Journal of Green Economy and Optimization Research / Special Issue 4, 2026

jgeor
GREEN HORIZONS

Vol. 1 · Special Issue Nº 4

CIRCULARITY · ESG

A special issue exploring pathways to sustainable development, environmental responsibility and green transformation.

e-ISSN: 3136-7968

Green Growth
Finance, efficiency and sustainable development

Resilience
Climate adaptation and ecosystem stability

Innovation
Digitalization, optimization and solutions for green transformation

JGEOR

Journal of Green Economy and Optimization Research

Vol. 1 • Special Issue № 4 • November 15, 2026

GREEN HORIZONS

Circularity · ESG · sustainable finance · green transition

ABOUT THIS ISSUE

Green Horizons *is a thematic special issue of the Journal of Green Economy and Optimization Research (JGEOR) dedicated to emerging pathways towards greener, more circular and resilient economies. The issue brings together interdisciplinary research examining the connections between* ***circular economy, environmental sustainability, ESG practices, green finance, resource efficiency, responsible production and sustainable development****. By integrating environmental, economic and policy perspectives, this special issue highlights practical and research-based approaches that can support the transition towards low-carbon development, more efficient use of natural resources and environmentally responsible economic growth.*

JOURNAL PROFILE

Publisher: Green Economy and Optimization Research Lab (GEORL), Baku, Azerbaijan

Publication model: Monthly · English · Double-blind peer review · Full Open Access

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Identifiers: e-ISSN 3136-7968 · Issue DOI 10.68210/jgeor.v1si4 · Article-level DOIs · ORCID support

Metadata & preservation: Structured article metadata · OAI-PMH harvesting · OJS publishing · Internet Archive presence

Website: jgeor.org **OAI-PMH:** jgeor.org/index.php/jgeor/oai

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FOREWORD FROM THE EDITOR-IN-CHIEF

❝ Beyond Green Growth

Dear readers,

The transition towards a greener economy is no longer defined only by environmental ambition. It increasingly depends on how effectively economies can redesign production systems, allocate capital, manage natural resources and integrate environmental and social considerations into long-term decision-making. Climate pressures, resource scarcity, biodiversity loss and growing demand for sustainable investment are reshaping the relationship between economic development and environmental responsibility. In this context, the principles of the **circular economy, ESG, sustainable finance and resource efficiency** have become increasingly important. Circular approaches seek to reduce waste and extend the productive life of materials and resources, while sustainable finance aims to direct capital towards activities that generate environmental and social value alongside economic returns. ESG frameworks, in turn, have strengthened attention to environmental performance, governance, transparency and corporate responsibility within both public and private decision-making. **Green Horizons**, Volume 1, Special Issue No. 4 of the *Journal of Green Economy and Optimization Research (JGEOR)*, brings together interdisciplinary research examining these transformations from environmental, economic, technological and policy perspectives. The issue reflects the growing need to understand not only why green transition is necessary, but also how it can be implemented in ways that are measurable, financially viable and socially resilient.

"A successful green transition requires more than environmental targets. It requires economic systems in which resources, investment and innovation are aligned with long-term ecological resilience."

The shift towards sustainable economic models also raises important questions. How can circularity be translated from principle into practice? How can green finance support genuine environmental outcomes rather than symbolic commitments? How should ESG indicators be designed and interpreted? How can businesses, governments and communities improve resource efficiency without weakening economic competitiveness? These questions require evidence-based answers and interdisciplinary cooperation. Scientific research has a central role in this process. Economic analysis can identify the costs and benefits of alternative pathways. Environmental research can measure ecological impacts and resource pressures. Finance can help mobilize investment for low-carbon and resource-efficient development, while policy research can clarify the institutional conditions needed for effective implementation.



Ulvi Mammadov

Editor-in-Chief · Journal of Green Economy and Optimization Research

Context sources

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JGEOR Journal of Green Economy and Optimization Research (JGEOR)

Volume 1 Special Issue 4, 2026
e-ISSN: 3136-7968
DOI: https://doi.org/10.68210/jgeor.a97
https://jgeor.org/index.php/jgeor/article/view/vol1-si4-pg5-7

Digital transformation in enterprises: Digital management systems, ERP and financial software, and electronic document management

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Article Information

Received: August 30, 2026
Revised: September 20, 2026
Accepted: September 26, 2026
Published: November 15, 2026
Academic Editor: Prof. Dr. Elnur Sadiqov

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Keywords
digital transformation; ERP; financial software; electronic document management; accounting information systems; digital maturity

ABSTRACT

Enterprises adopt digital management systems, enterprise resource planning (ERP) platforms, financial software and electronic document management in parallel, yet scholarship usually examines these tools one at a time. This article asks how the four can be understood as one transformation process. Using a qualitative, conceptual review of ten influential articles and books, we code the literature into four domains and compare their claims through functional–structural analysis. The synthesis yields a four-stage progression from digitization to digital maturity, an integrated system architecture built on a single data layer, and a map of strategic, technical, accounting-control and record-trust barriers. We propose, as a hypothesis for later testing, that enterprises gain most by moving from electronic document management to financial software, then to an ERP core, and finally to integrated analytics. The study contains no primary survey data; its contribution is a framework and set of propositions for empirical work, including work in Azerbaijani enterprises.

INTRODUCTION

Digital technologies have moved from supporting functions to the centre of how enterprises plan, execute and control their activities. The shift accelerated sharply during the COVID-19 pandemic, when many organizations had to move work, documents and decisions online within a short time (Amankwah-Amoah et al., 2021). Adopting technology, however, is not the same as transforming an enterprise. Vial (2019) describes digital transformation as a process in which digital technologies disrupt existing conditions, prompt strategic responses and structural change, and meet organizational barriers that can slow or distort the outcome.

Practitioners meet this problem in three recurring places: management systems chosen without a clear process logic, ERP and financial software that exchange data poorly, and electronic document flow that lacks a trustworthy record-keeping basis. Research on each area is rich but fragmented, so managers receive advice about individual tools rather than about their combination and order.

The aim of this article is to build an integrated conceptual framework of digital transformation at the enterprise level. Three research questions guide the work. *RQ1:* Through which stages does enterprise digital transformation progress? *RQ2:* How do digital management systems, ERP, financial software and electronic document management complement one another? *RQ3:* Which barriers recur across these domains, and what implementation order do they imply?

LITERATURE REVIEW

Digital transformation as organizational change

Verhoef et al. (2021) separate three notions that are often confused: digitization, the conversion of analogue information into digital form; digitalization, the use of digital technologies to change processes; and digital transformation, a company-wide change of business model and operations. Hanelt et al. (2021), reviewing the field systematically, treat digital transformation as technology-driven organizational change that touches strategy, structure and culture, and that can be incremental or radical. Westerman et al. (2014) add a managerial lens: firms become digitally advanced only when technological capability is combined with leadership capability, which explains why similar tools produce unequal results.

ERP and integrated systems

Davenport (1998) explains the appeal of enterprise systems: a single database and a common set of applications integrate information across functions. He also warns that packaged software carries built-in assumptions that can conflict with a firm's strategy, organization and

culture. Grabski et al. (2011) review ERP research with accounting information systems in mind and show that ERP changes accounting work, internal control and reporting, so that implementation questions cannot be separated from questions about the use and effects of the system.

Financial software and accounting information

Bhimani and Willcocks (2014) argue that digitisation and big data alter the nature of accounting information, making it more granular, more timely and broader in scope, and thereby challenge established roles in accounting and management control. Kokina and Davenport (2017) describe the emergence of artificial intelligence in auditing and accounting, where automation absorbs routine tasks and human work shifts toward judgment, which raises new questions about skills and oversight.

Electronic documents as records

Digitizing a document does not by itself make it a reliable record. Duranti and Thibodeau (2006), writing from the InterPARES research programme, examine what makes a record in digital environments, and stress reliability and authenticity, which depend on documented context, controlled creation and long-term preservation. This view links electronic document management directly to control, audit and legal evidence.

Research gap

The sources above converge on one point: technology alone does not explain outcomes. Yet each addresses mainly one domain. A framework that places document management, financial software, ERP and analytics in one sequence, and ties them to shared barriers, is still missing. This article offers such a framework.

MATERIALS AND METHODS

The study uses a qualitative, conceptual research design, shown in Figure 1. Ten sources were selected purposively for their influence and for coverage of four domains: digital transformation and strategy, ERP, financial and accounting software, and electronic records. All are peer-reviewed articles or books published between 1998 and 2021 (see References). Selection criteria were conceptual contribution, citation in later reviews, and direct relevance to enterprise-level systems.

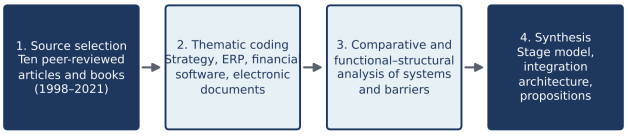


Figure 1. Research design of the study.

Analysis proceeded in three steps. First, content analysis coded each source for definitions, claimed benefits, reported risks and implied sequence of adoption. Second, a comparative analysis contrasted the four domains on function, benefit and risk. Third, functional–structural analysis examined how the systems divide tasks and exchange data, which produced the architecture in Figure 3. Process and systems perspectives guided the reading of the stage model (Verhoef et al., 2021; Vial, 2019).

Limitations. The source set is small and purposive rather than exhaustive, no primary data were collected, and the sequence proposed in Section 4.4 is a proposition, not a tested result.

RESULTS AND DISCUSSION

Stages of enterprise digital transformation

Synthesis of the sources supports a progression in four stages (Figure 2). The first three follow Verhoef et al. (2021): digitization, digitalization and digital transformation. We add a fourth, digital maturity, to describe the condition in which integrated data support real-time and predictive management; this extension is consistent with Westerman et al. (2014) but is our own proposition. Each stage changes the unit of analysis: from the document, to the process, to the business model, and finally to the data that connect them.

Functional roles of the four domains

Table 1 compares the domains. Each contributes a different kind of value and exposes a different risk, which is why they are complements rather than substitutes.

Table 1. Comparison of the four domains.

Domain	Primary function	Main benefit in the literature	Main risk	Sources
Digital management and strategy	Direction and governance of change	Alignment of technology with strategy and leadership	Technology adopted without organizational change	Vial (2019); Hanelt et al. (2021); Westerman et al. (2014)
ERP	Integrated planning and execution on one database	Cross-functional visibility and common data	Misfit between package logic and firm strategy or culture	Davenport (1998); Grabski et al. (2011)
Financial software	Recording, reporting and analysis of financial information	Timelier, richer information; automation of routine tasks	Skills gap and weaker oversight of automated work	Bhimani & Willcocks (2014); Kokina & Davenport (2017)
Electronic document management	Creation, approval, storage and retrieval of records	Traceable, controlled records supporting audit	Records that are not demonstrably reliable or authentic	Duranti & Thibodeau (2006)

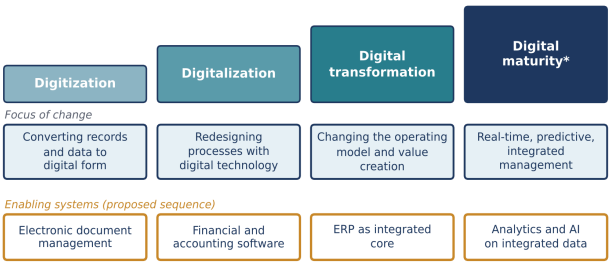


Figure 2. Stage model of enterprise digital transformation and the systems that enable each stage.

Integration architecture

Functional–structural analysis suggests the architecture in Figure 3. Three principles emerge. First, the ERP core provides one database for finance, procurement, inventory, human resources and sales, which removes repeated data entry and reduces inconsistency between

functions (Davenport, 1998). Second, document management and financial software connect to that core through controlled interfaces, so that every transaction can be traced to a record that is reliable and authentic (Duranti & Thibodeau, 2006; Grabski et al., 2011). Third, analytics and artificial intelligence sit on top of integrated data, not beside it, because more granular and timely information is useful only when it is consistent (Bhimani & Willcocks, 2014; Kokina & Davenport, 2017). Leadership, culture and skills frame the whole structure (Westerman et al., 2014).

Barriers and implementation sequence

Four barrier types recur. Strategic and organizational barriers arise when technology is introduced without changes in structure and culture (Vial, 2019; Hanelt et al., 2021). Technical barriers appear when a package does not fit existing processes (Davenport, 1998). Accounting-control barriers arise because ERP and automation change who performs and reviews tasks (Grabski et al., 2011; Kokina & Davenport, 2017). Record-trust barriers arise when electronic documents cannot be shown to be reliable and authentic (Duranti & Thibodeau, 2006). The pandemic raised the pressure to move quickly (Amankwah-Amoah et al., 2021), which makes careful sequencing more, not less, important.

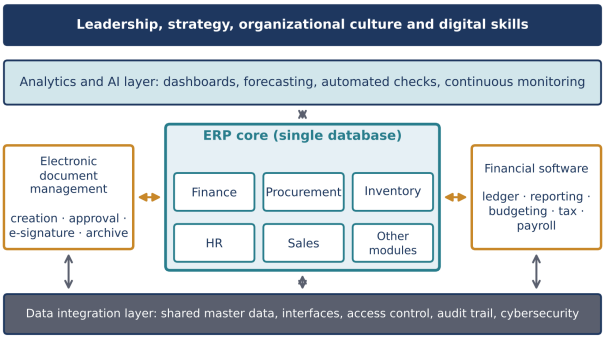


Figure 3. Integrated architecture of enterprise digital systems.

From this pattern we derive a proposition, **P1**: enterprises obtain the most durable benefit by moving through four steps. Electronic document management comes first because it creates controlled records and requires little process change. Financial software follows, because it builds on those records and raises the quality of information. An ERP core is introduced third, when processes are understood well enough to avoid misfit. Integrated analytics and AI come last, when data are consistent. The sources do not test this order directly; it is derived from their separate findings and should be examined empirically, since firm size, industry and existing systems may justify other paths. Our reading agrees with Westerman et al. (2014) and Vial (2019) that organizational capability, not tools, separates successful from unsuccessful transformation. It differs from single-domain accounts in making sequence and integration, rather than any one system, the object of analysis.

CONCLUSIONS

This article integrated four strands of literature into one framework of enterprise digital transformation. It offers a four-stage progression, an architecture in which an ERP core, document management and financial software share a governed data layer under analytics, and a typology of strategic, technical, accounting-control and record-trust barriers. It also proposes an implementation order for empirical testing. For managers, the framework suggests treating digital projects as a connected programme with attention to records, data and skills. For researchers, it supplies measurable constructs: the stage reached, the degree of integration and the barrier profile.

The main limitation is the absence of primary data and the small purposive source set. Future work should test proposition P1 in surveys or case studies of enterprises of different sizes and sectors, including Azerbaijani enterprises, and should measure how integration affects reporting quality and control.

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JGEOR Journal of Green Economy and Optimization Research (JGEOR)

Volume 1 Special Issue 4, 2026
e-ISSN: 3136-7968
DOI: https://doi.org/10.68210/jgeor.a98
https://jgeor.org/index.php/jgeor/article/view/vol1-si4-pg8-17

Birdwatching ecotourism potential in Shirvan and Gyzylaghaj wetlands

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Article Information

Received: July 20, 2026
Revised: October 11, 2026
Accepted: November 2, 2026
Published: November 15, 2026
Academic Editor: Prof. Dr. Elnur Sadiqov

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Keywords
birdwatching; ecotourism; wetland birds; Shirvan; Gyzylaghaj; green economy

ABSTRACT

The aim of this study is the comparative assessment of the birdwatching ecotourism potential and opportunities of green economy of Shirvan and Gyzylaghaj wetlands in Azerbaijan. The research makes use of a multi-source data set, which brings together official information from institutions, expert-based scoring, data from Avibase checklist, and data from Ramsar-based wetland indicators along with the summaries of bird observations from eBird and Protected Planet metadata. The methodology is based on the comparative analysis, analysis of the document, structured analysis of the dataset and 1 to 5 expert scoring process for each of the six criteria: Wetland bird observation potential, Protected and Rare species, Seasonal suitability, Infrastructure, Ecotourism development potential, and Green economy opportunities. The results show that the two areas are of great value for birdwatching-based ecotourism. This is because Shirvan National Park has a better status of the national park, and there is observation equipment in the park and a good potential for observing wetland birds. Gyzylaghaj is more internationally significant because of the Ramsar status, large number of waterbirds wintering, wide green economy potential and the wide wetland system. Active citizen science bird observation also is ongoing in both areas, as confirmed by summaries derived from eBird. The scientific novelty of the study consists in the combination in a single comparative framework of official data, international conservation records, checklist databases, citizen-science observations, and expert assessment. Birdwatching can contribute to low impact ecotourism, biodiversity awareness, a green income generation locally and sustainable management of protected areas in Azerbaijan, it concludes.

INTRODUCTION

Wetlands are and represent one of the most ecologically valuable ecosystems regarding biodiversity, protection of migratory birds, regulation of climate, water balance and tourism. They provide valuable habitats for breeding, wintering, feeding and migration of waterbirds, as well as environmental education and low impact ecotourism. Birdwatching can be incorporated into the management of the area as well as be a recreational activity, and is recognised as an important form of NbT in this context.

Birds and birdwatching are becoming more widely accepted as a means for protected area management and sustainable local development. Past research has shown how birdwatching tourism can provide funds, employment, education and tangible green economy benefits from the value of ecosystem services (Biggs et al., 2011; Liu et al., 2021; Ocampo-Peñuela & Winton, 2017). In the meantime, inappropriate nature based recreation activities can also present dangers of disturbance to birds, especially in sensitive wetland and breeding areas. Therefore, the assessment of birdwatching tourism should be not only from the point of view of an attraction for tourists, but also from the point of view of ecological sensitivity, preparedness of infrastructure, value of species, and seasonality and conservation management (Sobhani et al., 2022; Steven et al., 2011).

Wetland and semi-arid ecosystems are of importance in Azerbaijan, being sited along migratory bird flyways of regional and international importance. In these, Shirvan National Park, Gyzylaghaj are two important places for observing the wetlands birds and developing ecotourism. Shirvan National Park is a well known protected area which includes semi-desert, wetland and lake habitats, bird observation infrastructure and is one of the national protected areas. According to the Protected Planet profile, Shirvan National Park is a national park, under IUCN category II, with an area of 543.74 km² (UNEP-WCMC, 2026b). Gyzylaghaj, however, is of high international wetland value. It was designated under the Ramsar Sites Information Service code Ghizil-Agaj (1076) with an area of 99,060 ha on 21 May 2001 (Ramsar Sites Information Service, 2026). It is also an area of importance for wintering and nesting waterbirds in Europe and the Western Palearctic (Ramsar Sites Information Service, 2001).

Official and structured ecological research data also reveals the ecological significance of these sites. Official response – Biological Diversity Conservation Service under the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan (Biological Diversity Conservation Service under the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, 2026) provides information about the observation of wetland birds, protected species, observation periods, infrastructure. This official information was also treated as a data set for comparative analysis as a research (Qadimli & Mammadov, 2026). Furthermore, checklist data from Avibase are used in the

taxonomic verifications for Shirvan and taxonomic proxy verifications for Gyzylaghaj and detailed wetland/waterbird indicators are available for Gyzylaghaj from the Ramsar database (Mammadov, 2026d). Additionally, the summaries created using the eBird data show that citizen science bird observations were made in both the study areas for the 2020-2026 period (eBird Basic Dataset, 2026; Mammadov, 2026b).

Although these are separate data sources there has been no comprehensive assessment of the birdwatching ecotourism potential in Shirvan and Gyzylaghaj in a comparative green economy approach. The available data are scattered across official institutional records, international conservation databases, checklist records, Ramsar records, citizen science records, and expert knowledge. Therefore, there is a challenge to compare the two areas/regions with respect to Bird Observation potential, Protected Species values, Seasonal suitability, Infrastructure and Green Economy and Ecotourism development.

This paper aims to compare the birdwatching ecotourism potential and green economic opportunities of two wetlands, Shirvan and Gyzylaghaj wetlands in Azerbaijan. To achieve this goal, the study used a multi-source approach and included official data from institutions, expert-based scoring, Avibase checklist data, Ramsar indicators, eBird observation summaries and Protected Planet metadata. The specific objectives of the study are: Identification of the main ecological and tourism resources of each region; comparison of the birdwatching value according to well-defined criteria; evaluation of the value of protected and rare birds for ecotourism and practical recommendations for the sustainable birdwatching development.

A combined approach of official information, international wetland registration, checklist databases, citizen science observation summaries and expert assessment in a comparative context is the novel component of this research. In this way, it can be treated as bird watching and as a possibility for the use as a tool for green economy - for the development of local services, the sustainable environmental education, the visibility and awareness of protected areas in Azerbaijan.

METHODOLOGY

Thus, in order to determine the birdwatching ecotourism potential and green economy opportunities of Shirvan National Park and Gyzylaghaj National Park, Azerbaijan, the comparative multi-source research design was used. The methodological framework used official data obtained from institutions, databases from international protected areas, data from Ramsar wetlands, data from Avibase checklist, data from citizen-science summaries of eBird and expert based scoring. This method was chosen because there are no one source or indicator to evaluate the birdwatching ecotourism potential. This should be based on an analysis of ecological value, bird diversity, importance of protected species, seasonality for observations, infrastructure readiness, visitor accessibility, and green economy relevance.

Two protected sites, Shirvan National Park and Gyzylaghaj National Park, were selected as study area. The selection of these sites has been made based on the following: Both sites are significant for observing wetlands birds; the sites are ecologically distinct; the sites have international recognition; the sites have developed infrastructure; and the sites have potential for tourism development. Shirvan National Park was evaluated as a nationally designated protected area with existing birdwatching infrastructure, and Gyzylaghaj National Park was evaluated as an internationally significant wetland system with Ramsar status, and high concentration of waterbirds.

The research was carried out in four methodological stages. The first phase dealt with the collection and classification of data sources. The second stage was dedicated to structuring and verifying of ecological, institutional and bird observation indicators. The third stage involved an expert-based 1–5 scoring system to compare the two sites based on the six birdwatching ecotourism criteria. The fourth stage was an interpretation of the results from an ecotourism and green economy perspective. The primary data sources and their uses in the analysis are shown in Table 1.

Table 1. Data sources and role of analysis in the study

Data source	Type of data	Analytical role in the study
Official response of the Biological Diversity Conservation Service	Official institutional data	Used to identify wetland bird observation potential, protected species, observation periods, and existing infrastructure in Shirvan National Park and Gyzylaghaj National Park
Official response-based structured dataset	Author-prepared structured dataset	Used to systematize official data for comparative analysis
Protected Planet / WDPA profiles	International protected area metadata	Used to compare area size, designation, protected area status, IUCN category, and management-related metadata
Ramsar Sites Information Service materials	International wetland data	Used to describe Gyzylaghaj National Park's Ramsar status, wetland components, waterbird importance, wintering role, and international ecological significance
Ramsar-based structured dataset	Author-prepared structured dataset	Used to systematize Ramsar indicators for Gyzylaghaj National Park
Avibase-based checklist dataset	Taxonomic and checklist data	Used for species checklist verification for Shirvan National Park and regional proxy verification for Gyzylaghaj National Park
eBird-based structured observation summary	Citizen-science observation data	Used to compare observation records, sampling checklists, unique species, observation dates, protocols, and locality-level birdwatching activity
Expert-based comparative assessment dataset	Expert scoring data	Used to compare both sites through six birdwatching ecotourism criteria

Data on official institutional was obtained from the Biological Diversity Conservation Service, Ministry of Ecology and Natural Resources, the Republic of Azerbaijan, through the response letter. This source gave details on wetland birds observed, protected and rare birds, best time of day to see birds, and available birding facilities. The official information has also been organized for analytical use as a data set (Biological Diversity Conservation Service of the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, 2026; Qadimli & Mammadov, 2026).

Protected area profile of Shirvan National Park and Gyzylaghaj National Park were described based on Protected Planet data. The data were used to compare site area, designation, protected area type, IUCN category, status and management related metadata based on UNEP-WCMC (2026a, 2026b). The international wetland importance of the Gyzylaghaj National Park was evaluated using the Ramsar Sites Information Service materials, which includes the Ramsar site number, the date of the designation, the area of the site, the coordinates, the wetland components, the importance of wintering waterbirds, and the ecological role (Ramsar Sites Information Service, 2001, 2026). The indicators were also structured as a dataset in an author-prepared Ramsar-based structured dataset (Mammadov, 2026d).

Taxonomic verification was carried out using checklist data from Avibase. In the case of Shirvan National Park, Avibase offered direct checklist support. There was no direct Avibase checklist for Gyzylaghaj National Park, and so a regional proxy approach was used, based on checklist data from nearby areas (Lankaran, Masalli and Neftchala). This means that the Avibase data for Gyzylaghaj National Park were considered as additional regional checklist data only and not real park level occurrence data (Mammadov, 2026a).

Supplementary citizen-science data were used from eBird. eBird Basic Dataset files were not redistributed. Author-prepared structured summaries were, however, used. These summaries involved observation record, sampling checklist, locality level activity, observation period, observation protocol, top recorded species, and unique species for Shirvan National Park and Gyzylaghaj National Park and monthly activity. The data from eBird were not used alone to assess species richness or abundance, but rather to assess observation activity and public birdwatching visibility (eBird Basic Dataset, 2026; Mammadov, 2026b).

A comparison between the two sites was conducted using an expert-based assessment using a 1–5 scoring system. The six criteria considered were: wetland bird observation potential, protected or rare species, time period suitable for observation, facilities, ecotourism development potential and green economy opportunities. A separate score was given for each criterion for Shirvan national park and for Gyzylaghaj national park. Then, the relative birdwatching ecotourism potential of the two sites was compared with the expert scores (Mammadov, 2026c).

The outcome of the methodology is presented in the following section in the form of tables, maps, field photographs and charts. A comparison of the protected area and wetland profile is given in Table 2. The map of the study area Shirvan National Park is shown in Figure 1 and Gyzylaghaj National park is shown in Figure 2. The comparative scoring based on expert opinion is displayed in Table 3 and Chart 1. A summary of the observations is provided here using eBird and presented in Table 4, with the data displayed on Chart 2 and Chart 3. The interpretation of birdwatching infrastructure, landscape characteristics, visitor experience, and environmental education potential are supported by field photos taken at Shirvan National Park and Gyzylaghaj National Park and included in the discussion section.

There are a number of limitations in the study. For one, it is not based on systematic field counts by the authors in both areas in the same season. Secondly, the data for Gyzylaghaj National Park are derived from a regional proxy and not from a site-specific checklist. Third, eBird data are dependent on citizen-science activity and can be affected by distribution of observers, access, seasonality, and the intensity of reporting. Given this, eBird was not used as the primary source for ecological interpretation but rather as a supplemental data source to know where observation activity was occurring. The combination of the above-mentioned information sources – official information, Ramsar records, Protected Planet metadata, Avibase checklist verifications, eBird summaries, and expert assessments – gives a relatively good ground for the comparison of the birdwatching ecotourism potential in Shirvan National Park and Gyzylaghaj National Park.

RESULTS

Protected area and wetland profile

Comparative analysis demonstrates that Shirvan National Park and Gyzylaghaj National Park are two types of birdwatching ecotourism destinations, complementary to each other in Azerbaijan. This encompasses the presence of bird observation facilities, semi-desert and wetland habitats, IUCN category II profile, and a clear national park status of Shirvan National Park. Gyzylaghaj National Park, on the other hand, is characterized by the presence of a larger wetland system, Ramsar designation, coastal and shallow water ecosystems and international significance as a wintering and migratory waterbird site. The protected area and wetland profile of the two study sites is presented in Table 2.

Table 2. Comparative protected area and wetland profile of Shirvan National Park and Gyzylaghaj National Park

Indicator	Shirvan National Park	Gyzylaghaj National Park
Main ecological character	Semi-desert, wetland and lake-related habitats	Large coastal wetland, bays, reed belts and shallow water areas
Protected area profile	National park	National park and internationally important wetland system
Reported area in Protected Planet	543.74 km²	1303.85 km²
Protected area type	Terrestrial and inland waters protected area	Marine and coastal protected area
Designation	National Park	Emerald Network profile and Ramsar wetland context
IUCN category	II	Not reported
Status	Designated	Designated
Status year	2003	Not reported in Protected Planet; Ramsar designation in 2001
Ramsar status	Not applicable	Ghizil-Agaj Ramsar Site, site number 1076
Ramsar area	Not applicable	99,060 ha
Main birdwatching value	Accessible wetland bird observation and existing infrastructure	International waterbird importance and wintering bird concentration

Source: *Protected Planet / WDPA profiles, Ramsar Sites Information Service materials, and author-structured datasets (Mammadov, 2026d; Ramsar Sites Information Service, 2001, 2026; UNEP-WCMC, 2026a, 2026b).*

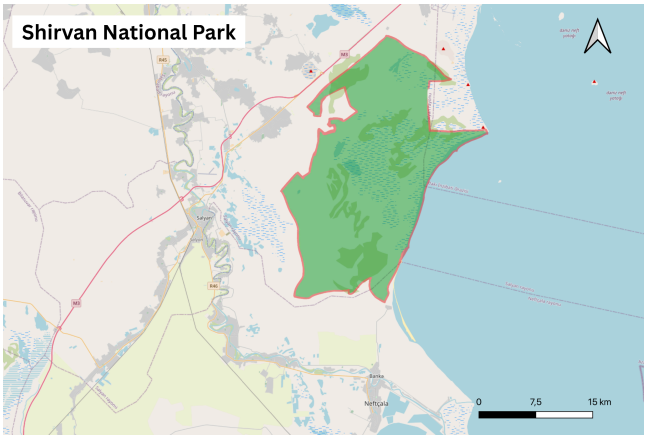


Figure 1. Map of Shirvan National Park
Source: *Author's own elaboration in QGIS.*



Figure 2. Map of Gyzylaghaj National Park / Gyzylaghaj wetland system
Source: *Prepared by the authors in QGIS based on Ramsar Sites Information Service boundary data for the Ghizil-Agaj Ramsar Site.*

The findings show that there is a more distinct national park management profile in Shirvan National Park. With its IUCN category II designation and nationally-designated protected area status, it can be managed for structured visitors, educational routes and controlled bird observation. They are also well endowed with existing observation infrastructure that further enhances their potential for organised birdwatching tourism.

The Gyzylaghaj National Park has a better international wetland profile. Its IUCN category is not included in the Protected Planet profile, but the Ramsar data indicates the international importance of the area. The Ghizil-Agaj Ramsar Site was designated on 21st May 2001 and has an area of 99,060 ha. This facilitates the international recognition of Gyzylaghaj National Park and opens up great opportunities for Ramsar based ecotourism branding, scientific tourism, birdwatching routes, and wetland education programmes.

Institutional data on wetlands' observation of birds.

The official institutional information is consistent with that both Shirvan National Park and Gyzylaghaj National Park are important for observation of wetland birds. The official answer from the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan's Biological Diversity Conservation Service, reveals that an annual winter survey of resident and migratory birds is held in various localities of Azerbaijan. These counts include waterbirds and other wetland associated species including ducks, coots, bustards, flamingos, pelicans, spoonbills, swans, geese and other species of conservation or ecological importance.

The official answer points out that Shirvan National Park and Gyzylaghaj National Park are of great significance for the observation of rare and protected wetland bird species. Species listed in the official institutional information are Great White Pelican, Dalmatian Pelican, Eurasian Spoonbill, Greater Flamingo, Mute Swan, Red-breasted Goose, Marbled Duck and swamphen species. These species contribute to the conservation and ecotourism values of both study areas, particularly for birdwatchers looking for rare, protected and visually interesting waterbirds.

The official data also give valuable information on observation seasonality. Those in April–May and September–October are considered as good observation periods as they are the migration and seasonal movement periods. Further, winter months are pertinent in relation to large numbers of wintering waterbirds. This seasonality indicates that the birdwatching ecotourism at Shirvan National Park and Gyzylaghaj National Park should not only be summer related. Rather, it can be expanded to a multi-season activity, particularly in spring migration, autumn migration and wintering seasons.

As far as the infrastructure is concerned, the official response shows that there are two facilities for bird watching in Shirvan National Park; an observation platform and a lake observation house or ornithological observation point. This is an advantage for Shirvan National Park, since the visitors are already prepared. The primary places for observation in Gyzylaghaj National Park relate to the coastal zones of Small and Big Gyzylaghaj bays. This means that Gyzylaghaj National Park has good observation potential in terms of habitat but needs to further develop its birdwatching infrastructure and planning for visitors.

Ramsar results for Gyzylaghaj National park

Based on the Ramsar results, it can be concluded that Gyzylaghaj National Park is of exceptional importance for wetland at international level. The Ghizil-Agaj Ramsar Site is one of the most important wetland systems in Azerbaijan and is known as an important wintering and nesting area for waterbirds. The area is one of the key locations in Europe and the Western Palearctic for waterbirds according to the documentation of Ramsar and this fact provides Gyzylaghaj National Park a solid international conservation and ecotourism identity.

According to the Ramsar data, the site is characterized by large wetland complexes, including the Large Gyzylaghaj Bay, the Small Gyzylaghaj Bay, reed beds and shallow waters as well as surrounding semi-desert. The habitat components provide the appropriate ecological conditions for various bird species, such as: ducks, geese, swans, pelicans, flamingos, herons, spoonbills, and other water associated species. It is particularly interesting for birdwatching due to the presence of open waters, shallow bays, reeds and coastal wetland habitats.

The Ramsar Information Sheet mentions that the site hosts over 20,000 waterbirds and has previously hosted very large waterbird wintering populations. Additionally, the structured data on basis of Ramsar also bring attention to the fact that the area is home to nearly 270 species of birds and approximately half a million wintering waterbirds in recent times. All these indicators indicate that the national park Gyzylaghaj is more concentrated on waterbirds in international aspects than Shirvan National Park.

The results of the Ramsar-based approach also indicate that there is a high potential for ecotourism in the Gyzylaghaj National Park, which is not yet utilised. According to the Ramsar documentation, the

reserve has great potential for tourism and recreation, which have to be managed. This is significant because birdwatching tourism cannot be of benefit to local economies if it impedes the wintering, feeding, and nesting birds.

Water regime changes, fluctuations of Caspian Sea level, reed expansion, grazing, poaching and human disturbance are the main ecological risks identified in information on Ramsar. As can be seen from these risks, development of birdwatching tourism in Gyzylaghaj National Park requires a low impact approach. Balancing development of tourism with conservation of wetlands would require observation towers, guided routes, seasonal regulations for access, visitor codes, and controlled viewing points.

Expert-based comparative assessment

The expert-based assessment provides a structured comparison of Shirvan National Park and Gyzylaghaj National Park according to six birdwatching ecotourism criteria. The results are presented in Table 3.

Table 3. Expert-based birdwatching ecotourism assessment of Shirvan National Park and Gyzylaghaj National Park

Assessment criterion	Shirvan National Park	Gyzylaghaj National Park	Interpretation
Wetland bird observation potential	5	4	Both sites have high potential; Shirvan was evaluated slightly higher for structured observation potential
Presence of protected and rare species	5	4	Both sites support protected and rare bird species
Seasonal suitability for observation	4	5	Gyzylaghaj has stronger seasonal value due to migration and wintering importance
Infrastructure	3	3	Both sites require further improvement in birdwatching infrastructure
Ecotourism development potential	4	5	Gyzylaghaj has stronger international ecotourism positioning
Green economy opportunities	3	5	Gyzylaghaj shows stronger potential for green economy-linked wetland tourism
Mean score	4.00	4.33	Gyzylaghaj has a slightly higher overall expert-based score

Source: Expert-based comparative assessment dataset (Mammadov, 2026c).

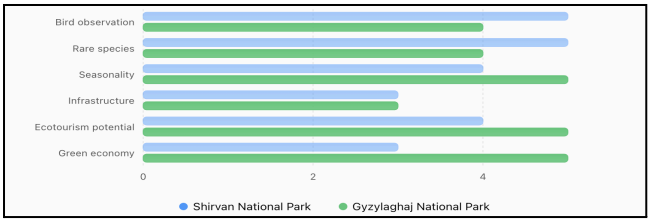


Chart 1. Expert score comparison between Shirvan National Park and Gyzylaghaj National Park

Source: Expert-based comparative assessment dataset (Mammadov, 2026c).

Results from the experts indicated that both locations are suitable for birdwatching ecotourism, but with different strengths. Shirvan National Park was the best score for wetland bird watching and protected and rare species. This outcome is a consequence of its current observation infrastructure, national park identity and suitability for birdwatching structured routes.

Gyzylaghaj National Park (GPG) was awarded higher scores for seasonal suitability, ecotourism development potential and green economy opportunities. This is a reflection of the park's Ramsar status, high wetland coverage, and significance for wintering waterbirds and the potential for international birdwatching tourism. The mean score of Shirvan National Park was 4.00 and the mean score of Gyzylaghaj National Park was 4.33. This means that the overall expert-based potential in Gyzylaghaj National Park is slightly higher, primarily due to its international wetland status and the greater opportunities for green economy.

Both sites were rated as 3 for infrastructure. This indicates that the birdwatching infrastructure of both areas is not fully developed. Shirvan National Park has existed observation facilities but they should be improved in terms of visitor interpretation, signage, route design and educational information. There is a high habitat value in the Gyzylaghaj National Park, but it is in the need of more structured birdwatching facilities such as hides, platforms for bird viewing, birdwatching routes and visitor management.

Data from bird observations made using eBird.

Results from eBird suggest citizen-science activities that reveal bird observations in both study areas. These measures are not definitive bird numbers but rather a reflective measure of observer efforts, checklist submissions, electronic detection and birdwatching participation. The results are shown in Table 4.

Table 4. eBird-based bird observation summary for Shirvan National Park and Gyzylaghaj National Park, 2020–2026

Indicator	Shirvan National Park	Gyzylaghaj National Park
Observation records	16,180	9,927
Sampling checklists	520	417
Unique species	295	258
Date range	2020-01-09 – 2026-05-23	2020-01-10 – 2026-05-22
Complete checklists	419	275
Total effort distance	5,850.88 km	1,873.53 km

Total duration	95,333 min	34,473 min

Source: *eBird Basic Dataset-derived structured summary (eBird Basic Dataset, 2026; Mammadov, 2026b).*

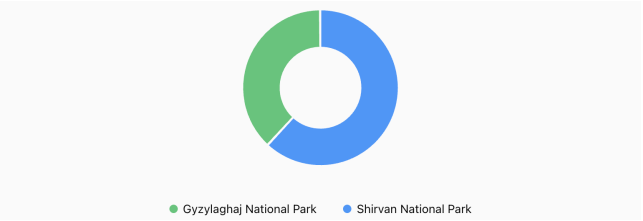


Chart 2. eBird observation records and sampling checklists in Shirvan National Park and Gyzylaghaj National Park
Source: eBird Basic Dataset-derived structured summary (eBird Basic Dataset, 2026; Mammadov, 2026b).

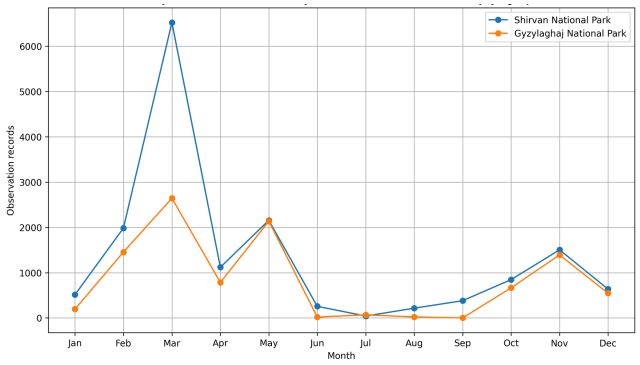


Chart 3. Monthly eBird observation activity in Shirvan National Park and Gyzylaghaj National Park
Source: eBird Basic Dataset-derived structured summary (eBird Basic Dataset, 2026; Mammadov, 2026b).

As is seen from results obtained from eBird, Shirvan National Park is more active in observation activity of citizens than Gyzylaghaj National Park. Shirvan National Park was also home to 16,180 observation records, 520 sampling checklists and 295 species in the timeframe of 2020-2026. During a comparable period in Gyzylaghaj National Park 9,927 observation records, 417 sampling checklists and 258 species were registered.

The reason for such an increase in the number of records in Shirvan National Park could be related to easier access, more frequent visits of observers, more structured routes or higher visibility among birdwatchers. It could also be a result of the underlying birdwatching infrastructure that exists and supports more frequent birdwatching activity. These however should not be read as an indication of the ecological value of Shirvan National Park compared to that of Gyzylaghaj National Park. eBird data are subject to observer distribution, access, and reporting behavior and checklist submission intensity.

There are less eBird records in Gyzylaghaj National Park, however, the ecological and international wetland value of this park is very high according to the results of Ramsar and experts. For this reason the difference between Shirvan National Park and Gyzylaghaj National Park in the eBird data should not be read as a difference in bird abundance or conservation relevance, but rather as a difference in observation activity recorded in the two parks.

They also demonstrate that both sites have a birdwatcher presence in digital citizen science platforms on eBird. The prominence of digital tools in the birdwatcher's toolkit, for planning trips, compiling species lists, recording sightings, and sharing the information, makes this significant for the development of ecotourism. The digital visibility of both national parks could be further enhanced by increasing quality of visitor information, observation points and route guidance.

Avibase-based checklist verification

The study is supplemented with checklist data from the Avibase. The case of Shirvan National Park was a direct checklist and used for supporting species richness and birdwatching relevance of the area. This enhances the status of Shirvan National Park as a known birding site.

A direct Avibase checklist was not available for Gyzylaghaj National Park. Thus, the regional proxy approach was employed, which is based on the analysis of the regions close to the study area (Lankaran, Masalli, Neftchala). These areas have ecological and geographical significance to the wider southern and coastal wetland region. But there are drawbacks to the proxy method. It is not a substitute for actual in the field monitoring or official site-level species records in Gyzylaghaj National Park. Rather, it offers additional regional checklist data to complement the general richness of the wetland and coastal area.

So the results obtained from Avibase differ for the two study areas. Avibase provides direct checklist support for Shirvan National Park. For Gyzylaghaj National Park it provides regional verification and taxonomic context. This separation is crucial to ensure that the checklist data are not over-interpreted and for methodological transparency.

Field visual interpretation

Birdwatching ecotourism potential is interpreted with the help of field pictures and maps. The map of Shirvan National Park and the map of Gyzylaghaj National Park were used to determine the spatial context of the study areas and to illustrate their significance in the context of protected area-based tourism planning. Both national parks have field photos of landscape, visitor facilities, conditions for viewing, and environmental education opportunities.



Figure 3. Shirvan National Park birdwatching infrastructure
Source: *Photo by Ulvi Mammadov.*



Figure 4. Shirvan National Park environmental education and field observation activity
Note: *The photo includes Hikmat Ganbarov, guide of Shirvan National Park, with permission.*
Source: *Photo by Ulvi Mammadov.*



Figure 5. Gyzylaghaj National Park wetland landscape
Source: *Minstry of Ecology and Natural Resources of Republic of Azerbaijan*



Figure 6. Gyzylaghaj National Park bird habitat and observation area
Source: *Minstry of Ecology and Natural Resources of Republic of Azerbaijan*

Other than species presence, birdwatching ecotourism depends on experience, landscape visibility, accessibility to birding opportunities, safety, educational interpretation and quality of the infrastructure, which are important factors to consider with visual materials. In the Shirvan National Park the field photographs are effective to demonstrate observation infrastructure, semi-desert wetland landscapes, routes for visitors and environmental education activities. In the Gyzylaghaj National Park, the use of field photography can be useful to illustrate the size of the area of wetland, the reed belts, the coastal viewing sites and the attractiveness of the birdwatching area.

What is the best way to integrate the findings; how to make sense of the results?

Based on the results of integration, Shirvan National Park and Gyzylaghaj National Park are not competing birding areas. Instead, they should be viewed as complementary sites within the framework of the birdwatching ecotourism in Azerbaijan.

In terms of benefits, Shirvan National Park has been superior when it comes to structured visitors access, birdwatching infrastructures, direct checklist support and bird observation activity on eBird. Suitable for education birdwatching routes, student field visits, for beginner birdwatching programs and for controlled nature based tourism activities.

The Gyzylaghaj National Park is more advantageous in terms of international importance, Ramsar identity, wintering waterbird concentration, seasonal observation value, green economy potential. This is suitable for specialised birdwatching tourism, Ramsar wetland education, international promotion of green tourism and community linked green tourism services.

The two sites can be used as a model for birdwatching ecotourism in Azerbaijan. Shirvan National Park can be developed as a more accessible and educative birdwatching site and Gyzylaghaj National Park can be developed as a flag bearer, Ramsar wetland site of high international ecological value. This complementary model would contribute to the awareness of the biodiversity and protected areas, green income in the local area and sustainable management of visitors.

DISCUSSION

The results of the study indicate that Shirvan National Park and Gyzylaghaj National Park have positive birdwatching ecotourism profiles, but with different characteristics. Shirvan National Park has observation-related infrastructure and a national park identity is being developed, so it is more suitable for conducting structured and accessible birdwatching activities and has a greater visibility in citizen-science activities. However, Gyzylaghaj National Park is more important in terms of international wetland significance due to its Ramsar status, the size of the wetland system, importance in terms of wintering waterbirds and potential for green economy oriented ecotourism development.

In an ecotourism point of view, these two locations are not seen as competitive destinations. Rather, they can establish a complementary network of birdwatching in Azerbaijan. Shirvan National Park is a potential birdwatching and education-oriented park for broader access and Gyzylaghaj National Park is a potential Ramsar wetland national park for specialized birdwatching, wetland education and international nature tourism. Such a complementary model is aligned with the broader view of birdwatching and avitourism as a type of low impact nature based tourism (NBT) that can foster conservation consciousness, education of visitors and local economic development (Biggs et al., 2011, Eagles et al., 2002, Steven et al., 2015).

Results also verified the need for planning birdwatching ecotourism activities in the context of seasonal ecological sensitivity. According to the official information concerning the institutions, the period of April-May and September-October are considered as appropriate observation periods, and the winter months are also important in terms of the observation of large numbers of wintering waterbirds. In both national parks this suggests the possibility for birdwatching tourism to be developed outside the traditional summer tourism season. Specialist observation routes, guided tours, educational field visits and citizen science activities can be developed based on the spring migration, autumn migration and wintering periods. But it is recommended that these activities should be arranged in a proper way that does not disturb feeding, resting, nesting and wintering birds (Biological Diversity Conservation Service, under the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, 2026; Steven et al., 2011).

According to the expert assessment, the state of infrastructure is a medium criterion in both national parks. This finding is significant because birdwatching tourism relies on birds, but also on the accessibility for visitors, safety for viewing, interpretative materials, tour design and viewing conditions. Shirvan National Park currently has facilities for observation and a lake house for observation and ornithological observation, which can be enhanced by providing better signage, route maps, species information boards, multilingual interpretation and visitor guidelines. National Park Gyzylaghaj has more identity as a wetland and Ramsar, but needs more organized infrastructure like observation hides, towers for viewing, marked routes, orientation points for visitors, and controlled areas.

When comparing the two parks with the data from eBird, it is observed that, the Shirvan National Park has more citizen-science observation activity compared to the Gyzylaghaj National Park. This could be due to improved access, increased visits or greater awareness to birdwatchers. However, use of eBird data should not be used as official abundance data. They are a reflection of observer activity and digital intensity of reporting and are influenced by access, seasonality, observer distribution or platform use. Therefore, eBird should not be relied upon as a primary information for conservation or tourism purposes, but rather as a complementary tool to understand birdwatching visibility (eBird Basic Dataset, 2026; Mammadov, 2026b).

The relatively low eBird activity in Gyzylaghaj National Park does not diminish its ecological significance. The site is of exceptional international importance for waterbirds as indicated in the Ramsar data, and supports large wintering populations and valuable wetland habitats. Thus, it is reasonable to put digital and physical visibility of Gyzylaghaj National Park as one of the strategic priorities, without applying additional pressure to the ecology. This can be done by establishing guided viewing routes, control viewing areas, limiting visitors during sensitive times, and enhancing visitor information on birds and research.

Ecotourism based on birdwatching is of special interest for green economy potential for both national parks. Birdwatching can help to generate local green income via trained local guides, eco-education initiatives, small-scale bird-watching services, local accommodation and transport, interpretation materials and NBT products. Meanwhile it can raise public awareness on wetland conservation and on protected species. When avitourism is coupled with well-managed protected areas and community involvement, it has been found to contribute to job creation and conservation funding in previous studies (Biggs et al., 2011; Liu et al., 2021; Ocampo-Peñuela & Winton, 2017).

But, birdwatching tourism should not be undertaken as mass tourism. There are sensitive habitats and protected species in both Shirvan National Park and Gyzylaghaj National Park. Noise, disturbance around nesting or wintering areas, uncontrolled visitor movement, disturbance by off-road activity and activities by drones could pose ecological risks. Hence, the management of visitors should be based on low impact principles, clear route planning and the seasonal restriction, with an emphasis on educating visitors about the environment. This is particularly relevant to Gyzylaghaj National Park (NGP), where Ramsar-related information indicates that ecological pressures are present, including water regime changes, grazing, poaching, reed expansion and human disturbance (Ramsar Sites Information Service, 2001, 2026).

Field visual materials further aid the practical interpretation of ecotourism potential. The photos taken in Shirvan National Park show the existence of observation infrastructures, the semi-desert wetland landscape, the visiting routes and the educational bird watching activities. Scale of wetland habitats, reed belts, coastal landscape and bird observation areas can be illustrated on the basis of similar field photographs from Gyzylaghaj National Park. The importance of these visual materials is that birdwatching tourism relies on both the ecology value and experience.

The key strategic recommendations on birdwatching ecotourism development in Shirvan national park and Gyzylaghaj national park are shown in Table 5.

Table 5. Recommendations for the implementation of birdwatching ecotourism in Shirvan National Park and Gyzylaghaj National Park

Direction	Recommendation	Expected contribution
Seasonal planning	Develop spring, autumn, and winter birdwatching routes based on migration and wintering periods	Extends ecotourism beyond summer and increases seasonal tourism value
Visitor infrastructure	Improve observation platforms, hides, signage, route maps, and interpretation boards	Increases visitor safety, learning quality, and birdwatching experience
Protected species awareness	Prepare multilingual species guides focusing on rare and protected wetland birds	Strengthens biodiversity awareness and conservation education
Local guide training	Train local guides in bird identification, visitor management, and wetland interpretation	Creates green jobs and supports local income generation
Citizen science	Encourage responsible use of eBird and similar platforms by visitors and researchers	Improves digital visibility and long-term observation data
Visitor management	Apply low-impact access rules, quiet zones, route control, and seasonal restrictions	Reduces disturbance to feeding, nesting, and wintering birds
Ramsar-based branding	Promote Gyzylaghaj National Park as an internationally important Ramsar wetland destination	Strengthens international ecotourism identity
Educational tourism	Develop school, university, and youth field programs in Shirvan National Park	Supports environmental education and youth engagement
Monitoring	Establish regular monitoring indicators linking biodiversity, tourism, and local economic benefits	Supports evidence-based protected area management
Green economy integration	Connect birdwatching with local services, eco-products, transport, and community participation	Transforms ecosystem value into sustainable local economic opportunity

CONCLUSION

The aim of this study was to compare the birdwatching ecotourism potential and green economy opportunities of Shirvan National Park and Gyzylaghaj National Park, Azerbaijan. The research was carried out by applying a multi-source methodological framework, which relied on official institutional information, Protected Planet metadata, data from Ramsar wetlands, Avibase checklist evidence, summaries of eBird citizen science data and expert based scoring.

It indicates that the two National Parks have a good potentiality for the development of bird watching based ecotourism, albeit with different strengths. Due to the clear national park status, availability of observation infrastructure, checklist and the higher visibility in citizen-science of Shirvan National Park, it is more suitable for structured and accessible birdwatching activities. Gyzylaghaj National Park is more important for international wetland significance because of its Ramsar status, larger wetland system, importance for waterbirds during the winter season, and higher scores of experts for seasonal suitability, ecotourism development potential and green economy opportunities.

The study validates the potential of birdwatching as an ecotourism activity without any great environmental impact, and as an approach to create awareness on biodiversity, environmental education, protected area visibility, local green income and sustainable management of visitors. Nevertheless, when planning the birdwatching tourism activities, it should be ensured that sensitive wetland habitats and feeding areas, nesting sites and wintering waterbirds are not disturbed.

The main scientific result of the study is the convergence of the official data, international conservation information, checklist databases, citizen-science summaries and expert assessment. It offers a means to evaluate the importance of birdwatching as a green economy instrument for protected area management in Azerbaijan, and as a leisure activity.

A final conclusion is that Shirvan NP is very likely to become an add-on to Gyzylaghaj NP for birdwatchers, rather than a competitor. Shirvan National Park could be developed to become a very easily accessible birdwatching educational park and Gyzylaghaj National Park could be promoted to become a Ramsar birdwatching flag park for international ecotourism. Both these national parks can play a role in creating a model for national birdwatching ecotourism that is rooted in the principles of biodiversity conservation, the involvement of communities, environmental education, and sustainable green economy.

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JGEOR Journal of Green Economy and Optimization Research (JGEOR)

Volume 1 Special Issue 4, 2026
e-ISSN: 3136-7968
DOI: https://doi.org/10.68210/jgeor.a99
https://jgeor.org/index.php/jgeor/article/view/vol1-si4-pg18-21

Green energy transition and energy security in Western Europe through a comparative analysis of Germany, France, and the Netherlands from 2015 to 2024

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Article Information

Received: October 16, 2026
Revised: October 29, 2026
Accepted: November 4, 2026
Published: November 15, 2026
Academic Editor: Assoc. Prof. Dr. Lala Valiyeva

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Keywords
renewable energy; energy security; import dependence; Western Europe; Eurostat

ABSTRACT

This study compares the trajectories of renewable energy transition and selected indicators of energy security in Germany, France, and the Netherlands from 2015 to 2024. Its principal objective is to assess whether an increased renewable energy share coincided with lower energy import dependence. The analysis draws on the Eurostat nrg_ind_ren and sdg_07_50 statistical series and applies descriptive trend analysis, end-point changes in percentage points, and a comparison of changes in import dependence during 2022. Between 2015 and 2024, the share of renewables in gross final energy consumption rose from 14.9% to 22.5% in Germany, from 14.8% to 23.2% in France, and from 5.7% to 20.2% in the Netherlands. Over the same period, energy import dependence increased from 62.1% to 66.8% in Germany and from 48.4% to 70.6% in the Netherlands, while decreasing from 45.9% to 41.7% in France. The findings show that a growing renewable energy share did not consistently coincide with declining import dependence across the three countries. The article argues that energy security assessments must also consider domestic production, cross-border energy trade, infrastructure, and resilience to supply shocks. The descriptive comparison does not establish causality, and its methodological limitations are explicitly acknowledged.

INTRODUCTION

The energy transition in Europe is no longer confined to the objective of reducing greenhouse gas emissions. International trade in energy commodities, geopolitical supply risks, and changes in domestic production structures increasingly link renewable energy policies with energy security. The disruptions affecting European energy markets in 2022, in particular, brought supply diversification, energy conservation, and the accelerated deployment of clean energy to the same policy agenda (European Commission, 2022; Council of the European Union, 2026).

Although a higher renewable energy share might intuitively be expected to reduce import dependence, the relationship is neither direct nor uniform across national energy systems. Domestic solar and wind generation may displace imported fuels, while declining domestic gas output, changes in aggregate energy demand, trade in petroleum products, and transit activities may simultaneously alter overall import dependence (Carfora et al., 2022).

A single indicator therefore cannot establish the direction or magnitude of these competing mechanisms. This study asks whether the increase in the renewable energy share between 2015 and 2024 was accompanied by a decline in energy import dependence in Germany, France, and the Netherlands. Although the three countries operate under a common European Union policy framework, their resource endowments and energy mixes differ. The empirical contribution lies in comparing two harmonised official indicators over the same observation period, while explicitly avoiding causal claims concerning the security effects of the energy transition.

LITERATURE REVIEW

Cherp and Jewell (2014) conceptualise energy security not merely as the physical availability of energy resources but in terms of the low vulnerability of vital energy systems. This approach considers infrastructure, adaptive capacity, and recovery from disturbances alongside access, affordability, and political risks. Energy import dependence is therefore a relevant, but incomplete, proxy for energy security. Carfora, Pansini, and Scandurra (2022) investigate energy flows and import demand in European Union countries and identify the potential benefits of substituting domestic renewable energy production for imports. Their empirical framework also underscores the importance of differences across countries. Sovacool et al. (2021) examine the social and institutional consequences of low-carbon transitions, highlighting energy justice, vulnerable populations, and interventions across multiple levels of governance.

Following amendments adopted in 2023, the European Union established a binding target for renewable energy to account for at least 42.5% of gross final energy consumption by 2030. Since 2022, the REPowerEU framework has presented energy savings, diversified supply, and the expansion of clean energy as interrelated strategic priorities (European Commission, 2023; Council of the European

Union, 2026). These policies provide the institutional setting of this study, but their separate effects on national indicators are not identified in the present analysis.

MATERIALS AND METHODS

This study employs a descriptive comparative design based on secondary statistics for Germany, France, and the Netherlands. The observation period covers ten annual data points from 2015 to 2024. The first variable, $R_{i,t}$, denotes the share of energy from renewable sources in gross final energy consumption (%) and is obtained from Eurostat dataset nrg_ind_ren. The second variable, $D_{i,t}$, measures net energy imports as a proportion of gross available energy (%) and is drawn from the Eurostat sdg_07_50 series, based on nrg_ind_id (Eurostat, 2026a, 2026b).

For each indicator and country, the end-point change is calculated as $\Delta X_i = X_{i,2024} - X_{i,2015}$ and reported in percentage points (pp). An additional comparison for import dependence in 2022 uses $\Delta D_{i,2022} = D_{i,2022} - D_{i,2021}$. Figure 2 was generated using Python and Matplotlib from the reported annual observations. No interpolation, forecasting, or synthetic data generation was used.

Figure 1. Historical map of Western Europe circa 180 CE, illustrating the region's territorial and geopolitical configuration during the Roman period.



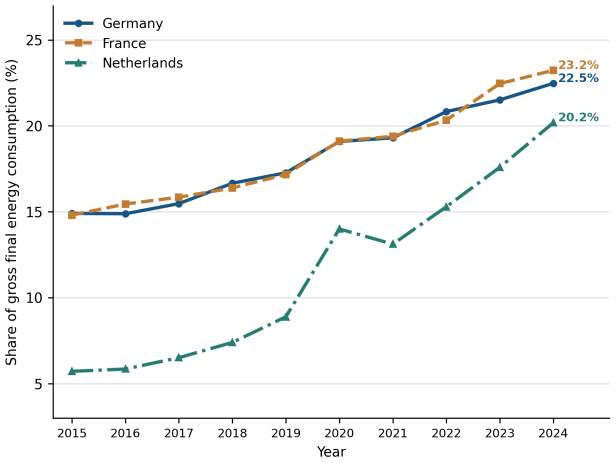
Source: William Robert Shepherd (c. 1911), Wikimedia Commons. Public domain.

The indicators have different denominators: renewable energy is expressed relative to gross final consumption, whereas import dependence is calculated relative to gross available energy. Although both changes are reported in percentage points, their levels cannot be added or subtracted to construct an energy balance. In view of the small, purposively selected sample, this study does not use regression estimates or statistical significance tests that could encourage an unwarranted causal interpretation.

RESULTS AND DISCUSSION

Figure 2 presents the growth trajectories of the renewable energy share in all three countries. In Germany, the indicator increased from 14.901% in 2015 to 22.474% in 2024, a rise of 7.573 percentage points. France recorded an increase from 14.803% to 23.229%, equivalent to 8.426 percentage points. The Netherlands experienced the largest increase, from 5.714% to 20.180%, or 14.466 percentage points (Eurostat, 2026a).

Figure 2. Share of renewable energy in gross final energy consumption in Germany, France, and the Netherlands, 2015–2024 (%)



Source: Eurostat, nrg_ind_ren (DOI: 10.2908/NRG_IND_REN). Chart prepared using Python/Matplotlib.

The chart also shows that the renewable energy share in the Netherlands increased from 8.886% in 2019 to 13.999% in 2020. After declining to 13.117% in 2021, it resumed its upward trajectory. Because this indicator measures a proportion rather than an absolute volume of energy, these changes do not by themselves establish the installed capacity of new facilities or the quantity of electricity they generated. Table 1 compares the beginning and end of the observation period for both indicators. From 2015 to 2024, energy import dependence increased by 4.680 percentage points in Germany and by 22.192 percentage points in the Netherlands, whereas it decreased by 4.223 percentage points in France (Eurostat, 2026b). Thus, the increase in renewable energy shares was not accompanied by a uniform direction of change in import dependence across the three countries.

Table 1. Comparison of renewable energy shares and energy import dependence by country, 2015–2024

Country	Renewable energy share (%) 2015 → 2024 (Δ pp)	Energy import dependence (%) 2015 → 2024 (Δ pp)
Germany	14.9 → 22.5 (+7.6 pp)	62.1 → 66.8 (+4.7 pp)
France	14.8 → 23.2 (+8.4 pp)	45.9 → 41.7 (−4.2 pp)
Netherlands	5.7 → 20.2 (+14.5 pp)	48.4 → 70.6 (+22.2 pp)

Note: Δ denotes the 2024 value minus the 2015 value, in percentage points (pp). Values are rounded to one decimal place. Sources: Eurostat, nrg_ind_ren and sdg_07_50 (based on nrg_ind_id).

These results suggest that import dependence cannot be understood solely through the renewable energy share. In the Netherlands, the marked increase in import dependence despite rapid renewable energy expansion warrants closer consideration of changes in domestic extraction and trade structures. Both indicators also increased in Germany, while they moved in opposite directions in France. Understanding the relative contribution of specific mechanisms would require additional variables concerning energy balances, electricity generation, oil and gas production, and international energy flows.

The 2022 energy crisis warrants separate consideration. Between 2021 and 2022, import dependence increased by 5.257 percentage points in Germany, 7.783 percentage points in France, and 21.791 percentage points in the Netherlands. These changes coincided with a period of heightened geopolitical supply risks, but a one-year difference cannot establish the effect of a particular event. REPowerEU seeks to integrate energy conservation, supply diversification, and accelerated renewable energy development (Council of the European Union, 2026).

From a policy perspective, a secure and equitable transition requires attention to the connections among energy infrastructure, supply chains, social impacts, and levels of governance. Figure 3 therefore provides a placement frame for an externally published scientific diagram concerning the policy dimensions of low-carbon transitions, developed in the research of Sovacool et al. (2021). The diagram illustrates a general policy framework and must not be interpreted as an empirical result from the three-country statistical comparison undertaken here.

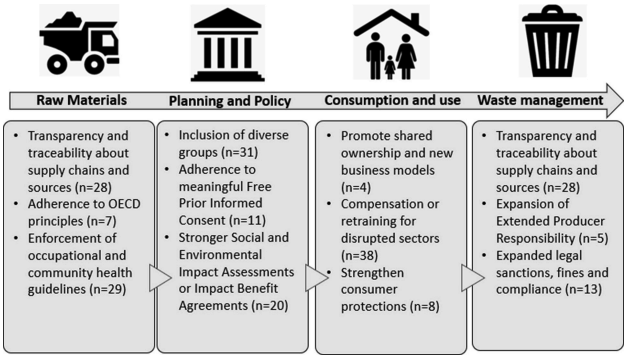


Figure 3. Multi-scalar policy measures for reducing vulnerability during low-carbon transitions - placement frame for an existing scientific diagram Original research associated with the image: Sovacool et al. (2021), World Development, 137, 105116, https://doi.org/10.1016/j.worlddev.2020.105116. The Wikimedia Commons file page documents its attribution and CC BY 4.0 licence.

The study has several limitations: a purposive selection of only three countries, reliance on two aggregate indicators, no separate decomposition of energy imports by fuel, production volume, prices, or cross-border network connections, and possible statistical revisions during the 2015–2024 period. The different denominators further preclude the construction of a direct mechanical relationship between the two percentages. Future research could develop a panel dataset incorporating sectoral energy balances, the origin of imports, electricity interconnections, and price shocks.

CONCLUSIONS

Between 2015 and 2024, the share of renewable energy in gross final consumption increased in Germany, France, and the Netherlands. Yet energy import dependence rose in Germany and the Netherlands and declined in France. In the Netherlands, renewable energy share grew by approximately 14.5 percentage points, while energy import dependence increased by 22.2 percentage points. A rising renewable energy share therefore does not automatically indicate an improvement in overall energy security as measured by import dependence.

The central implication is that the energy transition and energy security should be evaluated jointly, but through distinct measures. Policy planning should combine investments in renewable energy with energy efficiency, import diversification, grid integration, and measures to strengthen strategic resilience. The present analysis describes differences in observed trajectories and does not estimate the independent causal effects of specific policies.

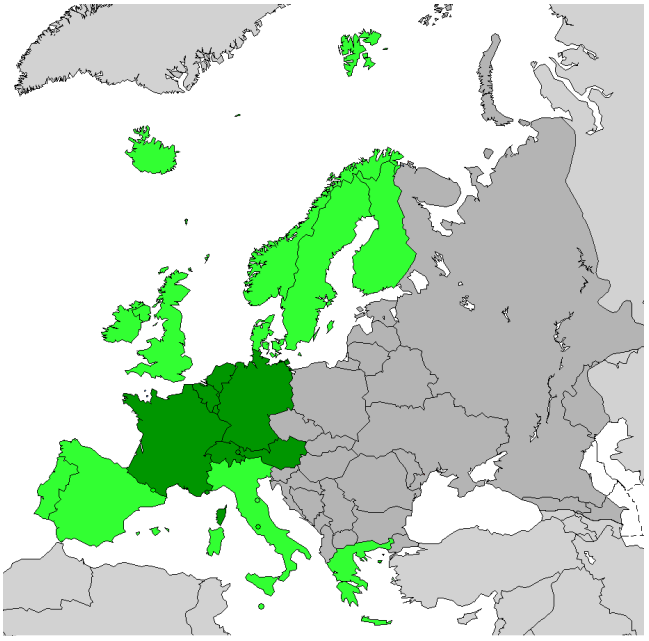


Figure 4. Share of energy from renewable sources in European countries in 2024.
Source: Eurostat (2025), Wikimedia Commons, CC BY 4.0.

AUTHOR CONTRIBUTIONS

Zamin Mammadov: study concept, methodological framework, and initial manuscript draft. Final review and approval by the author are required.

CONFLICTS OF INTEREST AND FUNDING

Declarations must be confirmed by the author. Information on funding and potential conflicts of interest has not yet been provided.

DATA AVAILABILITY

The secondary statistical data analysed in this study are publicly accessible through the Eurostat nrg_ind_ren and sdg_07_50 series. Dataset identifiers and access links are provided in the reference list. The statistical series were accessed through an archived data intermediary on 12 November 2026.

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JGEOR Journal of Green Economy and Optimization Research (JGEOR)

Volume 1 Special Issue 4, 2026
e-ISSN: 3136-7968
DOI: https://doi.org/10.68210/jgeor.a100
https://jgeor.org/index.php/jgeor/article/view/vol1-si4-pg22-26

Optimising AI-driven cyber defence for European energy infrastructure through economic risk modelling and cyber diplomacy

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Article Information

Received: October 4, 2026
Revised: October 16, 2026
Accepted: November 12, 2026
Published: November 15, 2026
Academic Editor: Dr. Elnur Arifzade

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Keywords
AI-driven cyber defence; energy infrastructure; economic optimisation

ABSTRACT

European electricity systems increasingly depend on interconnected digital control infrastructure while artificial intelligence (AI) is being introduced into cyber-threat detection. This study examines the economic and energy implications of AI-assisted cyber defence in the European energy sector and the relevance of cross-border cyber diplomacy for operational resilience. It integrates publicly documented indicators from ENISA, the International Energy Agency, Eurostat, and IBM with a transparent scenario-based decision model for a hypothetical critical-energy operator. ENISA analysed 4,875 cybersecurity incidents during July 2024–June 2025, of which 1.7% were classified in the energy sector. IEA estimates indicate European data-centre electricity use of 68 TWh in 2024 and 114 TWh under its 2030 Base Case. The decision model assumes a 15% annual probability of a significant incident, an illustrative EUR 2 million impact per incident, a EUR 60,000 annual fixed AI-defence cost, and a 10 kW incremental IT load. Under these assumptions, the required reduction in expected incident loss to break even is 27.6%. A 40% reduction yields an annual net benefit of approximately EUR 37,136, whereas a 25% reduction remains below break-even. All economic results are conditional simulations rather than measured field performance. The findings support risk-based procurement, energy metering, human oversight, and trusted cross-border incident-information exchange as complementary instruments of cyber resilience and green economic optimisation.

INTRODUCTION

Cybersecurity has become an important condition for the reliability of the low-carbon electricity transition. Digital monitoring, distributed generation, interconnectors, demand response, and supervisory control and data acquisition (SCADA) systems improve coordination but also create additional technical dependencies. A cyber incident affecting an electricity operator can therefore produce operational losses that are not captured by the number of publicly recorded incidents alone. For international security analysis, the issue is not only technical protection but also how public authorities exchange warnings, establish compatible regulatory expectations, and cooperate when disruptions cross national borders (ENISA, 2025; European Commission, 2025a).

Artificial intelligence may help security teams process telemetry, triage alerts, and identify anomalous network behaviour. Yet AI-driven monitoring has costs, including electricity demand, compute infrastructure, model validation, human oversight, and adversarial exposure. The International Energy Agency (IEA, 2026) forecasts a marked increase in electricity use by European data centres, reinforcing the relevance of measuring the resource cost of digital security. An economically rational defence programme should account for both the loss reduction that security controls might deliver and the additional resources needed to operate them.

The study addresses three questions. First, what do current official reports reveal about European cyber-threat exposure and the electricity context for AI deployment? Second, under what assumed incident probabilities, avoided losses, and computing loads would AI-enabled defence be economically justified? Third, how might cyber diplomacy and governance reduce coordination failures in cross-border critical infrastructure? The article contributes a reproducible decision-analytic framework, rather than claiming to estimate the causal effectiveness of an untested AI system.

LITERATURE REVIEW AND POLICY CONTEXT

Cyber risk in the energy sector has a distinctive public-interest dimension because service continuity affects households, business activity, health services, and neighbouring electricity systems. ENISA (2025) reports 4,875 curated events from July 2024 to June 2025, drawing substantially on public incident information. The energy sector represents 1.7% of the classified incident distribution, but the category percentage must not be treated as the probability of an energy-system outage or as an estimate of the monetary harm caused by an attack. Public reporting is uneven, a large fraction of incidents lack sector attribution, and incident type and impact are heterogeneous.

The European policy framework increasingly recognises such interdependencies. Directive (EU) 2022/2555 (NIS2) extends

cybersecurity risk-management and incident-reporting obligations to essential and important entities, including relevant parts of the energy sector. The EU Cyber Solidarity Act, which entered into force on 4 February 2025, provides for interconnected national and cross-border cyber hubs and a cybersecurity emergency mechanism. The European Commission explicitly identifies AI and advanced analytics among the technologies intended to support cross-border threat detection and early warning (European Commission, 2025a, 2025b).

NIST Cybersecurity Framework (CSF) 2.0 places governance alongside identify, protect, detect, respond, and recover as functions of organisational cyber-risk management (Pascoe et al., 2024). The NIST AI Risk Management Framework provides a complementary approach to trustworthy deployment of AI (Tabassi, 2023). Neither framework demonstrates that an AI detector reduces attacks by a particular percentage. Their value in this study is conceptual, guiding oversight, evidence documentation, controls testing, and the identification of residual risks.

The economic dimension is equally important. IBM (2025) reports a cross-industry global mean data-breach cost of USD 4.44 million, but this figure is not used here as an energy-sector loss estimate because the underlying population, loss definition, and currency differ. Instead, the analysis uses explicitly hypothetical values to show the threshold conditions under which an operator would choose an AI-enabled defence system. The methodology permits replacement of these inputs with operator-specific observations when they become available.

MATERIALS AND METHODS

Research design. The article combines descriptive analysis of published institutional statistics with a deterministic scenario model. The ENISA sectoral percentages refer to the July 2024–June 2025 reporting window. IEA figures describe total European data-centre consumption for 2023–2025 and the 2030 Base Case, not consumption solely attributable to cybersecurity or AI. Eurostat provides the contextual EU renewable-electricity share in 2024. All statistics retain their original denominators. The additional economic model is a hypothetical single-operator exercise and does not infer an empirical relationship between ENISA incident shares and breach probabilities.

Let p denote the baseline probability of an economically material cyber incident in one year, L the conditional loss in EUR, r the proportionate reduction in expected loss attributed to the new defence arrangement, F its fixed annual cost, P the incremental information-technology power in kW, h = 8,760 annual operating hours, u the facility power-usage-effectiveness (PUE), and c the electricity unit price in EUR/kWh. Annual energy use and expected net benefit are defined by Equations (1) and (2).

$$E = P \times h \times u \ (kWh/year) \quad (1)$$

$$NB = pLr - F - cE \ (EUR/year) \quad (2)$$

$$r^* = (F + cE)/(pL) \quad (3)$$

$$Q = Eg/1{,}000 \ (t\ CO_2/year) \quad (4)$$

The break-even reduction is r* = [F + cE(P)]/(pL) when pL > 0 (Equation 3). Illustrative additional operating emissions are Q = E(P) × g/1000 tonnes CO_2/year, where g is an explicitly assumed emissions intensity (Equation 4). These are accounting identities, not estimated causal parameters. No claim is made that AI energy overhead scales linearly with achieved security efficacy.

For transparent sensitivity analysis, the baseline scenario assumes p = 0.15/year, L = EUR 2,000,000 per incident, F = EUR 60,000/year, u = 1.45, c = EUR 0.18/kWh, g = 0.20 kg CO_2/kWh, P = 5, 10, or 20 kW, and r = 0.10, 0.25, 0.40, or 0.55. The European PUE value of 1.45 for 2024 is reported by IEA (2026); all other numeric operating-cost and risk inputs are illustrative, not observational estimates. The model excludes the initial capital expenditure, possible cloud subscription changes, rebound effects, and service quality impacts. These omissions are discussed as limitations.

RESULTS AND DISCUSSION

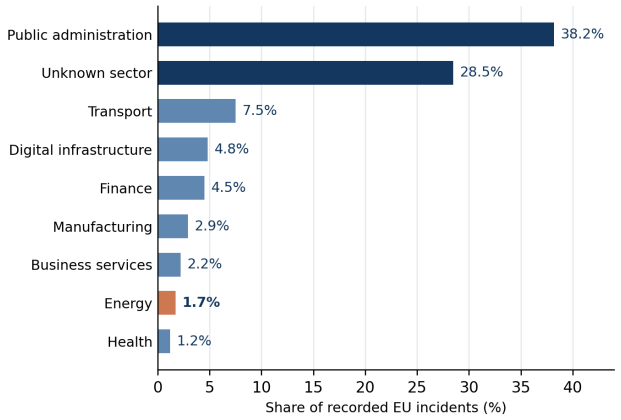


Figure 1. Sectoral distribution of recorded EU cyber incidents in ENISA Threat Landscape 2025

Source: Author-created chart from ENISA (2025), Fig. 7. Shares are percentages of curated, publicly recorded events and do not measure severity.

Figure 1 shows that public administration accounted for 38.2% of the incident distribution, while 28.5% of incidents lacked a specified sector. The energy sector represented 1.7% of reported events. Given the denominator and missing attribution, the latter is not a reliable basis for assigning an annual loss probability to a specific electricity utility. This distinction is central to responsible modelling: the empirical distribution establishes a policy context, while the probability p in Equation (2) remains a scenario parameter.

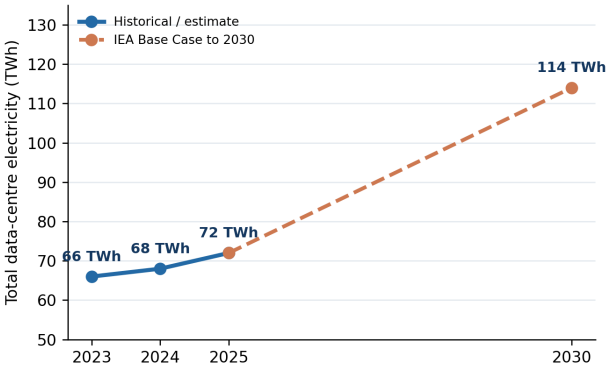


Figure 2. European data-centre electricity demand in 2023–2030

Source: Author-created chart from IEA (2026), Annex A, Table A.4. 2030 is the IEA Base Case forecast; the series covers all data centres, not cyber-defence systems.

Figure 2 indicates 68 TWh of electricity consumption by European data centres in 2024 and a projected 114 TWh in 2030, a 67.6% rise from the 2024 baseline. The implied six-year compound growth rate is (114/68)^(1/6) − 1 = 8.99% per year. This growth provides a rationale for including electricity demand in cybersecurity procurement, but no fraction of this regional total can be attributed to cyber-defence software from the available data. Eurostat (2026) reports that 47.5% of EU gross electricity consumption was from renewable sources in 2024, reinforcing the need to distinguish green-electricity penetration from the absolute load of digital services.

Table 1. Verified contextual indicators and analytical interpretation

Indicator	Value	Meaning for study
ENISA recorded events	4,875	EU cyber context, 2024–25
Unclassified sector	28.5%	Limits sector attribution
Energy sector share	1.7%	Not an annual breach probability
European DC demand 2024	68 TWh	All data centres
European DC demand 2030	114 TWh	IEA forecast, Base Case
EU renewable electricity 2024	47.5%	Gross consumption share

Sources: ENISA (2025); IEA (2026); Eurostat (2026). DC = data centre. Reporting windows and denominators are not interchangeable.

For the hypothetical energy operator, the reference AI configuration has P = 10 kW and u = 1.45. Equation (1) gives 127,020 kWh/year (127.02 MWh) of incremental facility electricity and EUR 22,863.6/year in electricity expenditure. Together with fixed annual costs of EUR 60,000, total recurring expense is EUR 82,863.6. Baseline expected cyber loss equals pL = EUR 300,000/year. Consequently, Equation (3) yields r* = 82,863.6/300,000 = 27.6212%. At a 25% assumed reduction, the net annual benefit is negative EUR 7,863.6; at a 40% reduction, it is positive EUR 37,136.4. These values are model outputs, not observed savings attributable to a named algorithm.

Table 2. Scenario break-even conditions for a hypothetical energy operator

AI IT load	Energy/y	Cost/y	Break-even r*
5 kW	63.51 MWh	EUR 71,431.8	23.81%
10 kW	127.02 MWh	EUR 82,863.6	27.62%
20 kW	254.04 MWh	EUR 105,727.2	35.24%

Illustrative parameters: p = 0.15; L = EUR 2.0 million; F = EUR 60,000; c = EUR 0.18/kWh; PUE = 1.45. Costs include fixed defence costs and incremental electricity.

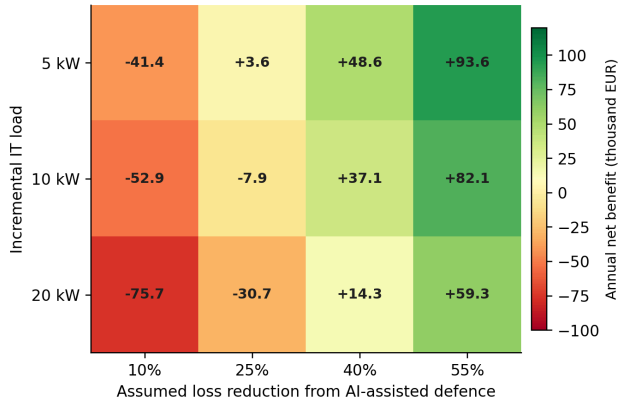


Figure 3. Scenario sensitivity of the annual net benefit to AI effectiveness and power demand

Source: Author calculations using Equation (2) and Table 2 parameters. Values inside cells are thousands of EUR/year. Neither probability nor AI efficacy is empirically calibrated.

Figure 3 makes the interaction between security efficacy and computing resources visible. Even an assumed 25% reduction in expected incident losses does not cover the cost of the 10 kW reference deployment; a reduction of 40% does. Moving from a 5 kW system to a 20 kW system raises the annual electricity bill by EUR 34,295.4 under the assumed tariff, even if loss reduction remains unchanged. Hence, procurement based solely on detection accuracy, without monitoring electricity and realised loss avoidance, can produce a socially and financially inefficient outcome.

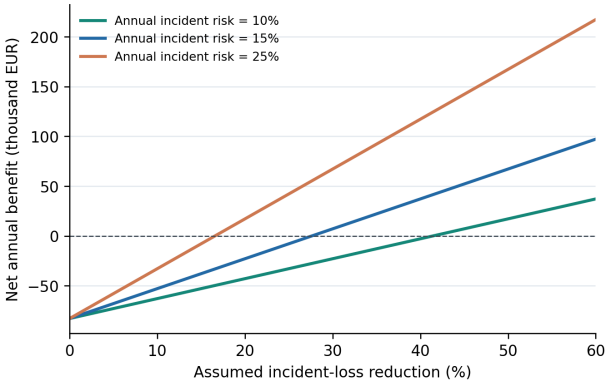


Figure 4. Influence of baseline incident probability on the financial break-even point

Source: Author calculations for the 10 kW reference deployment. The 10%, 15%, and 25% risk probabilities are deliberately hypothetical.

The financial threshold also depends on the exposure to be protected. At p = 0.10, the 10 kW deployment breaks even when r reaches 41.43%; at p = 0.25, the threshold falls to 16.57%. A higher estimated risk or a larger conditional loss increases the potential value of effective controls. Conversely, energy price escalation, additional labour expenditure, false alerts, or model-retraining costs increase the required effect size. A decision to procure a specific system therefore requires actual incident histories, auditable operating costs, and a pre-specified effectiveness evaluation.

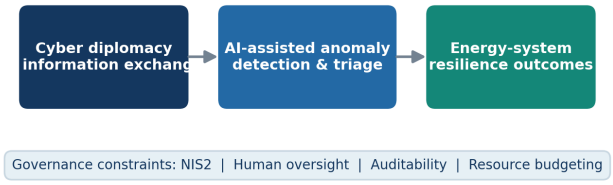


Figure 5. Conceptual integration of cyber diplomacy, AI defence and green economic resilience

Source: Original conceptual diagram developed for this study. Governance principles are informed by NIS2, the EU Cyber Solidarity Act, NIST CSF 2.0 and the NIST AI RMF.

Figure 5 highlights the institutional element of the optimisation problem. Information-sharing agreements, common incident taxonomies, and cross-border cyber hubs may improve warning quality and incident coordination, while energy operators remain responsible for auditable technical decisions. A coordination arrangement should specify access control, retention rules, the authority to override AI recommendations, and a protocol for

communicating cross-border events. Such policy mechanisms are plausible resilience enablers, but the present data cannot assign them a quantified causal benefit.



Figure 6. Source-image placement frame for an authoritative scientific framework diagram
Original NIST diagram and source attribution: https://www.nist.gov/image/nist-cybersecurity-framework-20 (NIST / Natasha Hanacek, 2024). The source image is linked, not reproduced.

ENVIRONMENTAL AND DIPLOMATIC IMPLICATIONS

The energy cost in Equation (1) is not environmentally neutral. Under the assumed emissions factor g = 0.20 kg CO_2/kWh, the reference deployment entails 25.40 tonnes of additional annual operational emissions; the 5 kW and 20 kW options imply 12.70 and 50.81 tonnes, respectively. These are hypothetical accounting estimates, not measured emissions of EU operators. A renewable electricity contract or a different grid mix could change the relevant marginal emissions. Reporting only an annual electricity bill would therefore omit a potentially material externality of cybersecurity operations.

Cross-border protection has consequences for green investment. Electricity networks are subject to geographical interdependence: a cyber incident or a failure to share timely threat information can disrupt both conventional electricity delivery and the integration of distributed low-carbon generation. The EU Cyber Solidarity Act describes national and cross-border cyber hubs that use advanced technology and data analytics to share warnings. Effective cyber diplomacy in this setting encompasses reciprocal communication channels, legally compatible information sharing, operational exercises, and safeguards against the misuse of sensitive industrial-control information. These measures support the objective of continuity without implying that threat intelligence alone guarantees security.

Three governance safeguards follow. First, energy operators should measure incremental IT electricity and facility PUE rather than treating AI compute as costless. Second, cyber-defence vendors should evaluate false-positive rates, drift, adversarial robustness, and human-in-the-loop incident response against comparable baselines. Third, procurement and interstate cooperation agreements should document obligations under applicable NIS2 measures and arrange escalation pathways for transboundary events. A transparent cost–risk threshold offers a common analytical language for regulators, operators, and international partners.

LIMITATIONS

The ENISA sectoral distribution is based on a curated incident dataset rather than a complete census of compromises, and the 2025 report has subsequently been revised. The IEA series is regional and reflects all data centres, not only AI systems or cyber monitoring. IBM breach costs are cross-industry global averages and do not identify the loss distribution of European grid operators. The model's probability, conditional loss, assumed risk reduction, fixed cost, tariff and emissions factor are illustrative. They were selected for interpretability, not statistically fitted. No empirical identification, Monte Carlo calibration, confidence interval or deployment experiment is claimed.

The model also treats annual expected loss reduction as an aggregate decision parameter and does not distinguish prevention, earlier detection, faster containment or business continuity. It omits costs of false alarms, cyber insurance, redundancy, initial capital expenditure, and cybersecurity staff training. Future research should link operator-level energy meters and incident data to controlled security trials and compare cross-border governance arrangements under comparable reporting rules.

CONCLUSIONS

AI-enabled cyber defence in European energy infrastructure should be assessed as both a security investment and a resource-consuming digital service. Official data establish a substantial cyber-risk context and a rising European data-centre electricity requirement, but they do not provide evidence that a particular defence system reduces energy-sector incidents by a fixed percentage. A transparent annualised model shows how the economic result depends on baseline expected loss, protection efficacy, fixed costs, IT power and facility PUE. Under the stated illustrative reference conditions, AI-enabled defence breaks even only above a 27.6% reduction in expected incident losses.

The central policy implication is to integrate energy-aware procurement with demonstrable cybersecurity performance and trusted cyber diplomacy. Cross-border alert exchange, regulatory compatibility and human oversight can complement technical controls. The methodology provides an auditable framework for JGEOR-oriented analysis of cost, resilience and green transition, while empirical evaluation with operator-specific data is necessary before drawing effectiveness or investment conclusions for a real institution.

AUTHOR CONTRIBUTIONS

Zulfiyya Mustafayeva is the proposed author. Conceptual and computational materials in this working draft must be reviewed, corrected, and approved by the author before submission. Final CRediT roles require author confirmation.

CONFLICTS OF INTEREST AND FUNDING

To be completed and confirmed by the author before submission. No conflict-of-interest or funding declaration has been presumed.

DATA AVAILABILITY AND REPRODUCIBILITY

The institutional secondary indicators are publicly accessible from ENISA (2025), IEA (2026), and Eurostat (2026), with original URLs in the references. All simulated values are deterministically reproducible from Equations (1)–(4), the stated parameter settings and Table 2. Figures were produced using Python/Matplotlib and the manuscript compiled with python-docx. No operator-specific confidential data were used.

APPENDIX A. NUMERICAL AUDIT OF THE DECISION MODEL

A full reproducibility check is possible without any confidential energy-sector data. For the 10 kW configuration, incremental IT electricity is 10 kW × 8,760 hours × PUE 1.45 = 127,020 kWh/year. Multiplication by the assumed EUR 0.18/kWh tariff gives EUR 22,863.6/year in variable power cost. Adding EUR 60,000/year of recurring operational expenditure yields EUR 82,863.6/year. With a baseline incident probability of 0.15 and conditional impact of EUR 2 million, annual expected loss without the new system is EUR 300,000. The minimum reduction in expected loss required to cover recurring cost is thus EUR 82,863.6 / EUR 300,000 = 0.276212, or 27.62%.

For an assumed 40% loss reduction, avoided expected loss equals 0.15 × EUR 2,000,000 × 0.40 = EUR 120,000. The resulting annual net benefit is EUR 120,000 − EUR 82,863.6 = EUR 37,136.4. If the assumed reduction is 25%, the net benefit changes to EUR 75,000 − EUR 82,863.6 = −EUR 7,863.6. At P = 10 kW, the additional operational emissions are 127,020 kWh × 0.20 kg CO_2/kWh / 1,000 = 25.404 tonnes CO_2/year. Scenario calculations are deterministic and should not be interpreted as confidence intervals or validated forecasts.

For application to a real operator, the parameter p should be estimated from comparable incident histories and exposure models, L from consistent accounting of direct and indirect losses, F and P from an audited operating budget, and r from a prospective evaluation against a transparent baseline. The electricity-emissions factor g should reflect the operator's stated accounting boundary, and PUE should be metered rather than transferred automatically from regional averages. These requirements define a feasible next-stage empirical research protocol.

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JOURNAL OF GREEN ECONOMY AND OPTIMIZATION RESEARCH

Published by
Green Economy and Optimization Research Lab
Azerbaijan

Website
jgeor.org

Publisher
https://georesearch.institute
office@georesearch.institute

Editorial Office
office@jgeor.org

ISSN: 3136-7968
e-ISSN: 3136-7968

Frequency: Monthly
Publication model: Open Access

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Journal of Green Economy and Optimization Research
Advancing research in green economy, sustainability, optimization and interdisciplinary studies.

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Azerbaijan

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