DuneFront

Deliverable D14.1

January 2026

DuneFront

Developing the Blueprint Guideline for DD-hybrid Nature-based Solutions

Deliverable 14.1 – D14.1

Deliverable information

Title	Developing the Blueprint Guideline for DD-hybrid Nature-based Solutions
Deliverable number	D14.1
WP number	14
Author(s)	Nasrin Hassanpour (JDN), Vicky Stratigaki (JDN), Joe El Rahi (JDN), Dries Bonte (UGent), Tomas Sterckx (DEME), Marc Huygens (DEME)
Lead beneficiary	Jan de Nul NV
Contributors	DEME
Type	Report
Dissemination level	Public
How to cite	Hassanpour, N., Stratigaki, V., El Rahi, J., Bonte, D., Sterckx, T., Huygens, M. 2026. Developing the Blueprint Guideline for DD-hybrid Nature-based Solutions. DuneFront Project Deliverable 14.1, Version 1.0.
Copyright license*	© Authors and DuneFront consortium, 2026. This work is openly licensed via CC BY 4.0

Versioning and contribution history

Version	Date	Authors (Institution)	Notes
Version 0.1	21/01/2026	Nasrin Hassanpour (JDN), Vicky Stratigaki (JDN), Joe El Rahi (JDN), Dries Bonte (UGent), Tomas Sterckx (DEME), Marc Huygens (DEME)	Draft created by Beneficiary Jan De Nul NV

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union

Cover page

Dune–dike hybrid Nature based Solutions (DD-hybrid NbS) represent a new generation of coastal protection systems that integrate engineered safety structures with dynamic, biodiverse dune environments. As climate change accelerates sea level rise, intensifies storm regimes, and increases coastal erosion across Europe, the need for adaptive, multifunctional, and ecologically grounded coastal infrastructure has become urgent. While DD-hybrid NbS are increasingly recognised for their potential to enhance coastal resilience, biodiversity, and societal well-being, their large-scale implementation remains limited by fragmented knowledge, insufficient operational guidance, and a lack of integrated design frameworks that bridge engineering, ecology, socio economics, financing, and policy.

This deliverable (D14.1) addresses these gaps by developing a Blueprint Guideline for the design, installation, and long-term management of DD-hybrid NbS. The Blueprint provides a structured, step by step roadmap that supports practitioners, coastal managers, engineers, and policymakers throughout the full project lifecycle—from early conception and feasibility assessment to implementation, monitoring, and adaptive management. It consolidates evidence from the 12 DuneFront Demonstrators, integrates insights from technical, ecological, and socio-economic work packages, and translates them into a practical, operationally grounded framework.

The Blueprint is built around five core pillars—Ecological, Technical, Social, Financing, and Policy—which together reflect the multidimensional nature of DD-hybrid NbS. Within each pillar, the Blueprint identifies Key Target Indicators (KTIs) and associated parameters that influence system performance, constructability, ecological functioning, stakeholder acceptance, financial viability, and regulatory compliance. These KTIs serve as a design-oriented complement to Key Performance Indicators (KPIs), enabling practitioners to anticipate boundary conditions, evaluate design choices, and ensure that DD-hybrid NbS are robust, scalable, and aligned with local and regional objectives.

A central contribution of this deliverable is the clarification of the relationship between the Decision Support System (DSS) and the Blueprint. The DSS determines whether a DD-hybrid NbS is an appropriate solution for a given site and objective, based on hazard reduction, ecosystem services, socio economic benefits, and trade-offs. Once this strategic decision is made, the Blueprint provides the operational guidance on how to design, implement, and maintain the selected solution. Together, the DSS and Blueprint form a coherent decision to implementation pathway that supports evidence based, nature inclusive coastal management.

The Blueprint also adopts the PESTEL framework to the specific context of DD-hybrid NbS. Political and legal dimensions are translated into policy and permitting requirements; economic dimensions into financing and lifecycle costing; social dimensions into stakeholder engagement and co creation; technological dimensions into engineering feasibility and monitoring; and environmental dimensions into ecological functioning, biodiversity enhancement, and carbon sequestration. This structured approach ensures that DD-hybrid NbS are not only technically sound but also socially accepted, financially viable, and ecologically meaningful.

Table of Content

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Explanation
D	Deliverable
WP	Work Package
NbS	Nature-based solutions
DD-hybrid	Dune-dike hybrid
KTIs	Key Target Indicators
KPIs	Key Performance Indicators
PDT	Predictive Digital Twins
PESTEL	Political, Economic, Social, Technological, Environmental, Legal

1. Overview

1.1 Overview of Work Package 14

Work Package 14 (WP14) provides the strategic and operational backbone for the design, implementation, and upscaling of dune–dike hybrid Nature-based Solutions (DD-hybrid NbS). It brings together ecological, engineering, socio-economic, financial, and policy expertise to develop tools and guidance that support the transition from conceptual NbS ideas to practical, scalable, and market-ready coastal protection solutions.

WP14 has four overarching goals:

- **Develop a Blueprint Guideline** that translates scientific evidence and demonstrator insights into a structured, operational design and implementation roadmap for DD-hybrid NbS.
- **Develop a Decision-Support System (DSS)** that evaluates whether DD-hybrid NbS are appropriate for a given site, objective, and socio-ecological context.
- **Identify and assess upscaling opportunities** across European and global coastlines, based on demonstrator evidence, hazard profiles, and ecosystem service needs.
- **Accelerate market uptake** by integrating financial, operational, and governance considerations into a robust business case for DD-hybrid NbS.

Together, these outputs ensure that DD-hybrid NbS can be designed, implemented, and maintained in a way that is technically feasible, ecologically meaningful, socially accepted, financially viable, and aligned with policy frameworks.

1.2 Tasks of Work Package 14

Task 14.1 — Development of the Blueprint for DD-Hybrid NbS

This task produces the Blueprint Guideline presented in this deliverable. It synthesises evidence from DuneFront Demonstrators, integrates insights from technical and ecological work packages, and identifies Key Target Indicators (KTIs) that influence DD-hybrid NbS performance. The Blueprint provides a structured, step-by-step roadmap for design, installation, monitoring, and adaptive management.

Task 14.2 — Development of the Decision-Support System (DSS) for DD-Hybrid NbS

The DSS evaluates whether DD-hybrid NbS are suitable for a given site by integrating hazard reduction, ecological functioning, socio-economic benefits, financing logic, and policy constraints. It supports decision-makers in comparing DD-hybrid NbS with conventional alternatives and identifying optimal adaptation pathways.

Task 14.3 — Exploration of potential sites for upscaling DD-hybrid NbS

This task maps potential European and global sites where DD-hybrid NbS could be implemented. It draws on demonstrator data, DSS outputs, and coastal hazard profiles to identify priority locations where hybrid solutions can deliver high ecological and socio-economic value.

Task 14.4 — Accelerating upscaling market potential for DD-hybrid NbS

This task integrates industrial expertise to develop a business case for DD-hybrid NbS, addressing CAPEX/OPEX, financing mechanisms, operational feasibility, and long-term value creation. It supports the transition from pilot-scale demonstrators to market-ready solutions.

Task 14.5 — Co-creation guidelines for DD-hybrid NbS

This task develops a practical handbook for stakeholder engagement and co-creation processes in coastal zone management. It ensures that DD-hybrid NbS are socially accepted, context-appropriate, and aligned with local governance structures.

1.3 Milestones and Deliverables of Work Package 14

WP14 includes several key milestones and deliverables that mark progress toward the development and application of Blueprint, the DSS, and upscaling strategies. Key outputs include the delivery of the Blueprint for DD-hybrid NbS (this deliverable), the DSS, the identification and mapping of potential upscaling sites, the development of a market-oriented business case, and the publication of co-creation guidelines.

1.4 Aims and Objectives

This deliverable aims to develop a Blueprint Guideline that provides a structured, operational roadmap for DD-hybrid NbS development. It addresses key barriers to large-scale implementation, including:

- fragmented knowledge on hybrid system functioning,
- limited integration of ecological, technical, social, financial, and policy dimensions,
- insufficient operational guidance for installation and maintenance,
- uncertainty regarding long-term performance and monitoring requirements.

The Blueprint consolidates evidence from 12 DuneFront Demonstrators and integrates insights from work packages on morphodynamics, ecology, vegetation, sediment transport, digital twins, and socio-economic analysis. It identifies Key Target Indicators (KTIs) that influence DD-hybrid NbS performance and translates them into a practical design and implementation framework.

The Blueprint supports:

- **Evidence-based design**,
- **Nature-inclusive engineering**,
- **Stakeholder-aligned decision-making**,
- **Financially viable implementation**, and
- **Policy-compliant coastal management**.

2. Introduction

2.1 Scope / Background

Coastal regions have historically been and continue to be vital zones for human settlement, playing a crucial role in the economic and social development of many nations. These areas serve as hubs for commerce, tourism, and industry, significantly contributing to national wealth and prosperity (Lamberti et al., 2005). In Europe, the coasts of The North Sea, the Baltic Sea, and the Atlantic are anticipated to experience substantial flood risks from sea-level rise, and climate extremes are also expected to impact southern Europe Mediterranean coasts (Vousdoukas et al., 2020). Future coastal management surpasses the current fixed and non-adaptive flood coastal protection setup: Hybrid NbS that can efficiently integrate static hard infrastructure with dynamic aeolian, and vegetated sediments are currently developed along urbanized areas of most of the European sandy coasts, yet still at small scales (Figure 1).

Figure 1. Marram grass Dune-Dike at Westende, Belgian Coast *(Stratigaki et al., 2024; photo courtesy Herman Troch)*

The integration of dikes and dunes for coastal protection is a key example of such infrastructure and is typically referred to as DD-hybrid NbS. Such infrastructure can provide advantages for coastal safety and protection that cannot be reached by hard (dikes, seawalls) or soft (beach nourishments, existing dunes) infrastructure alone. Key to their adaptability to sea-level rise is the integration of hard safety lines (dikes) and resilient biodiverse dune systems that only function when both physical and biological boundary conditions are met. This type of infrastructure will deliver an integrated, multidisciplinary coastal management system (Figure 2). The applications of DD-hybrid NbS even reach out towards marine environments as the future design and installation of emerging concepts of energy/barrier islands largely relies on so far not developed roadmaps from replicated coastal solutions.

Figure 2. Example of Dune-Dike hybrid Nature-based-Solutions at Westende, Belgian Coast *(Stratigaki et al., 2024)*

In line with the European Green Deal and New European Bauhaus initiative, the overall objective of the DuneFront project is to optimize DD-hybrid NbS as a new generation of sustainable, inclusive and aesthetic blue-grey coastal management infrastructure, that further mainstreams biodiversity into one of the most important socio-economic challenges along European coasts. Such blue-grey infrastructure can provide advantages for coastal safety and protection that cannot be reached by hard (dikes, seawalls) or soft (beach nourishments, existing dunes) infrastructure alone. Key to their adaptability to sea-level rise is the integration of hard safety line (dikes) and resilient biodiverse dune systems that only function when both physical and biological boundary conditions are met. This blue-grey infrastructure will deliver an integrated, multidisciplinary coastal management system. The applications of DD-hybrid NbS even reaches out towards marine environments as the future design and installation of emerging concepts of energy/barrier islands largely relies on so far not developed roadmaps from replicated coastal solutions. The graphical concept of the DuneFront is shown in Figure 3.

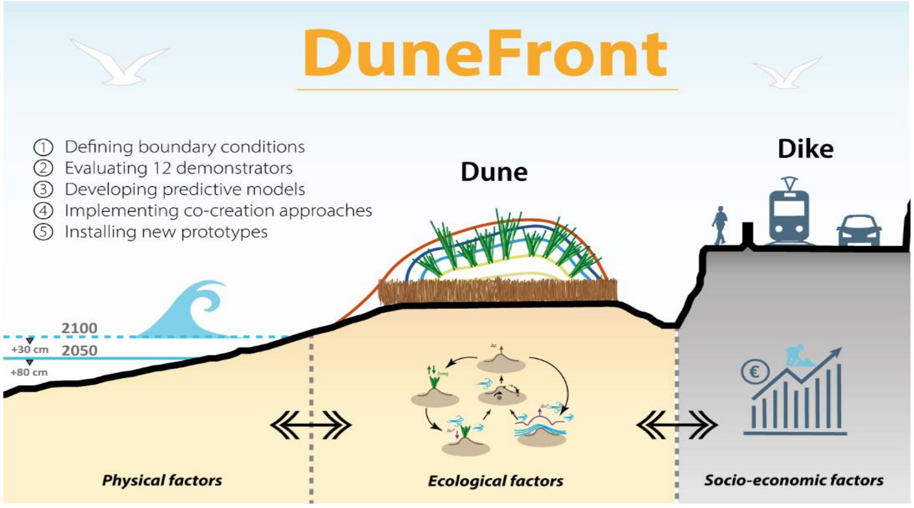


Figure 3. The DuneFront concept in one graphical abstract

2.2 State-of-the-art

Hybrid coastal protection concepts have gained increasing attention as sea-level rise, storm intensification, and long-term shoreline retreat challenge the effectiveness and sustainability of conventional coastal defence. Predictions indicate that shoreline change and beach erosion may substantially intensify under climate change, particularly along sandy coasts shaped by sea-level rise and storm-driven processes (Vousdoukas et al., 2020). This has accelerated the shift from single-purpose coastal protection towards multi-functional solutions that jointly reduce flood and erosion risk while supporting ecological integrity and societal co-benefits. Dune-dike coastal protection is one of the few examples in which hybrid soft-hard applications have been implemented at targeted locations along European coasts. Research has established a strong scientific basis for understanding beach–dune morphodynamics, sediment transport, dune formation, and the role of vegetation in stabilising coastal landforms, and this knowledge is increasingly being translated into engineering design considerations (D'Alessandro et al., 2022). At the same time, studies of nature-based flood defence concepts (e.g., vegetated foreshores and hybrid designs) show that nature-based features can contribute to hazard reduction while offering ecological benefits, although their reliability and performance under extreme events and over long-time horizons require careful assessment (Vuik et al., 2018). While significant advancements have been made in the design and safety assessment of hard coastal protection systems, interactions between hard structures and soft infrastructure, such as sand dikes and dunes, remain less well understood (EurOtop, 2018), even though the performance of hybrid systems depends on coupled processes (hydrodynamics, sediment dynamics, vegetation establishment, maintenance regimes, and spatial constraints such as coastal squeeze).

In parallel with scientific progress, the past decade has seen a rapid increase in guidelines, standards, and handbooks that function as "blueprints" for planning and evaluating Nature-based Solutions (NbS). At the global level, the IUCN Global Standard for NbS provides a widely used verification framework based on criteria and indicators to support credible design, implementation, and scaling, including explicit attention to biodiversity and ecosystem integrity (IUCN, 2020). At the EU level, NbS are similarly framed as solutions that deliver simultaneous environmental, social, and economic benefits while supporting resilience, reinforcing the need for integrated evaluation across multiple dimensions (European Commission, 2025). The European Commission and affiliated initiatives have also developed evaluation frameworks to assess NbS impacts across societal challenge areas, offering structured indicator sets and methodologies to compare outcomes and document co-benefits (European Commission, 2021).

However, many NbS assessment handbooks are designed to be broadly applicable across sectors and often remain at a relatively general when applied to complex coastal systems where engineering feasibility, constructability, and long-term morphodynamic response are critical. Existing guidance is frequently either (i) general NbS verification and impact evaluation, (ii) oriented towards navigation and port infrastructure, or (iii) focused on flood risk reduction strategies that do not fully specify the operational realities of installing and maintaining hybrid systems such as dune–dike NbS across diverse European contexts. Consequently, the translation of ecological and socio-economic ambitions into site-specific, engineering-feasible, constructible, and monitorable design choices remains challenging for practitioners.

Decision-support-systems (DSS) and classification frameworks have also advanced substantially, primarily in coastal risk assessment and climate adaptation planning. For example, the THESEUS project developed a conceptual coastal risk assessment approach grounded in the Source–Pathway–Receptor–Consequence model, supporting structured analysis of flood risk and risk reduction strategies (Zanuttigh et al., 2014). The Coastal Hazard Wheel provides a universal coastal classification and management framework intended to support decision-making across multiple coastal challenges (Coastal Hazard Wheel, n.d.). The Coastal Resilience platform (TNC and partners) offers a spatial decision-support environment where ecological, social, and economic information can be assessed alongside hazard scenarios, supporting planning and stakeholder communication (Coastal Resilience, n.d.). These tools support problem framing, scenario exploration, and comparative assessment of adaptation pathways. However, they are typically oriented towards site screening, risk identification, and strategic planning rather than operational guidance on how to engineer and realise hybrid coastal NbS in practice. Many DSS approaches prioritise hazard reduction (e.g., flooding and erosion) and may include ecological information but often do not fully integrate practical requirements that determine whether hybrid NbS can be implemented reliably and cost-effectively at scale, such as constructability constraints, installation methods, monitoring design, and long-term maintenance requirements.

In summary, the state-of-the-art provides: (i) a strong scientific basis for coastal morphodynamics and dune system functioning; (ii) rapidly evolving NbS standards and impact evaluation frameworks; (iii) engineering guidance philosophies that promote working with nature; and (iv) DSS tools supporting coastal risk planning and adaptation. Nevertheless, these developments remain only partially integrated for DD-hybrid NbS, where successful adoption requires coherent alignment between technical feasibility, ecological performance, socio-economic value, financing logic, and policy constraints across design, installation, operation, and maintenance. This motivates the WP14 focus on developing an integrated DSS and Blueprint tailored to DD-hybrid NbS, informed by demonstrator evidence and consolidated project-wide outputs.

Building on the state-of-the-art outlined above, the following knowledge gaps and challenges summarise the key limitations that currently constrain the wider adoption and implementation of DD-hybrid NbS.

2.3 Knowledge Gaps and Challenges

Despite growing interest and advances in hybrid coastal protection, several critical gaps limit the widespread adoption of DD-hybrid NbS:

1. Fragmented knowledge across disciplines

Engineering, ecology, socio-economics, and policy are often addressed separately, leading to incomplete or inconsistent design approaches.

2. Limited operational guidance

Existing NbS frameworks do not provide detailed instructions on:

- installation methods,
- constructability constraints,
- monitoring design,
- adaptive management,
- maintenance regimes.

3. Insufficient integration of ecological functioning

Biodiversity, vegetation dynamics, sediment–vegetation feedback, and habitat development are often secondary considerations rather than core design drivers.

4. Uncertainty in long-term performance

Hybrid systems evolve over time, and their performance depends on:

- climate forcing,
- sediment supply,
- vegetation establishment,
- maintenance interventions.

5. Lack of financial and policy alignment

DD-hybrid NbS require:

- new financing models,
- lifecycle costing approaches,
- alignment with EU and national permitting frameworks,
- integration into coastal zone management policies.

6. Limited upscaling pathways

Demonstrator projects provide valuable insights but are often site-specific. A structured framework is needed to translate lessons learned into scalable, transferable design principles.

2.4 Methodological Approach

The Blueprint developed in this deliverable provides a structured, step-by-step guideline for DD-hybrid NbS development. It is informed by:

- evidence from 12 DuneFront Demonstrators,
- outputs from technical and ecological work packages (WP2–WP13),
- industrial expertise from JDN and DEME,
- stakeholder engagement insights,
- EU NbS frameworks and coastal engineering principles.

The Blueprint in this deliverable is **evidence-based development,** and it integrates:

- morphodynamic modelling results,
- ecological monitoring data,
- vegetation and sediment dynamics,
- digital twin outputs,
- stakeholder feedback,
- industrial installation experience.

This ensures that the Blueprint is scientifically grounded, operationally feasible, and aligned with real-world constraints.

The Blueprint developed in this deliverable functions as:

- a **checklist** of key parameters and boundary conditions,
- a **design support tool** for engineers and ecologists,
- a **communication tool** for stakeholders and policymakers,
- a **bridge** between scientific evidence and operational practice.

The relationship between DSS and Blueprint follows as:

- The **DSS** answers: Is a DD-hybrid NbS appropriate for this site and objective?
- The **Blueprint** answers: How should the DD-hybrid NbS be designed, installed, monitored, and managed?

Together, they form a complete decision-to-implementation pathway.

In this deliverable, the Blueprint developed based on the logic of the **PESTEL framework**, while adapting it to the specific requirements of designing and implementing of DD-hybrid NbS. Context analysis - PESTEL is a method, originally intended for organisational analysis, entailing a variety of steps and techniques to gather relevant knowledge on the macro environment, needed to understand key factors which may impact (direct or indirectly) the intervention. "PESTEL" refers to a mnemonic guideline of the domains it considers: Political, Economic, Social (or Socio-cultural), Technological, Environmental and Legal. PESTEL is built as a guiding check list, helping to systematize the collection of information on environment and to identify specific relevant factors - i.e. economic trends, social attitudes, technological developments, etc.- that are significant in the intervention design phase ("PESTEL," n.d.). Table 1 summarises the PESTEL framework and its six macro-environmental dimensions considered in this deliverable.

Table 1. Overview of the PESTEL dimensions considered in this deliverable

P	Political	Political factors are government, trade and tax policies, general political issues, changes in leadership regulation, and political trends
E	Economic	Economic factors may include inflation, interest rates, exchange rates, economic growth and unemployment levels
S	Social	Social factors are cultural trends and patterns in society. They may include lifestyle trends, age distribution, and consumer behaviour.
T	Technological	Technological factors may include technological advancements and developments, innovations and scientific breakthroughs.
E	Environmental	Environmental factors may include climate change, environmental regulations, waste management policies and consumer environmental awareness.
L	Legal	Legal factors may include labour and import/export regulations, health and safety policies and guidelines.

In this deliverable, the PESTEL analysis is used to provide a structured understanding of the broader context in which DD-hybrid NbS are developed and adopted, supporting decision-makers and coastal infrastructure managers in identifying relevant opportunities, constraints, and risks, and in informing strategic decision-making throughout the project. Similar to PESTEL, the Blueprint adopts a systematic, checklist-based structure to identify and organise Key Target Indicators (KTIs) and their associated parameters/variables that may directly or indirectly influence the development of DD-hybrid NbS. The identified KTIs are grouped into five core pillars reflecting the main PESTEL dimensions. Political and legal dimensions are addressed through the “Policy” pillar, economic considerations through the “Financing” pillar, the socio-cultural dimension through “Social” pillar, technological considerations through the “Technical” pillar, and environmental dimensions through the “Ecological” pillar. Each dimension is translated into Key Target Indicators (KTIs) and associated parameters that influence design and implementation.

Table 2 shows how the Blueprint translates the PESTEL dimensions into design-oriented pillars supporting the development of DD-hybrid NbS.

Table 2. Mapping PESTEL dimensions to the Blueprint pillars

PESTEL Dimensions	Blueprint Pillar(s)	How the dimension is translated to the Blueprint
Political/Legal	**Policy**	Translated into policy alignment, regulatory requirements, permitting, governance conditions and compliance with national, EU, and Natura 2000 frameworks relevant to DD-hybrid NbS
Economic	**Financing**	Translated into financial feasibility, cost–benefit optimisation, lifecycle costing, and funding strategies supporting viable DD-hybrid NbS deployment.
Social/ Socio-cultural	**Social**	Translated into stakeholder engagement, co-creation processes, social acceptance, aesthetics, recreation opportunities, and well-being outcomes linked to DD-hybrid NbS.
Technological	**Technical**	Translated into technical feasibility, performance, and monitoring requirements, including energy attenuation, shoreline stabilisation, flood risk reduction, structural integrity, and climate resilience of DD-hybrid NbS.
Environmental	**Ecological**	Translated into ecological performance requirements, including biodiversity optimisation, ecosystem functioning, habitat development, connectivity, and carbon sequestration of DD-hybrid NbS.

3. Implementing the Blueprint for DD-Hybrid NbS

3.1 Introduction

A key objective of DuneFront is to identify the biological, physical, and socio-economic boundary conditions and their interactions in order to tailor marine and coastal DD-hybrid NbS that jointly safeguard human assets, blue-economy activities, and biodiversity gain and restoration. To achieve this, DuneFront translates evidence on biodiversity, morphodynamics, design, life-cycle performance, and socio-economics derived from 12 Demonstrators along vulnerable European coastlines (Belgium, the Netherlands, Germany, Sweden, France, and Portugal) into new roadmaps for the design and installation of DD-hybrid NbS. These roadmaps support context-specific solutions that integrate coastal protection and ecosystem functioning, moving beyond traditional single-purpose flood protection approaches. Figure 4 illustrates how DuneFront synthesises evidence from multiple Demonstrators into functioning, actionable guidelines by identifying and integrating biological, physical, and socio-economic boundary conditions to support biodiversity-inclusive, morphodynamically informed coastal protection.

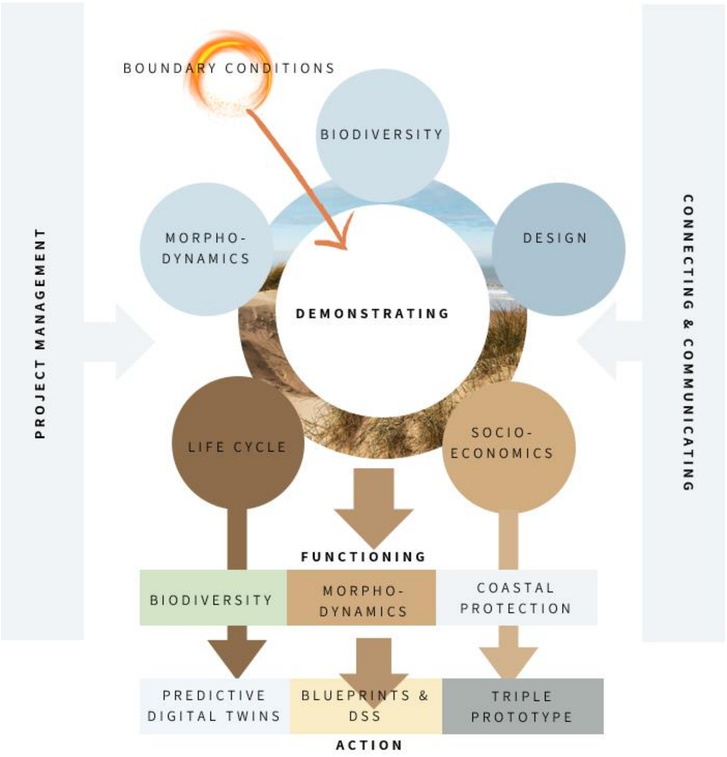


Figure 4. Translating demonstrator evidence into DD-Hybrid NbS design and implementation

3.2 Developing DD-hybrid NbS Steps

Building on the integrated assessment of boundary conditions derived from the DuneFront Demonstrators, and results from the other work packages, the Blueprint translates these insights into a structured development process for DD-hybrid NbS. This process is organised around five core pillars-Ecological, Technical, Financing, Social, and Policy- that together ensure balanced consideration of environmental performance, engineering feasibility, economic viability, societal value, and governance requirements. To translate this integrated framework into practice, the Blueprint defines nine sequential development steps that guide the full project life cycle. Figure 5 shows this Blueprint structure.

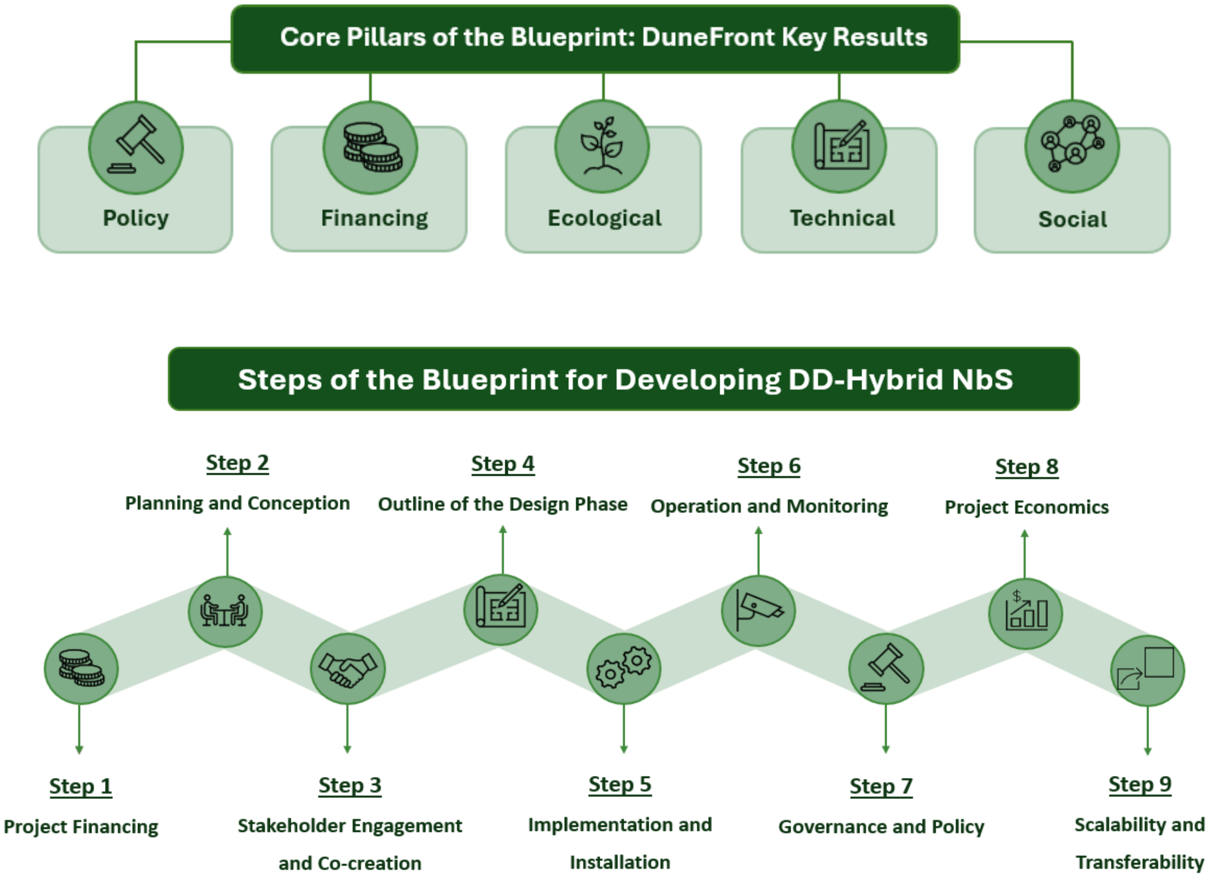
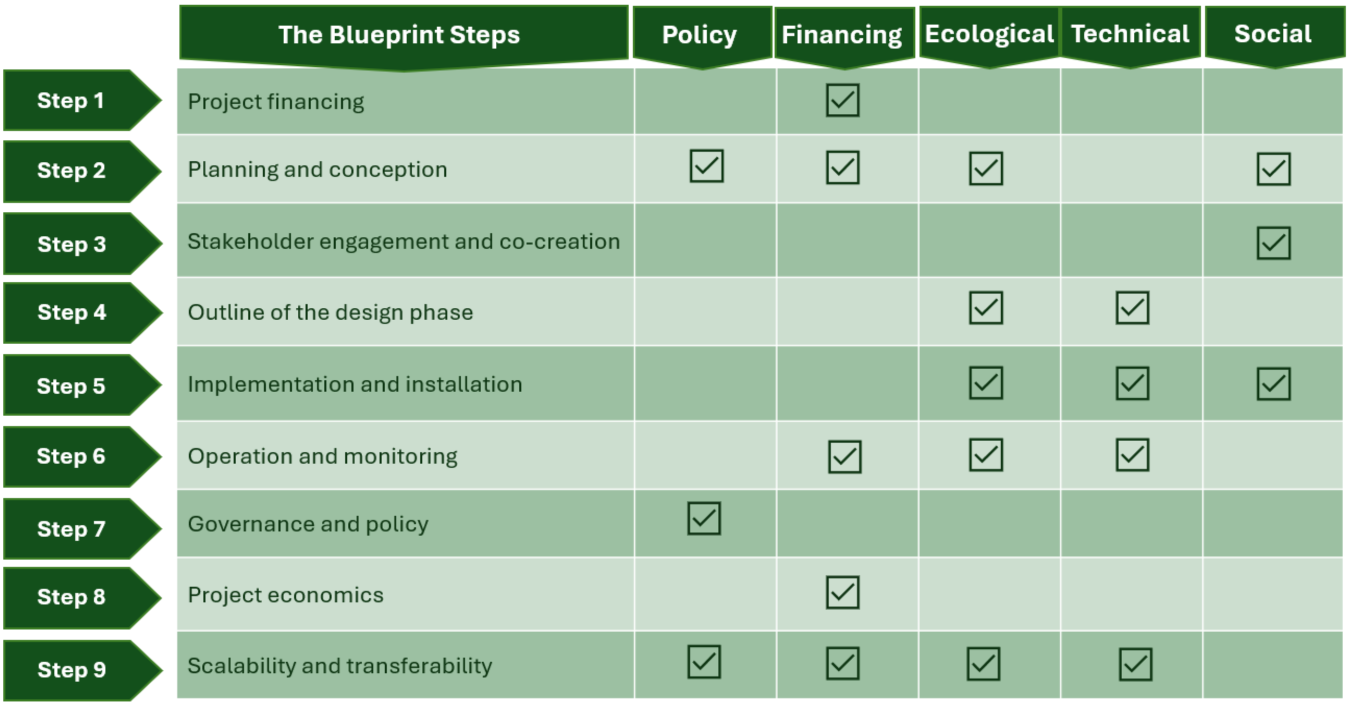


Figure 5. Integrated Blueprint framework for developing DD-Hybrid NbS

The nine steps provide a logical progression for project development, starting with project financing, where funding sources, investment needs, and financial feasibility are identified to enable subsequent planning and implementation. The process then moves to planning and conception, in which the project context, objectives, and boundary conditions are defined, followed by stakeholder engagement and co-creation, ensuring that local knowledge, societal needs, and stakeholder priorities are embedded from the outset. The Blueprint then advances to the design phase, where ecological ambitions are integrated with technical feasibility, policy requirements, and financial considerations. Subsequent steps focus on implementation and installation, translating design concepts into practical and constructible solutions, followed by operation and monitoring, which support adaptive management and ensure the long-term performance of the DD-hybrid NbS. The final steps address governance and policy alignment and project economics, and scalability and transferability, enabling replication and upscaling beyond individual demonstration sites.

Across all nine steps, the Blueprint applies the five pillars as a consistent analytical and design lens. The Ecological pillar ensures that biodiversity, ecosystem functioning, and nature-inclusive objectives are integrated throughout the process. The Technical pillar addresses technical feasibility, constructability, safety, and performance under dynamic coastal conditions. The Social pillar emphasizes stakeholder involvement, co-creation, social acceptance, and alignment with local needs and values. The Financing pillar focuses on cost structures, funding mechanisms, and long-term financial viability, while the Policy pillar ensures coherence with regulatory frameworks and governance requirements at local, national, and European levels. As a result, the Blueprint supports a coherent translation of strategic objectives into actionable design and implementation pathways for DD-hybrid NbS.

Figure 6 shows the mapping of the five core pillars across the nine Blueprint development steps, indicating which pillars must be considered at each stage of the DD-hybrid NbS development process.



	The Blueprint Steps	Policy	Financing	Ecological	Technical	Social
Step 1	Project financing		☑			
Step 2	Planning and conception	☑	☑	☑		☑
Step 3	Stakeholder engagement and co-creation					☑
Step 4	Outline of the design phase			☑	☑	
Step 5	Implementation and installation			☑	☑	☑
Step 6	Operation and monitoring		☑	☑	☑	
Step 7	Governance and policy	☑				
Step 8	Project economics		☑			
Step 9	Scalability and transferability	☑	☑	☑	☑	

Figure 6. Integration of ecological, technical, financing, social, and policy pillars across the Blueprint steps

3.3 Key Target Indicators

The development of Key Target Indicators (KTIs) forms the analytical backbone of the Blueprint for DD-hybrid NbS. KTIs translate the complex interactions between ecological processes, engineering requirements, socio-economic dynamics, financial feasibility, and policy constraints into a structured set of parameters that guide design and implementation. They serve as the bridge between scientific understanding and practical decision-making, ensuring that hybrid systems are conceived, constructed, and managed in a way that is both technically robust and ecologically meaningful.

KTIs differ from Key Performance Indicators (KPIs) in their purpose and timing. While KPIs are typically used to evaluate outcomes after implementation, KTIs are forward-looking they identify the conditions that must be met for a DD-hybrid NbS to function effectively. They therefore play a critical role during the design phase, helping practitioners anticipate boundary conditions, assess feasibility, and select appropriate interventions. By structuring KTIs across five pillars—ecological, technical, financing, social, and policy—the Blueprint ensures that all relevant dimensions are considered in an integrated manner.

The ecological pillar captures the biological and environmental conditions that underpin the functioning of dune–dike hybrid systems. These include vegetation establishment, sediment availability, dune morphology, habitat development, and ecological connectivity. Ecological KTIs ensure that hybrid systems are designed to support biodiversity, enhance ecosystem functioning, and maintain the natural processes that contribute to long-term resilience. They also help identify potential ecological constraints, such as limited sediment supply or insufficient vegetation cover, that may affect system performance.

The technical pillar encompasses the engineering and physical parameters that determine the structural integrity and functional reliability of DD-hybrid NbS. These include hydrodynamic forcing, wave attenuation, sediment transport, structural stability, and climate resilience. Technical KTIs ensure that hybrid systems meet safety requirements while maintaining compatibility with natural processes. They also support the integration of predictive modelling, digital twins, and monitoring technologies into the design and management of hybrid systems.

The financing pillar addresses the economic feasibility of DD-hybrid NbS. Hybrid systems often require different investment strategies compared to traditional coastal protection measures, particularly because their benefits extend beyond flood protection to include ecosystem services, recreation, and long-term adaptability. Financial KTIs therefore consider capital and operational expenditures, lifecycle costing, funding mechanisms, and the valuation of ecosystem services. They help ensure that hybrid systems are not only technically viable but also economically sustainable and attractive to investors and public authorities.

The social pillar reflects the importance of stakeholder engagement, public acceptance, and societal co-benefits. DD-hybrid NbS interact directly with local communities, influencing recreation, aesthetics, cultural values, and perceptions of safety. Social KTIs help identify the needs, expectations, and concerns of stakeholders, ensuring that hybrid systems are co-created with local communities and aligned with societal priorities. They also support the integration of participatory processes into the design and implementation of hybrid systems.

The policy pillar captures the regulatory, governance, and permitting frameworks that shape the feasibility of DD-hybrid NbS. Hybrid systems must comply with national and European legislation, including coastal zone management policies, environmental directives, and Natura 2000 requirements. Policy KTIs help identify relevant regulatory constraints, governance structures, and institutional responsibilities. They also support alignment with broader policy objectives, such as the European Green Deal, the EU Climate Adaptation Strategy, and biodiversity restoration targets.

Together, these five pillars provide a comprehensive structure for identifying and organising the parameters that influence the development of DD-hybrid NbS. The KTIs do not prescribe specific design solutions; rather, they offer a systematic method for evaluating site conditions, identifying opportunities and constraints, and guiding the selection of appropriate interventions. By integrating ecological, technical, financial, social, and policy considerations into a unified framework, the KTIs ensure that DD-hybrid NbS are designed in a way that is scientifically grounded, operationally feasible, and aligned with societal and environmental objectives.

The following sections elaborate each pillar in detail, describing the underlying rationale, the associated parameters, and their relevance to the design and implementation of DD-hybrid NbS. This structured approach ensures that practitioners can navigate the complexity of hybrid systems while maintaining a clear focus on the conditions required for successful and sustainable implementation.

Table 3 summarises the KTIs defined for each of the five Blueprint pillars for developing of DD-hybrid NbS.

Table 2. Key target indicators (KTIs) for each Blueprint pillar in DD-Hybrid NbS development

Blueprint Pillars	Key Target Indicators (KTIs)	
Policy	**KTI-1**	Policy alignment
	KTI-2	Policy input/feeding
Financing	**KTI-1**	Cost benefit optimization
	KTI-2	Financing maximization
Ecological	**KTI-1**	Biodiversity optimization
	KTI-2	Ecological functioning and processes
	KTI-3	Habitat coverage
	KTI-4	Carbon sequestration

	KTI-5	Set-up a monitoring plan to evaluate ecological functioning of DD-hybrid NbS
Technical	**KTI-1**	Energy attenuation
	KTI-2	Shoreline stabilisation below water line
	KTI-3	Coastal flood risk management
	KTI-4	Structural integrity
	KTI-5	Climate resilience
	KTI-6	Dune stabilisation above water line
	KTI-7	Set-up a monitoring plan to evaluate technical functioning of DD-hybrid NbS
Social	**KTI-1**	Stakeholder involvement
	KTI-2	Aesthetics optimization
	KTI-3	Tourism and recreation opportunities
	KTI-4	Health and well-being

3.3.1 Ecological Key Target Indicators and associated Parameters/Variables for Developing Blueprint

The ecological dimension of DD-hybrid NbS forms the foundation upon which all other aspects of the system depend. Dune–dike hybrids function as living coastal landscapes, shaped by the interplay between sediment dynamics, vegetation development, hydrodynamic forcing, and habitat evolution. Ecological Key Target Indicators (KTIs) therefore play a central role in determining whether a hybrid system can establish, persist, and deliver the intended protective and ecological functions over time. They help identify the biological and environmental conditions that must be present—or actively created—to support dune formation, stabilisation, and long-term resilience.

A central ecological consideration is the availability and mobility of sediment. Dune systems rely on a continuous supply of aeolian and marine sediments to build and maintain their volume. If sediment supply is insufficient, or if sediment transport pathways are disrupted by hard structures or human activities, the dune may fail to develop the morphology required to contribute meaningfully to coastal protection. The Blueprint therefore emphasises the need to assess sediment budgets, grain size distributions, and the connectivity between beach, foreshore, and dune compartments. These parameters influence not only the initial feasibility of dune construction but also the long-term capacity of the system to adapt to sea-level rise and storm impacts.

Vegetation dynamics represent another critical ecological KTI. Pioneer species such as Ammophila arenaria play a key role in trapping wind-blown sand, stabilising dune surfaces, and initiating the feedback loops that drive dune growth. Their establishment depends on factors such as substrate characteristics, moisture availability, salinity, and disturbance regimes. Successful vegetation development also requires protection from trampling, grazing, and excessive erosion during early stages. As the dune matures, vegetation communities diversify, enhancing habitat quality and ecological resilience. The Blueprint therefore integrates vegetation establishment, species selection, planting strategies, and early-stage protection measures into the design process.

Hydrodynamic and meteorological conditions further shape the ecological functioning of DD-hybrid NbS. Storm surge frequency, wave run-up, wind climate, and inundation patterns influence both sediment transport and vegetation survival. These conditions determine the stress thresholds that the dune system must withstand and the degree to which ecological processes can operate without being overwhelmed by extreme events. Understanding these dynamics is essential for defining realistic ecological targets and for designing hybrid systems that balance natural variability with engineered robustness.

Ecological KTIs also encompass habitat development and biodiversity potential. Dune–dike hybrids can support a range of habitats, from embryonic dunes to grey dunes and species-rich grasslands, depending on local conditions and management objectives. These habitats contribute to broader ecological networks, offering refuges for flora and fauna and enhancing landscape connectivity. The Blueprint therefore encourages practitioners to consider not only the protective function of dunes but also their ecological value, aligning hybrid systems with biodiversity restoration goals and Natura 2000 requirements where relevant.

Finally, ecological KTIs help identify potential constraints that may limit the feasibility or performance of DD-hybrid NbS. These include restricted sediment supply, invasive species pressures, limited space for dune development, or conflicts with existing land uses. By identifying such constraints early in the design process, practitioners can explore mitigation strategies or alternative configurations that maintain ecological integrity while meeting safety objectives.

In summary, ecological KTIs provide the essential parameters needed to understand and support the natural processes that underpin dune–dike hybrid systems. They ensure that ecological functioning is not treated as an afterthought but as a core design driver that shapes the feasibility, performance, and long-term resilience of DD-hybrid NbS. The following sections build on this foundation by examining the technical, financial, social, and policy KTIs that complete the multidimensional framework of the Blueprint.

Table 4 summarises the ecological KTIs, their associated parameters/variables, and the corresponding work packages supporting their development within DuneFront project.

Table 3. Ecological KTIs and related parameters/variables for DD-Hybrid NbS development

Ecological KTIs	Key Parameters/Variables	Relative Work Packages
Biodiversity optimization	• Functional species richness	➢ WP5
	• Presence and cover of invasive species	➢ WP5
	• Species distribution	➢ WP4
	• Along- and across-shore ecological connectivity	➢ WP5
	• Species of conservation concern (target species)	➢ WP4 ➢ WP5
	• Habitat development and projections	➢ WP5 ➢ WP6 ➢ WP10
Ecological functioning and processes	• Integrity of biological assemblage	➢ WP5
	• Biofiltration (Filtration capacity)	➢ WP6
	• Water quality	➢ WP6
	• Resistance against erosion	➢ WP6 ➢ WP10
	• Sediment stabilization (e.g., through plant-vegetation-sediment mechanism)	➢ WP6
	• Biogenic reef resilience	➢ WP16 ➢ WP17 ➢ WP18
Habitat coverage	• Total habitat area	➢ WP5
	• Temporal change in area	➢ WP5
	• Habitat continuity/ fragmentation	➢ WP5
	• Habitat condition (basic quality status) (indicators to be developed)	➢ WP5
	• In case of Natura 2000 priority habitat (check any additional development requirements)	➢ WP5
Carbon Sequestration	• Aboveground biomass carbon	➢ WP14
	• Belowground biomass carbon	➢ WP14
	• Soil organic carbon (SOC)	➢ WP14
	• Dead organic matter carbon	➢ WP14
Set-up a monitoring plan to evaluate ecological	• Parameters of Biodiversity optimization	➢ WP4 ➢ WP5 ➢ WP6 ➢ WP10

functioning of DD-hybrid NbS	• Parameters of Ecological functioning and processes	➢ WP5 ➢ WP6 ➢ WP10 ➢ WP16 ➢ WP17 ➢ WP18
	• Parameters of Habitat coverage	➢ WP5
	• Parameters of Carbon sequestration	➢ WP14

3.3.2 Technical Key Target Indicators and associated Parameters/Variables for Developing Blueprint

The technical dimension of DD-hybrid NbS defines the physical and engineering conditions under which dune–dike systems can reliably deliver coastal protection. While ecological processes shape the natural evolution of dunes, the technical KTIs ensure that hybrid systems meet safety standards, withstand hydrodynamic forcing, and maintain structural integrity under both typical and extreme conditions. These indicators translate engineering knowledge into practical design requirements, enabling practitioners to balance natural dynamics with the robustness expected of coastal defence infrastructure.

At the core of the technical KTIs lies the interaction between hydrodynamic forcing and dune morphology. Waves, tides, storm surges, and run-up patterns determine the extent to which a dune can absorb energy, dissipate wave action, and reduce overtopping. The geometry of the dune—its height, width, slope, and cross-shore profile—must therefore be aligned with local hydrodynamic conditions. In hybrid systems, the dune acts as the first line of defence, reducing the load on the underlying dike. This requires careful assessment of design storm conditions, return periods, and projected changes in sea level. The technical KTIs thus help define the minimum morphological characteristics needed for the dune to function effectively as part of the hybrid system.

Sediment transport processes represent another essential technical consideration. The stability and evolution of the dune depend on the availability and mobility of sediment across the beach–dune system. Marine and aeolian transport pathways must remain sufficiently open to allow natural accretion, while engineered interventions must avoid creating barriers that disrupt sediment fluxes. In some cases, sediment nourishment or redistribution may be required to initiate or sustain dune development. Technical KTIs therefore incorporate parameters such as sediment grain size, beach width, foreshore slope, and the presence of sediment sinks or sources. These indicators help determine whether natural processes alone can maintain the dune or whether periodic interventions will be necessary.

The structural interaction between the dune and the underlying dike is a defining feature of DD-hybrid NbS. The dike provides a controlled, engineered safety line, while the dune reduces wave energy and overtopping before it reaches the structure. This layered defence concept requires precise integration of natural and engineered components. Technical KTIs therefore address the geometry, materials, and stability of the dike, ensuring that it remains compatible with dune dynamics. For example, the crest height and landward slope of the dike must be designed to accommodate potential erosion of the dune during extreme events without compromising safety. Similarly, the interface between dune and dike must be engineered to avoid scouring, piping, or structural undermining.

Monitoring and modelling technologies play an increasingly important role in the technical assessment of hybrid systems. Advances in remote sensing, digital twins, and numerical modelling allow practitioners to simulate dune evolution, wave–structure interactions, and sediment transport under a range of scenarios. Technical KTIs incorporate the data requirements and modelling parameters needed to support these tools, ensuring that design decisions are informed by robust, site-specific evidence. This integration of predictive technologies enhances the reliability of hybrid systems and supports adaptive management over time.

Finally, technical KTIs address constructability and operational feasibility. Hybrid systems must be designed not only for long-term performance but also for practical implementation. Access for construction equipment, availability of suitable materials, compatibility with existing infrastructure, and the logistics of vegetation planting all influence the feasibility of a project. These considerations ensure that the design remains grounded in real-world constraints and that the system can be installed and maintained without compromising ecological or social objectives.

In summary, technical KTIs provide the engineering foundation for DD-hybrid NbS. They ensure that hybrid systems are structurally sound, hydrodynamically resilient, and compatible with natural processes. By integrating hydrodynamic analysis, sediment dynamics, structural design, modelling, and constructability considerations, the technical KTIs form a critical component of the Blueprint, guiding practitioners toward solutions that are both robust and adaptive.

Table 5 summarises the technical KTIs, their associated parameters/variables, and the corresponding work packages.

Table 4. Technical KTIs and related parameters/variables for DD–Hybrid NbS development

Technical KTIs	Key Parameters/Variables	Relative Work Packages
Energy Attenuation	• Wave height	➢ WP4 ➢ WP12
	• Current	➢ WP4 ➢ WP12
	• Water level	➢ WP4
	• Biogenic reef interaction with waves / current	➢ WP16 ➢ WP17 ➢ WP18

Shoreline Stabilization below Water Line	• Horizontal shoreline location	➢ WP6 ➢ WP11
	• Sediment erosion, accretion and volume	➢ WP6
	• Coastal squeeze	➢ WP4
Coastal Flood Risk Management	• Surge extent / height	➢ WP12
	• Storm surge height	➢ WP12
	• Wave overtopping	➢ WP12
	• Storm return period	➢ WP4
Structural Integrity	• Durability and adaptivity/ longevity	➢ WP12 ➢ WP15
	• Resistance to extreme weather events	➢ WP12
Climate Resilience	• Mean sea level change	➢ WP4 ➢ WP11 ➢ WP13
	• Conditions under climate change scenarios	➢ WP4 ➢ WP7 ➢ WP13
	• Monthly means daily max and min temperatures	➢ WP4
	• Heatwave incidence	➢ WP4
Dune Stabilization above Water Line	• Erosion	➢ WP6 ➢ WP11
	• Sedimentation	➢ WP6
	• Beach profile	➢ WP4 ➢ WP6
	• Sediment grain size	➢ WP5 ➢ WP6
	• Seagrass sediment interaction	➢ WP6 ➢ WP10
	• Availability of sediment	➢ WP4 ➢ WP6
	• Aeolian sand transport	➢ WP6 ➢ WP10
Set-up a monitoring plan to evaluate technical functioning of DD-hybrid NbS	• Parameters of Energy attenuation	➢ WP4 ➢ WP12 ➢ WP16 ➢ WP17 ➢ WP18
	• Parameters of Shoreline Stabilization below water line	➢ WP4 ➢ WP6 ➢ WP11

	• Parameters of Coastal flood risk management	➢ WP4 ➢ WP12
	• Parameters of Structural integrity	➢ WP12 ➢ WP15
	• Parameters of Climate resilience	➢ WP4 ➢ WP7 ➢ WP11 ➢ WP13
	• Parameters of Dune stabilization above water line	➢ WP4 ➢ WP5 ➢ WP6 ➢ WP10 ➢ WP11

3.3.3 Financing Key Target Indicators and associated Parameters/Variables for Developing Blueprint

The financial dimension of DD-hybrid NbS is often underestimated, yet it plays a decisive role in determining whether a project can move from conceptual ambition to practical implementation. Financing KTIs help clarify the economic conditions under which a dune–dike hybrid system becomes feasible, sustainable, and attractive to both public authorities and private stakeholders. Unlike traditional coastal protection measures, which are typically evaluated solely on the basis of capital expenditure and structural performance, DD-hybrid NbS generate a broader suite of benefits—ranging from ecosystem services to recreational value—that complicate but also enrich the financial assessment. The financing KTIs therefore provide a structured approach to capturing these diverse economic dimensions and integrating them into the design and decision-making process.

A central financial consideration is the distinction between capital expenditure (CAPEX) and operational expenditure (OPEX). Hybrid systems often require higher initial investments than conventional hard structures, particularly when sediment nourishment, vegetation establishment, or ecological restoration measures are included. However, their long-term operational costs may be significantly lower, as natural processes contribute to system maintenance and adaptation. Financing KTIs help quantify these cost trajectories, enabling practitioners to compare hybrid systems with traditional alternatives over the full lifecycle of the project. This lifecycle perspective is essential for demonstrating the long-term cost-effectiveness of DD-hybrid NbS, especially in the context of rising climate adaptation costs.

Another important financial dimension concerns the valuation of ecosystem services. Dune–dike hybrids provide a range of co-benefits beyond flood protection, including carbon sequestration, habitat creation, recreational opportunities, and aesthetic enhancement. These benefits can generate economic value for local communities and contribute to broader societal objectives, yet they are often overlooked in traditional cost–benefit analyses. Financing KTIs encourage the integration of ecosystem service valuation into project assessments, helping to capture the full economic potential of hybrid systems. This broader valuation framework aligns with emerging European policies that promote nature-positive investments and the integration of natural capital into financial decision-making.

Financing KTIs also address the availability and suitability of funding mechanisms. DD-hybrid NbS can draw on a diverse range of financial instruments, including public funding, EU adaptation and biodiversity programmes, private investment, and blended finance models. The choice of mechanism depends on factors such as project scale, governance structure, risk distribution, and expected returns. By identifying relevant funding pathways early in the design process, financing KTIs help ensure that hybrid systems are not only technically and ecologically feasible but also financially viable. This is particularly important for large-scale or long-term projects that require sustained investment and cross-sectoral collaboration.

Risk and uncertainty represent another critical financial consideration. Hybrid systems are dynamic and may evolve in ways that differ from initial projections. While this adaptability is one of their strengths, it also introduces uncertainty into financial planning. Financing KTIs therefore incorporate risk assessment parameters that account for variability in sediment supply, vegetation development, storm frequency, and climate projections. These indicators support the development of adaptive financing strategies that can accommodate changing conditions without compromising system performance or financial stability.

Finally, financing KTIs highlight the importance of aligning economic considerations with social and policy objectives. Public acceptance, regulatory compliance, and long-term governance arrangements all influence the financial feasibility of hybrid systems. For example, projects that deliver clear social benefits or align with national climate adaptation strategies may be more likely to secure funding. By integrating financial, social, and policy dimensions, the KTIs help create a coherent framework that supports both investment decisions and long-term sustainability.

In summary, financing KTIs provide the economic foundation for DD-hybrid NbS. They ensure that hybrid systems are evaluated not only in terms of their engineering and ecological performance but also in terms of their financial viability, long-term sustainability, and contribution to societal value. By incorporating lifecycle costing, ecosystem service valuation, funding mechanisms, risk assessment, and policy alignment, the financing KTIs form a crucial component of the Blueprint and support the broader goal of mainstreaming nature-based coastal protection.

Table 6 summarises the financing KTIs, their associated parameters/variables, and the corresponding work packages supporting their development within the Blueprint.

Table 5. Financing KTIs and related parameters/variables for DD-Hybrid NbS development

Financing KTIs	Key Parameters/Variables	Relative Work Packages
Cost Benefit Optimization	• ROI (Return on Investment)	➢ WP8
	• Market based benefits (avoided damage to buildings)	➢ WP8
	• Co-benefits (Carbon storage, Carbon credits, Stakeholder benefits etc.)	➢ WP9
	• LCA (Life Cycle Analysis)	➢ WP8
	• LCC (Life Cycle Cost analysis)	➢ WP8
Financing Maximization	• CAPEX	➢ WP8
	• OPEX	➢ WP8 ➢ WP14
	• Funding / Financial plan	➢ WP14
	• Funding (public/private/EU for NbS restoration)	➢ WP14

3.3.4 Social Key Target Indicators and associated Parameters/Variables for Developing Blueprint

The social dimension of DD-hybrid NbS is fundamental to their long-term success. Hybrid coastal systems do not exist in isolation; they are embedded within lived landscapes, shaped by the values, expectations, and behaviours of the communities that interact with them. Social Key Target Indicators (KTIs) therefore help ensure that dune–dike hybrids are not only technically and ecologically sound but also socially legitimate, publicly supported, and aligned with local needs and identities. Without this social foundation, even the most robust design may encounter resistance, underuse, or conflict, ultimately undermining its effectiveness.

A central aspect of the social KTIs is public perception of safety. Coastal protection infrastructure carries a symbolic weight that extends beyond its physical function. Traditional hard structures often convey a sense of security through their visible solidity, whereas hybrid systems—relying partly on natural elements—may initially be perceived as less reliable. Understanding how communities interpret the protective role of dunes, vegetation, and natural dynamics is therefore essential. Social KTIs help identify whether additional communication, signage, or participatory processes are needed to build trust in the hybrid system and ensure that residents and visitors understand its function.

Recreation and accessibility represent another important social dimension. Dune–dike hybrids often occupy spaces that are used for walking, cycling, beach access, nature observation, and tourism. Their design must therefore balance protective and ecological functions with the desire for public enjoyment. Social KTIs help assess how people currently use the coastal zone, how these uses might change with the introduction of a hybrid system, and how design choices—such as pathways, viewpoints, or restricted zones—can support both ecological integrity and public access. This is particularly important in densely populated or tourist-intensive regions, where coastal landscapes serve multiple, sometimes competing, functions.

Cultural and historical values also shape the social context of DD-hybrid NbS. Many coastal areas hold deep cultural significance, whether through traditional land uses, heritage sites, or long-standing community identities. Hybrid systems must therefore be sensitive to these cultural dimensions, ensuring that interventions do not disrupt valued landscapes or undermine local traditions. Social KTIs help identify such cultural anchors and integrate them into the design process, supporting solutions that resonate with local identity rather than imposing unfamiliar forms.

Stakeholder engagement is a further cornerstone of the social KTIs. The development of DD-hybrid NbS involves a diverse set of actors, including residents, local authorities, environmental organisations, tourism operators, and landowners. Their perspectives, concerns, and aspirations must be incorporated into the design and implementation process to ensure legitimacy and reduce conflict. Social KTIs therefore emphasise the need for transparent communication, participatory planning, and co-creation processes that allow stakeholders to influence decisions meaningfully. This collaborative approach not only enhances acceptance but also enriches the design by integrating local knowledge and experience.

Finally, social KTIs address potential conflicts and trade-offs. Hybrid systems may require temporary restrictions during construction, changes in land use, or adjustments to recreational patterns. They may also introduce new management practices, such as limiting access to sensitive dune areas to protect vegetation. Identifying these potential conflicts early allows practitioners to develop mitigation strategies that balance ecological and technical needs with social expectations. This proactive approach helps maintain public support and ensures that the hybrid system remains a valued part of the coastal landscape.

In summary, social KTIs ensure that DD-hybrid NbS are grounded in the lived realities of the communities they serve. By addressing perceptions of safety, recreational use, cultural values, stakeholder engagement, and potential conflicts, these indicators help create hybrid systems that are not only effective in physical terms but also embraced by society. This social foundation is essential for the long-term sustainability and acceptance of nature-based coastal protection.

Table 7 summarises the social KTIs, their associated parameters/variables, and the corresponding work packages supporting their development within the Blueprint.

Table 6. Social KTIs and related parameters/variables for DD-Hybrid NbS development

Social KTIs	Key Parameters/Variables	Relative Work Packages
Stakeholder Involvement	• Co-creation	➢ WP15
	• Stakeholder mapping and engagement	➢ WP16
	• Public participation/ engagement	➢ WP16
	• Coalition building	➢ WP16 ➢ WP17
	• Sense of empowerment: perceived control and influence over decision-making	➢ WP16
Aesthetics Optimization	• Appeal to people (landscape architecture)	➢ WP16
Tourism and Recreation Opportunities	• Waterfront accessibility	➢ WP15
	• Awareness and use of waterfront	➢ WP16
	• Job opportunities	➢ WP16 ➢ WP17 ➢ WP18
	• Cultural heritage	➢ WP16 ➢ WP17 ➢ WP18
Health and Well-being	• Health (Life expectancy, cardiovascular disease	➢ WP9
	• Food (Food security index	➢ WP9
	• Shelter & Security (Housing quality index	➢ WP9
	• Happiness	➢ WP9
	• Freedom to be and do all	➢ WP9
	• Quality of life	➢ WP9
	• Self-reported mental health and well being	➢ WP9

3.3.5 Policy Key Target Indicators and associated Parameters/Variables for Developing Blueprint

The policy dimension of DD-hybrid NbS forms the institutional framework within which these systems must be conceived, approved, implemented, and maintained. Policy Key Target Indicators (KTIs) help ensure that dune–dike hybrids are not only technically and ecologically feasible but also legally compliant, administratively supported, and aligned with broader strategic objectives at local, regional, and European levels. Without this alignment, even the most scientifically robust design may encounter delays, regulatory barriers, or governance conflicts that hinder implementation.

A central policy consideration concerns the regulatory environment governing coastal protection and spatial planning. Hybrid systems must comply with national legislation on flood risk management, coastal zone planning, environmental protection, and public safety. They must also align with European directives such as the Floods Directive, the Habitats Directive, the Water Framework Directive, and the Marine Strategy Framework Directive. Policy KTIs help identify which regulatory instruments apply to a given site and how they influence design choices. For example, Natura 2000 designations may impose restrictions on construction timing or require specific ecological mitigation measures, while national flood safety standards may dictate minimum dune or dike dimensions.

Permitting processes represent another critical policy dimension. The implementation of DD-hybrid NbS often requires multiple permits, involving different authorities responsible for coastal defence, environmental protection, land use, and public access. These processes can be complex and time-consuming, particularly when hybrid systems introduce novel design elements that do not fit neatly within existing regulatory categories. Policy KTIs therefore help map the permitting landscape, identify potential bottlenecks, and support early engagement with regulatory bodies. This proactive approach reduces uncertainty and facilitates smoother project progression.

Governance structures also play a decisive role in the feasibility of hybrid systems. Coastal zones typically involve overlapping responsibilities among municipalities, regional authorities, water agencies, environmental organisations, and private landowners. Effective implementation requires clear delineation of roles, responsibilities, and long-term management arrangements. Policy KTIs help clarify which actors must be involved, how decision-making authority is distributed, and what governance mechanisms are needed to support ongoing maintenance and adaptive management. This is particularly important for hybrid systems, which rely on both engineered and natural components and therefore require coordinated stewardship.

Policy KTIs also address alignment with broader strategic objectives. DD-hybrid NbS contribute to multiple policy agendas, including climate adaptation, biodiversity restoration, sustainable tourism, and the transition to nature-positive infrastructure. Aligning hybrid systems with these strategic priorities can enhance political support, unlock funding opportunities, and strengthen the legitimacy of the project. For example, projects that contribute to the EU Climate Adaptation Strategy or the European Green

Deal may be eligible for specific funding streams or benefit from accelerated approval processes. Policy KTIs therefore help position hybrid systems within these broader policy narratives, demonstrating their relevance and added value.

Finally, policy KTIs consider long-term institutional support. Hybrid systems require ongoing monitoring, maintenance, and adaptive management, which must be embedded within stable governance and funding arrangements. Policy KTIs help identify whether existing institutions have the capacity and mandate to support these long-term needs or whether new arrangements—such as inter-agency agreements or public–private partnerships—may be required. Ensuring long-term institutional commitment is essential for maintaining the protective and ecological functions of the hybrid system over time.

In summary, policy KTIs provide the institutional and regulatory foundation for DD-hybrid NbS. They ensure that hybrid systems are legally compliant, administratively feasible, strategically aligned, and supported by robust governance structures. By integrating regulatory requirements, permitting processes, governance arrangements, strategic alignment, and long-term institutional support, the policy KTIs complete the multidimensional framework of the Blueprint and help create the enabling conditions necessary for successful implementation.

Table 8 summarises the policy KTIs, their associated parameters/variables, and the corresponding work packages supporting their development within the Blueprint.

Table 7. Policy KTIs and related parameters/variables for DD–Hybrid NbS development

Financing KTIs	Key Parameters/Variables	Relative Work Packages
Policy Alignment	• Permits, regulations	➢ WP15
	• National and Local Policies	➢ WP16
	• EU policies and Natura 2000	➢ WP16
	• Regulations between project partners	➢ WP1
Policy Input/Feeding	• Dissemination	➢ WP16 ➢ WP17
	• Communication	➢ WP16 ➢ WP17
	• Monitoring	➢ WP15 ➢ WP18
	• Guidelines	➢ WP14
	• Policy papers	➢ WP17 ➢ WP18
	• DuneFront Tools (PDT, DSS)	➢ WP13 ➢ WP14

3.4 Integrating the KTIs into the Blueprint

The integration of the Key Target Indicators into the Blueprint represents the point at which the multidimensional nature of DD-hybrid NbS becomes operational. While each KTI pillar—ecological, technical, financial, social, and policy—captures a distinct set of conditions and requirements, their true value emerges only when they are considered together as part of a coherent design and implementation process. Hybrid coastal systems function at the intersection of natural dynamics, engineered structures, societal expectations, and institutional frameworks. The Blueprint therefore provides a structured method for synthesising these diverse indicators into a unified approach that guides practitioners from initial concept to long-term management.

The integration process begins with a holistic assessment of the site. Rather than treating ecological, technical, financial, social, and policy considerations as separate analyses, the Blueprint encourages practitioners to examine how these dimensions interact. For example, sediment availability (a technical KTI) influences dune development and habitat formation (an ecological KTI), which in turn affects construction and maintenance costs (a financial KTI) and may require specific permitting conditions (a policy KTI). Similarly, stakeholder expectations regarding recreation or landscape aesthetics (social KTIs) may shape design choices that influence vegetation establishment or dune geometry. By recognising these interdependencies, the Blueprint helps avoid fragmented decision-making and supports the development of solutions that are both feasible and context-appropriate.

A key feature of the integration process is its iterative nature. Hybrid systems evolve over time, and their design must accommodate uncertainty and change. The Blueprint therefore does not present the KTIs as a linear checklist but as a set of parameters that must be revisited throughout the project lifecycle. Early ecological assessments may reveal constraints that require adjustments to technical design; financial analyses may highlight the need for phased implementation; stakeholder engagement may uncover concerns that necessitate modifications to access routes or vegetation management. This iterative approach ensures that the final design reflects a balanced consideration of all relevant factors and remains adaptable to new information.

The Blueprint also emphasises the importance of transparency and communication in integrating the KTIs. Because hybrid systems involve multiple disciplines and stakeholders, clear documentation of how each KTI has been evaluated and incorporated into the design is essential. This transparency supports regulatory approval, facilitates stakeholder engagement, and enhances the credibility of the project. It also provides a foundation for monitoring and adaptive management, as the rationale behind design decisions becomes traceable and can be revisited as conditions evolve.

Another important aspect of integration is the translation of KTIs into concrete design choices. While the KTIs identify the conditions necessary for successful implementation, the Blueprint guides practitioners in interpreting these conditions in practical terms. For example, ecological KTIs related to vegetation establishment may translate into specific planting strategies or dune stabilisation measures. Technical KTIs concerning hydrodynamic forcing may inform dune crest height or dike geometry. Financial KTIs may influence the choice between natural accretion and mechanical nourishment. Social KTIs may shape the layout of pathways or viewing points, while policy KTIs may determine construction timing or monitoring requirements. Through this translation process, the KTIs become actionable elements of the design.

Finally, the integration of KTIs supports the long-term sustainability of DD-hybrid NbS. By embedding ecological processes, engineering robustness, financial viability, social acceptance, and policy compliance into a single framework, the Blueprint helps ensure that hybrid systems remain functional and valued over time. This integrated approach aligns with contemporary coastal management paradigms that emphasise resilience, adaptability, and multifunctionality. It also supports the broader objectives of European climate adaptation and biodiversity strategies, positioning DD-hybrid NbS as a forward-looking solution for coastal protection.

In summary, the integration of KTIs into the Blueprint transforms a set of analytical indicators into a practical, operational framework for designing and implementing DD-hybrid NbS. It ensures that hybrid systems are conceived holistically, designed iteratively, communicated transparently, and managed adaptively. This integrated approach is essential for realising the full potential of nature-based coastal protection and for supporting its adoption across diverse European coastal contexts.

4. Conclusions

The development of the Blueprint for DD-hybrid NbS represents a significant step forward in the evolution of coastal protection strategies that integrate natural dynamics with engineered robustness. Through the synthesis of ecological, technical, financial, social, and policy dimensions, the Blueprint provides a comprehensive and operational framework that supports practitioners throughout the entire lifecycle of hybrid coastal systems. It translates the diverse insights generated across the DuneFront project into a coherent methodology that can be applied across a wide range of European coastal contexts.

The conclusions drawn from this work highlight the transformative potential of DD-hybrid NbS. By combining the adaptive capacity of dunes with the reliability of engineered dikes, hybrid systems offer a multifunctional approach to coastal protection that aligns with contemporary climate adaptation and biodiversity objectives. They provide not only physical safety but also ecological enhancement, recreational value, and long-term adaptability—qualities that are increasingly essential in the face of accelerating climate change and rising societal expectations.

A central insight emerging from the Blueprint is the importance of integration. Hybrid systems cannot be designed or managed effectively through isolated disciplinary lenses. Their success depends on the interplay between sediment dynamics, vegetation development, hydrodynamic forcing, stakeholder engagement, financial planning, and regulatory compliance. The Blueprint therefore emphasises the need for iterative, cross-disciplinary collaboration and transparent communication throughout the design and implementation process. This integrated approach ensures that hybrid systems are not only technically feasible but also ecologically meaningful, socially accepted, and institutionally supported.

Another key conclusion concerns the value of adaptability. DD-hybrid NbS are living systems that evolve over time, responding to natural processes and human interventions. Their long-term performance depends on continuous monitoring, evaluation, and adjustment. The Blueprint embeds adaptive management into every stage of the project lifecycle, ensuring that hybrid systems remain resilient in the face of changing environmental conditions and emerging knowledge. This adaptability distinguishes hybrid systems from traditional hard infrastructure and positions them as forward-looking solutions for sustainable coastal protection.

The Blueprint also underscores the importance of context. While the framework provides a structured and transferable methodology, the design of any hybrid system must be tailored to local geomorphology, ecological communities, governance structures, and societal priorities. The DuneFront Demonstrators illustrate the diversity of European coastal environments and highlight the need for flexible, site-specific design principles. The Blueprint supports this flexibility by offering a method for identifying relevant parameters and translating them into context-appropriate interventions.

Finally, the conclusions of this deliverable point toward the broader implications of DD-hybrid NbS for coastal management. As Europe seeks to implement the objectives of the Green Deal, the Climate Adaptation Strategy, and biodiversity restoration initiatives, hybrid systems offer a practical and scalable means of integrating nature into infrastructure. They demonstrate that coastal protection can be achieved in ways that enhance, rather than degrade, ecological and social values. The Blueprint provides the guidance needed to realise this potential and to support the mainstreaming of nature-based coastal protection across Europe.

In summary, the Blueprint developed in this deliverable offers a scientifically grounded, operationally feasible, and context-sensitive framework for the design and implementation of DD-hybrid NbS. It reflects the complexity and dynamism of hybrid systems while providing clear guidance for practitioners. By integrating diverse knowledge domains into a unified methodology, the Blueprint contributes to the advancement of sustainable, resilient, and multifunctional coastal protection.

5. Annex

1. Date (dd/mm/jj): title.

6. References

Coastal Hazard Wheel, n.d. Facilitating global coastal resilience [WWW Document]. Coast. Hazard Wheel. URL https://www.coastalhazardwheel.org/ (accessed 1.12.26).

Coastal Resilience, n.d. Tools | Coastal Resilience [WWW Document]. URL https://coastalresilience.org/tools/?utm_source=chatgpt.com (accessed 1.12.26).

D'Alessandro, F., Tomasicchio, G.R., Frega, F., Leone, E., Francone, A., Pantusa, D., Barbaro, G., Foti, G., 2022. Beach–dune system morphodynamics. J. Mar. Sci. Eng. 10, 627.

European Commission, 2025. Nature-based-Solutions European Commission [WWW Document]. URL https://research-and-innovation.ec.europa.eu/research-area/environment/nature-based-solutions_en (accessed 1.12.26).

European Commission, 2021. Evaluating the impact of nature-based solutions: a summary for policy makers. Publications Office of the European Union.

EurOtop, 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.

IUCN, I.U. for C. of, 2020. IUCN global standard for nature-based solutions.

Lamberti, A., Archetti, R., Kramer, M., Paphitis, D., Mosso, C., Di Risio, M., 2005. European experience of low crested structures for coastal management. Coast. Eng., Low Crested Structures and the Environment 52, 841–866. https://doi.org/10.1016/j.coastaleng.2005.09.010

PESTEL [WWW Document], n.d. URL https://wikis.ec.europa.eu/spaces/ExactExternalWiki/pages/50109048/Context+analysis+%E2%80%93+PESTEL (accessed 12.29.25).

Stratigaki, V., Bonte, D., Troch, P., Gruwez, V., Dahirel, M., Van Tittelboom, K., De Belie, N., Hofland, B., Reniers, A., Tissier, M., 2024. DUNEFRONT PROJECT: DEMONSTRATION OF DUNE-DIKE HYBRID NATURE-BASED SOLUTIONS, in: ICCE 2024, Location: Rome.

Vousdoukas, M.I., Ranasinghe, R., Mentaschi, L., Plomaritis, T.A., Athanasiou, P., Luijendijk, A., Feyen, L., 2020. Sandy coastlines under threat of erosion. Nat. Clim. Change 10, 260–263.

Vuik, V., Van Vuren, S., Borsje, B.W., van Wesenbeeck, B.K., Jonkman, S.N., 2018. Assessing safety of nature-based flood defenses: Dealing with extremes and uncertainties. Coast. Eng. 139, 47–64.

Zanuttigh, B., Simcic, D., Bagli, S., Bozzeda, F., Pietrantoni, L., Zagonari, F., Hoggart, S., Nicholls, R.J., 2014. THESEUS decision support system for coastal risk management. Coast. Eng. 87, 218–239.