressing Divergent Population Trajectories and Transboundary Challenges

The White-naped Crane presents a "tale of two populations," a narrative of starkly contrasting fates that underscores the geographically specific nature of threats and conservation effectiveness. The success of the eastern population, which winters in the well-managed and protected landscapes of the Korean DMZ and Japan's Izumi feeding station, demonstrates that targeted conservation action can yield positive results. The dramatic increase in the number of cranes wintering in Korea is a clear indicator that providing secure, food-rich habitats can support population growth.

Conversely, the precipitous decline of the western population serves as a dire warning. This population is being squeezed by pressures at both ends of its migratory route: habitat degradation in its Mongolian breeding grounds and, most critically, the severe alteration of its wintering habitat at Poyang Lake in the Yangtze basin due to large-scale water management projects and agricultural intensification. The PVA confirms that this population is on a trajectory toward extirpation and has no resilience to additional stressors from new energy infrastructure. Consequently, a conservation strategy for the White-naped Crane cannot be monolithic. It requires a dual approach: maintaining and reinforcing the successful management of the eastern population's habitats while launching an urgent, transboundary emergency intervention to diagnose and reverse the drivers of decline for the western population.

3.2.3 The Hooded Crane: Mitigating the Extreme Risk of Population Concentration

The threat landscape for the Hooded Crane is dominated by a single, overwhelming factor: the concentration of over 80% of its global population at the Izumi wintering site in Japan. This situation is both a management success—the artificial feeding program at Izumi has been instrumental in stabilizing the population—and the species' greatest liability. The PVA results confirm this intuition quantitatively, showing that the population is highly resilient to small, diffuse threats but extraordinarily sensitive to a single catastrophic event at this one location.

This "all eggs in one basket" scenario means that the primary conservation challenge is one of risk management. While protecting the Izumi site from local threats like disease, pollution, or nearby infrastructure development is paramount, a truly resilient conservation strategy must focus on reducing this dependency. The most critical long-term goal for the Hooded Crane is therefore the identification, protection, and active management of alternative wintering sites to encourage the dispersal of the population across a wider geographical area. This would create redundancy in the system, buffering the species against the potentially devastating consequences of a single localized disaster. This represents a proactive, forward-looking conservation approach aimed at building long-term resilience rather than simply maintaining the current, precarious status quo.

3.3 Policy, Mitigation, and Conservation Frameworks

Addressing the ecological risks posed by energy infrastructure to migratory birds in NEA requires not only technological solutions but also the development and enforcement of effective governance frameworks. These include national environmental policies, international conservation agreements, science-based mitigation measures, and collaborative flyway-scale management.

3.3.1 EIAs' Systems and Regulatory Gaps in NEA

EIAs serve as the primary regulatory mechanism to predict, assess, and mitigate the environmental consequences of energy development projects across NEA. However, the effectiveness of these frameworks varies among countries and often faces challenges in implementation. China, under its EIAs' Law, has recently strengthened regulatory oversight of large-scale renewable energy projects. Since 2024, provincial ecological authorities have been tasked with approving EIAs for major wind and solar developments exceeding 500,000 kW capacity (Climate Cooperation China 2025). The country has emphasized lifecycle impact assessments and integrated spatial planning using Artificial Intelligence (AI) and big data to avoid sensitive ecological zones, including bird migration corridors. Legal provisions further enable public interest litigation against projects causing environmental harm, demonstrating a growing emphasis on biodiversity protection in policy discourse.

In Japan, the Basic Environment Law mandates EIAs for major development projects. The Ministry of the Environment's Technical Guidebook outlines biodiversity considerations, including those relevant to migratory birds (Ministry of the Environment, Japan 2018). However, procedural delays and administrative pressures to accelerate renewable energy permitting have sometimes undermined the rigor of biodiversity assessments. Nonetheless, Japan's bilateral treaties on migratory bird protection with the United States and Russia provide an additional layer of conservation responsibility, reinforcing the need to incorporate avian risk assessments into project planning.

ROK's two-tiered EIA system includes SEA for policy-level reviews and project-level EIAs for individual developments. Notably, the country's experience with assessing bird collision risks for projects like the Jeju Second Airport reflects growing awareness of avian conservation in national planning (The Korea Times 2025). However, comprehensive post-construction monitoring and cumulative impact assessments remain underdeveloped.

Mongolia, under its Environmental Protection Law, requires EIAs for all major developments, including mining and energy projects. Internationally financed projects, such as those supported by the World Bank, often conduct Environmental and Social Impact Assessments (ESIAs) in line with global standards, explicitly including migratory bird considerations (Heiner et al. 2019, Murat 2017). Despite this, enforcement in remote regions, such as the Gobi Desert, can be inconsistent.

In Russia, environmental assessments are legally mandated, yet implementation is uneven. Large-scale linear infrastructure projects, such as pipelines and transmission lines across the RFE, often proceed with limited ecological scrutiny (Kalashnikov et al. 2011). Nonetheless, Russia's bilateral conservation agreements with Japan and ROK facilitate some level of cross-border ecological cooperation, providing a platform for joint research and habitat protection initiatives.

Across all jurisdictions, the consistent application of EIA principles to address migratory bird conservation remains limited. Key shortcomings include inadequate baseline data, insufficient evaluation of indirect or cumulative effects, and the lack of long-term ecological monitoring. Strengthening EIA systems requires not only procedural reforms but also the integration of flyway-scale data, stakeholder engagement, and adaptive management frameworks that can respond to emerging conservation challenges over time.

3.3.2 International Conventions and Regional Partnerships

International governance frameworks such as the Convention on Migratory Species (CMS) and the Ramsar Convention provide foundational support for migratory bird conservation across NEA. The CMS, through its Energy Task Force, has developed globally recognized guidelines for managing the risks of renewable energy development to migratory species (Convention on the Conservation of Migratory Species of Wild Animals 2024). These guidelines advocate for strategic siting, impact mitigation, and the maintenance of ecological connectivity, principles highly relevant to energy expansion in this region.

The Ramsar Convention complements these efforts by promoting the conservation of wetland habitats, many of which serve as critical stopover or wintering sites for migratory waterbirds along the EAAF. Designation of Ramsar sites elevates the conservation status of these areas, yet effective management depends on national implementation and resourcing. The EAAFP serves as a regionally tailored platform for coordinating conservation actions among governments, NGOs, and the private sector. Its Flyway Site Network identifies and promotes the management of key migratory bird habitats, while initiatives like the Regional Flyway Initiative aim to mobilize large-scale investments for habitat restoration and community engagement.

Despite these frameworks, their effectiveness is often constrained by voluntary commitments, limited enforcement, and insufficient alignment with national energy and development policies. Ensuring that these international mechanisms translate into measurable conservation outcomes requires stronger political will, enhanced institutional capacity, and cross-sectoral policy integration.

3.3.3 Challenges, Gaps, and Future Directions in Research and Monitoring

Despite a growing body of research, significant knowledge gaps continue to hamper effective conservation planning for the flagship species. The analysis in the preceding chapters, particularly the assessment of data availability for PVA, points to a clear agenda for future research and monitoring.

A primary challenge is the lack of comprehensive, long-term demographic data for many species. As highlighted in the PVA analysis, robust estimates of age-specific survival and fecundity are missing for all three flagship species, particularly for the cranes. Without these fundamental parameters, population models rely on inference and assumptions, which limits their predictive power.

For the Black-faced Spoonbill, the most urgent research need is to quantify the demographic cost of the OWF barrier effect. This requires moving beyond simple documentation of route alteration to modeling how this behavior translates into reduced survival or reproductive success. Coordinated telemetry studies that track the ultimate fate of birds that are displaced by wind farms are essential.
For the White-naped Crane, the critical priority is to fill the profound data void for the declining western population. A dedicated research program is needed to determine its basic demographic parameters (survival, fecundity) and to pinpoint the primary drivers of its decline, whether they be at its breeding grounds, stopover sites, or wintering areas. Furthermore, empirical studies on the displacement effects of wind farms on cranes in the Asian context are needed to validate the use of proxy data from North American species.

For the Hooded Crane, research should focus on the risks associated with its wintering concentration. This includes active disease surveillance at Izumi and ecological feasibility studies to identify and assess potential alternative wintering sites in Japan, Korea, or China that could support dispersed flocks.

Beyond species-specific research, there is a broader need to evaluate the real-world effectiveness of mitigation measures. While strategies like turbine curtailment or bird-friendly power line design are promoted, their efficacy for NEA species and conditions is largely untested. Rigorous, long-term post-construction monitoring at energy facilities is rarely implemented, leaving a critical gap in our understanding of what works.

Finally, all research and monitoring must be designed to account for the interacting effects of energy infrastructure and climate change. Integrated models that project how climate-driven shifts in species distribution and phenology will intersect with planned energy developments are needed to facilitate proactive, forward-looking conservation planning.

3.3.4 Strategic Recommendations for the Conservation of Flagship Species

Based on the comprehensive analysis of the threats, population vulnerabilities, and policy context for the three flagship species, the following strategic recommendations are proposed to guide conservation action by governments, the energy sector, and regional partnerships.

a) Recommendations for Siting and Mitigation of Energy Infrastructure

- *Adopt Strategic, Flyway-Scale Spatial Planning*: Governments and energy developers must move beyond project-level EIAs and adopt strategic sensitivity mapping to guide infrastructure siting at a landscape scale. This involves identifying and formally designating "no-go" zones for energy development in areas of highest ecological importance.

- *For the Black-faced Spoonbill*: The core migratory bottleneck across the Yellow Sea should be designated as a high-risk zone. No new OWFs should be permitted in this corridor without a comprehensive regional SEA that demonstrates negligible cumulative impacts.

- *For the White-naped and Hooded Cranes*: A mandatory 5-kilometer buffer zone should be established around all key breeding, stopover, and wintering sites (e.g., Poyang Lake, the Korean DMZ, Izumi) for any new wind energy development, based on the best available proxy data for crane displacement.

- *Mandate and Enforce Best-Practice Mitigation*: Where impacts are unavoidable, rigorous mitigation measures must be a mandatory condition of project approval.

- *For Offshore Wind*: For any OWFs impacting the Black-faced Spoonbill flyway, operational mitigation, including seasonal or real-time shutdowns during peak migration periods, must be required. Post-construction monitoring must be designed to assess not only direct collision but also behavioral responses and barrier effects.

- *For Power Lines*: All new transmission and distribution lines constructed in or near crane habitats must adhere to the latest avian-safe designs to prevent electrocution and must be marked with high-visibility devices to reduce collision risk. Internationally, successful case studies demonstrate that marking power lines with devices such as bird flight diverters, flappers, or spirals can significantly reduce collision mortality. A large-scale experiment in South Africa, for instance, found that marking power lines reduced collision rates for Blue Cranes (*Grus paradisea*) by 92% and for all large birds combined by 51%. However, the same study found no effect on bustards, highlighting that the effectiveness of mitigation can be species-specific and requires further research to identify the optimal solutions for different bird guilds and local conditions.

b) Recommendations for Species-Specific Monitoring and Research

- *Launch Coordinated, Flyway-Wide Telemetry Studies: A multi-partner research initiative should be established to conduct large-scale GPS tracking of all three flagship species. The primary goal is to collect the robust, long-term data on migratory connectivity, habitat use, and age-specific survival needed to fill the critical gaps identified in the PVA.*

- *Establish a Dedicated Monitoring Program for the Western White-naped Crane Population: An emergency research and monitoring program, involving collaboration between China, Mongolia, and Russia, should be created to diagnose the causes of this population's decline and to test the effectiveness of potential interventions.*

- *Develop a Contingency and Risk-Spreading Plan for the Hooded Crane: A formal contingency plan should be developed by Japanese authorities and international partners to respond to a potential catastrophic event at the Izumi wintering site. This should be coupled with a proactive, long-term strategy to identify, secure, and manage a network of alternative wintering sites to encourage population dispersal.*

c) Recommendations for Strengthening Transboundary Policy and Cooperation

- *Develop Dynamic, Threat-Responsive Action Plans for Cranes: The revision of the Black-faced Spoonbill ISSAP, which explicitly incorporates emerging threats like renewable energy, should be used as a model for developing similarly adaptive and comprehensive international action plans for the White-naped and Hooded Cranes.*

- *Establish a NEASPEC/EAAFP Task Force on Energy and Migratory Birds: A dedicated regional task force should be created to harmonize EIA standards, develop flyway-wide guidelines for mitigating energy infrastructure impacts, and promote the sharing of data and best practices among member countries. A key focus should be on developing methodologies for assessing cumulative impacts.*

- *Strengthen Bilateral and Trilateral Cooperation for Critical Habitats: Enhance targeted cooperative agreements to protect transboundary ecosystems critical to the flagship species. This includes strengthening cooperation between China, Mongolia, and Russia to protect the breeding grounds of the western White-naped Crane population, and between the ROK, DPRK, and international partners to maintain the ecological integrity of the Korean DMZ as a vital crane wintering site.*

By implementing these integrated strategies, stakeholders across NEA can work towards a future where the development of sustainable energy systems proceeds in harmony with the conservation of the region's irreplaceable migratory bird heritage.

3.3.5 Mitigation Measures for Reducing Energy Infrastructure Impacts

The imperative to diminish the detrimental effects of energy infrastructure on migratory bird populations necessitates a carefully orchestrated suite of mitigation strategies, typically structured around a hierarchical framework prioritizing avoidance, minimization, restoration, and offsetting. The effective implementation of this multi-tiered approach is paramount to ensuring the sustainable coexistence of energy development and the conservation of these ecologically significant avian species.

At the apex of this hierarchy lies avoidance through strategic siting. This represents the most ecologically prudent and ultimately effective means of mitigating potential harm by proactively steering development away from or in close proximity to areas recognized for their ecological sensitivity. These high-risk zones are often identified through the application of sophisticated sensitivity mapping tools, which delineate critical habitats such as Ramsar-designated wetlands, IBAs, and well-established migratory corridors. The exemplary adoption of guidelines from international conservation agreements, such as those stipulated by the Convention on the CMS, within national infrastructure standards, as demonstrated by Mongolia, underscores the efficacy of this proactive avoidance principle (e.g., Chimeddorj, et al. 2024).

When outright avoidance proves infeasible due to various constraints, the subsequent tier focuses on minimization through bird-friendly design. This necessitates the integration of specific avian safety measures directly into the design and construction phases of energy infrastructure projects. For power lines, this involves employing bird-safe pole configurations that reduce the risk of electrocution, insulating electrical conductors to prevent accidental contact, and deploying visual marking devices like spirals or flappers to enhance the visibility of lines and thereby reduce collision incidents (Avian Power Line 2025). In areas identified as posing a heightened risk of avian collisions, the feasibility of implementing underground cabling should be given serious consideration. Regarding wind turbines, minimization strategies include the careful micro-siting of turbines to avoid areas characterized by high bird traffic or concentrated flight paths, the application of visual modifications to turbine blades (such as differential painting to improve detectability against the sky), and the strategic management of lighting systems to minimize their nocturnalattractiveness to birds. In the context of solar farms, design modifications aimed at reducing the reflectivity of solar panels, which can disorient birds or be mistaken for water bodies, and the installation of appropriate site-specific fencing to deter terrestrial and wetland birds from entering potentially hazardous areas are crucial minimization techniques (e.g., ScienceDaily 2025).

Beyond design considerations, operational mitigation and smart curtailment offer dynamic approaches to reducing avian risks. The emergence of technologies which leverages artificial intelligence (AI) to detect approaching birds in real-time and automatically trigger the curtailment of turbine operations, showcases the potential for adaptive risk management (e.g., Energy Global 2025). While these advanced systems hold considerable promise for minimizing avian mortality, their effectiveness and applicability necessitate thorough validation within the specific ecological contexts of NEA, taking into account the region's unique avian species assemblages and migratory patterns.

Finally, in situations where residual impacts remain unavoidable even after the implementation of avoidance and minimization measures, habitat restoration and offsetting may be pursued as compensatory actions. This involves either restoring degraded habitats to a functional state or creating ecologically equivalent alternative habitats to compensate for losses. However, it is critical to acknowledge the inherent complexities and uncertainties associated with replicating the ecological functions of lost habitats, particularly critical areas such as wetlands or migratory stopover sites. Successful offsetting requires a long-term commitment to rigorous monitoring, scientific oversight to ensure ecological equivalence, and an adaptive management framework that allows for adjustments based on performance evaluations to ensure the intended ecological benefits are realized.

3.3.6 Transboundary Cooperation and Flyway-Scale Management

Given the transboundary nature of migratory bird conservation, collaborative governance at the flyway level is essential. The EAAFP provides a model for such cooperation, bringing together diverse stakeholders to manage the Flyway Site Network and implement joint conservation programs. Bilateral and trilateral agreements further facilitate cross-border research, monitoring, and species recovery efforts. ROK's partnerships with Australia, China, and Japan have enabled targeted conservation actions, such as the reintroduction of the Crested Ibis (Nipponia nippon) (Ministry of Environment, ROK 2022) and joint monitoring of Black-faced Spoonbill populations.

Regional initiatives in transboundary ecosystems, such as the Amur-Heilong River Basin and the Tumen River estuary, highlight the potential for coordinated landscape-scale conservation. This report highlights connectivity conservation underscores the importance of maintaining ecological networks that support migratory species across political boundaries.

Key elements for effective transboundary cooperation include standardized data sharing, harmonized policy frameworks, coordinated site management, and joint advocacy. Mobilizing resources for flyway-scale conservation, particularly through mechanisms like the RFI, is critical to addressing cumulative threats and ensuring the resilience of migratory bird populations in the face of expanding energy infrastructure. Despite these efforts, gaps in data integration, policy alignment, and capacity remain. Strengthening these cooperative frameworks is vital for safeguarding the ecological integrity of the EAAF and ensuring that energy development proceeds in harmony with biodiversity conservation objectives.

3.4 Synthesis: Challenges, Gaps, and Future Directions

The expansion of energy infrastructure across NEA presents multi-faceted challenges for migratory bird conservation. Increasing energy demands, policy-driven decarbonization, and large-scale deployment of renewable energy technologies are reshaping landscapes and seascapes that are critical for migratory birds along the EAAF. As energy development intensifies, balancing biodiversity conservation with infrastructure expansion becomes increasingly complex.

One of the most pressing challenges lies in reconciling the need for energy security and climate mitigation with the ecological requirements of wide-ranging migratory species. Migratory birds depend on a network of interconnected habitats across national borders, many of which now face direct or indirect pressure from wind farms, solar arrays, transmission corridors, LNG terminals, and coastal reclamation. Although EIA frameworks exist in China, Japan, ROK, Mongolia, and Russia, their implementation often falls faces challenges in adequately addressing cumulative and flyway-scale impacts. Project-specific assessments rarely capture the broader ecological consequences of energy expansion at landscape or regional scales, leaving migratory species vulnerable to fragmented planning and insufficient mitigation.

Data gaps are a significant barrier to effective impact assessment and conservation planning. While major species such as cranes and shorebirds have received research attention, there remains a lack of comprehensive demographic data on survival rates, reproductive success, and migratory connectivity for many species. Uncertainty is particularly high for emerging risks from offshore wind energy, where collision mortality, displacement, and barrier effects on seabirds and coastal migrants remain poorly quantified. For example, evidence from Europe shows species-specific responses to offshore wind farms, yet comparable data are lacking for the YS and Japanese coastal waters, despite ongoing development.

Moreover, the real-world effectiveness of mitigation measures, such as turbine curtailment, bird-friendly infrastructure design, and habitat restoration, remains insufficiently evaluated in the regional context. While operational strategies like smart curtailment and technological innovations such as bird detection systems show promise, they require localized testing to verify their efficacy for NEA species and conditions. Without robust post-construction monitoring, the success of mitigation remains speculative.

The expansion of renewable energy infrastructure introduces new ecological risks that are not yet fully understood. Floating OWFs, desert-based solar installations, and grid-scale energy storage solutions may bring novel disturbance regimes, habitat alterations, or pollution risks. Understanding these impacts before they scale up is critical to avoid repeating mistakes made in earlier phases of energy development.

The interaction between energy infrastructure impacts and climate change adds another layer of complexity. Climate-driven shifts in species distributions, migration timing, and habitat suitability could increase bird exposure to infrastructure risks in unpredictable ways. For instance, changing prey availability or coastal habitat loss due to sea-level rise may force seabirds and shorebirds to use alternative sites that coincide with energy developments, creating new conservation conflicts. Integrated research and planning that account for these interactions are urgently needed to build ecological resilience.

Policy frameworks at national and international levels provide a foundation for action but face challenges in enforcement and coordination. Regional initiatives like the EAAFP and the North-East Asian Subregional Programme for Environmental Cooperation (NEASPEC) support cooperation across countries, but translating high-level commitments into effective on-the-ground measures remains difficult. National policies often prioritize economic development, and EIA processes may lack the rigor or scope needed to fully protect migratory birds from cumulative and transboundary impacts.

Looking ahead, the energy landscape in NEA is expected to shift toward more decentralized renewable systems, with continued investment in solar, wind, LNG, and potentially new nuclear capacities. This shift, while necessary for climate mitigation, must be carefully managed to avoid displacing environmental harm from fossil fuels onto biodiversity. A nature-positive energy transition requires not only technological innovation but also robust spatial planning, cross-sectoral policy integration, and strengthened environmental governance.

Key research priorities include improving demographic and ecological data for migratory species, developing regionally adapted risk models, and rigorously testing mitigation measures. Equally important is the need for SEAs at the policy and sectoral levels to manage cumulative impacts before project approvals are granted. Transboundary cooperation must be enhanced through harmonized monitoring, joint research, and coordinated conservation planning at the flyway scale.
Ultimately, safeguarding migratory birds in NEA requires integrating energy development, climate adaptation, and biodiversity conservation into a cohesive strategy that recognizes the interconnectedness of ecological, social, and economic systems. Achieving this balance remains one of the region’s most urgent and complex sustainability challenges.

3.5 Conclusions and Strategic Recommendations

The expansion of energy infrastructure across NEA presents growing ecological risks for migratory bird conservation. As the region accelerates its transition toward renewable energy to meet climate and energy security goals, the deployment of onshore and offshore wind farms, solar arrays, LNG terminals, and transmission grids increasingly overlaps with key habitats along the EAAF. This overlap underscores the urgent need for integrated, science-based strategies that address these expanding pressures while safeguarding biodiversity at national and flyway scales.

Energy infrastructure development affects migratory birds across diverse ecosystems, including coastal wetlands, inland lakes, grasslands, and marine environments. Documented impacts include habitat loss and degradation, increased collision mortality at wind turbines and power lines, electrocution on unsafe grid infrastructure, and disturbance from noise, lighting, and human activity. Despite the presence of EIAs' systems in China, Japan, ROK, Mongolia, and Russia, implementation often faces challenges in adequately addressing cumulative and transboundary impacts. Project-by-project assessments rarely address wider ecological consequences at the landscape or flyway level, leaving migratory species exposed to fragmented planning and uncoordinated mitigation.

Data gaps remain one of the most significant barriers to effective conservation. Key knowledge gaps include species-specific survival rates, demographic trends, and behavioral responses to energy infrastructure. For instance, the lack of empirical data on seabird mortality and displacement at offshore wind farms in the YS and along the coastal waters of NEA limits the application of evidence-based mitigation. Similarly, the long-term ecological effects of large-scale solar farms in desert regions or floating offshore wind technologies remain poorly understood.

While mitigation measures such as turbine curtailment, bird diverters on power lines, and habitat restoration are available, their real-world effectiveness in NEA ecological contexts remains under-evaluated. Many projects proceed without robust post-construction monitoring or adaptive management, limiting confidence in claimed mitigation outcomes. Addressing this requires dedicated investment in long-term, standardized monitoring and the development of regionally appropriate best-practice guidelines. The interaction between energy infrastructure and climate change adds further complexity. Climate-driven shifts in species distributions, migration timing, and habitat availability may alter bird exposure to infrastructure risks in ways not yet fully accounted for in current planning frameworks. Integrated assessments that consider both climate adaptation and energy development impacts are urgently needed to build ecological resilience and ensure that the renewable energy transition does not further erode migratory bird populations.

Policy and governance reforms are essential to address these challenges. EIA and SEA processes must be strengthened to include rigorous baseline data collection, CEAs, and long-term monitoring requirements. National energy policies should incorporate biodiversity priorities, supported by spatial planning tools such as sensitivity mapping to guide infrastructure siting away from high-risk areas. Regulatory agencies must enforce mitigation measures through transparent, science-based, and participatory processes.

The energy sector also has a critical role to play. Companies should adopt corporate biodiversity policies that prioritize avoiding impacts on key habitats, implement effective mitigation measures, and invest in technological innovations to reduce avian mortality. Developers must work with independent ecological experts to conduct thorough impact assessments, fund long-term monitoring, and report outcomes transparently.

Regional cooperation is indispensable. International frameworks such as the CMS, the EAAFP, and NEASPEC provide valuable platforms for collaboration. However, stronger political commitment, harmonized data sharing, and coordinated conservation actions are required to translate high-level agreements into tangible outcomes. Regional and bilateral partnerships must move beyond dialogue to implement joint monitoring, capacity building, and policy alignment across the flyway.
Finally, targeted research is essential to fill critical knowledge gaps. Priorities include developing region-specific risk models, evaluating mitigation effectiveness under local conditions, and advancing integrated assessments of climate and infrastructure impacts. Ensuring that research findings are effectively communicated to policymakers and practitioners is vital for evidence-based decision-making. Balancing energy development with migratory bird conservation demands integrated, forward-looking strategies that recognize ecological interdependencies across borders. Only through coordinated action by governments, industry, scientists, and civil society can NEA secure both its renewable energy future and the ecological integrity of one of the world's most important migratory bird flyways.

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