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Cooling Technology Selection for Coastal Nuclear Power Plants in Shallow Semi-Enclosed Seas: Study Analysis for the Southern Baltic Sea

Michał Bartyzel , Paweł Gilewski  and Mirosław Szyłak-Szydlowski * 

Faculty of Environmental Engineering, Warsaw University of Technology, ul. Nowowiejska 20, 00-653 Warsaw, Poland; michalbartyzel4@gmail.com (M.B.); pawel.gilewski@pw.edu.pl (P.G.)

* Correspondence: miroslaw.szydlowski@pw.edu.pl

Abstract

The planned Lubiatowo–Kopalino nuclear power plant (NPP) on the Polish Baltic coast requires a cooling technology that balances energy security, economic efficiency, and compliance with a multi-layered framework governing thermal discharge in a sensitive sea. This article integrates regulatory analysis across four instruments (EU Water Framework Directive, Polish discharge standards, HELCOM Baltic guidelines, and IAEA practice) with site-specific evidence from a 2D advection-diffusion thermal plume model. Four cooling options (once-through seawater, closed-loop towers, dry-air, and hybrid) are evaluated against regulatory criteria and against the documented vulnerabilities of the southern Baltic: eutrophication, restricted flushing, and ongoing warming. The modelling indicates that the acute thermal plume ($\Delta T \geq 2^\circ\text{C}$) remains limited to approximately 1.18 km^2 even under summer 90th-percentile conditions, whereas low-magnitude warming ($\Delta T = 0.1\text{--}0.5^\circ\text{C}$) extends over approximately 1886.6 km^2 . Although the once-through system with a multi-port diffuser satisfies current regulatory criteria, the extensive far-field anomaly represents an additional ecological stressor for an already eutrophic and warming marine ecosystem. A staged hybrid approach, with the first unit on validated once-through cooling and subsequent units on hybrid dry/wet systems, emerges as the most sustainable pathway, balancing empirical learning, regulatory foresight, and long-term climate resilience. The analysis offers a transferable framework for thermal-discharge assessment in shallow, microtidal, nutrient-enriched coastal seas, while demonstrating consistency with established regulatory practice and published knowledge on thermal-plume behaviour.

Keywords: nuclear power plant; thermal discharge; cooling systems; ecological risk assessment; Baltic Sea; climate adaptation



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1. Introduction

1.1. Energy Transition, Coastal Nuclear Siting, and the Cooling Challenge

The global energy transition toward decarbonisation has renewed interest in nuclear power as a stable, dispatchable low-carbon electricity source that can complement variable renewable generation and reduce reliance on fossil fuels. The International Energy Agency identifies nuclear power as an important low-emission source of electricity, currently providing around 10% of global electricity generation, and in global net-zero pathways nuclear energy is considered together with renewables, grids, and storage as part of a

diversified clean-energy transition [1–3]. The European Union’s 2022 Taxonomy Regulation and the ‘REPowerEU’ initiative reaffirmed the nuclear role in meeting climate and energy security targets [4–6].

Poland’s Energy Policy until 2040 (PEP2040) defines the national energy transition around energy security, competitiveness, and environmental impact, and designates the implementation of nuclear power as one of its strategic directions [7]. The first Polish NPP is planned at the Lubiatowo–Kopalino site in the Choczewo municipality on the Baltic coast, designed with three Westinghouse AP1000 reactor units of approximately 1250 MWe gross capacity each, for a total planned capacity of about 3750 MWe [8]. The three units are planned to be commissioned sequentially, allowing operational experience from the initial unit to inform subsequent phases of plant development. Like all large thermal power plants, each unit must dissipate approximately 2400 MWth of waste heat [9]. For coastal locations, open-loop (once-through) seawater cooling is technologically straightforward: seawater is drawn through condenser heat exchangers and discharged at an elevated temperature. Alternative configurations, such as closed-loop cooling with towers, dry-air cooling, or hybrid systems, can reduce the direct marine thermal footprint but introduce other trade-offs, including higher capital costs, efficiency penalties, land requirements, and operational complexity [10,11]. The cooling system is therefore not a purely technical component but a strategic design choice with regulatory, ecological, and sustainability implications.

In the Polish context, the cooling challenge is not only a site-specific engineering issue but also part of a broader water-management problem associated with the national energy transition. Recent studies emphasise that sustainable energy development in Poland increasingly requires an Integrated Water Resources Management perspective, particularly where electricity production depends on large-scale water abstraction and where climate change may intensify seasonal water stress [12]. Cooling water already represents a dominant component of surface-water abstraction for electricity production in Poland, and future changes in the power sector may alter both the spatial distribution and environmental significance of this pressure [13]. The Lubiatowo–Kopalino project therefore sits at the intersection of three policy domains: decarbonisation and energy security, regulatory control of thermal pollution, and the need to protect vulnerable aquatic and marine ecosystems under changing climatic conditions.

The once-through approach imposes a persistent anthropogenic thermal load on the receiving marine ecosystem. The southern Baltic represents a particularly sensitive receiving environment for thermal discharges because of its ecological vulnerability and ongoing climate change [14,15]. This study evaluates cooling technology options against regulatory requirements and quantitative ecological risk, providing site-specific evidence to support long-term policy and engineering decisions.

1.2. The Southern Baltic as a Vulnerable Receiving Environment

The Baltic Sea is a unique hydrographic system: a large, shallow, semi-enclosed brackish sea with pronounced physical and ecological sensitivity. A mean depth of only about 54 m and water exchange with the North Sea restricted through the narrow Danish straits favour water accumulation, with retention times of 25 to 40 years far longer than in open shelf seas [15]. This confinement, combined with freshwater inputs from approximately 250 rivers, produces a brackish, density-stratified, poorly mixed system. Eutrophication is endemic: the basin receives nitrogen and phosphorus inputs from nine surrounding countries, and in-basin recycling has driven much of the southern and central basins toward persistent nutrient excess, producing periodic deep-water hypoxia and recurrent summer cyanobacterial blooms in shallow coastal zones [16]. The Lubiatowo–Kopalino site lies

within or immediately adjacent to several Natura 2000 special areas of conservation (SACs) designated under the EU Habitats Directive, including rocky reef habitats whose benthic communities are sensitive to sustained environmental change [8,17]. Climate projections indicate the Baltic is warming at about 0.06 to 0.08 °C per decade, with a further increase of 1.5 to 2.5 °C by 2070 under intermediate emissions scenarios [14,18]. This combination of endemic eutrophication, restricted water exchange, ongoing climate warming, and the presence of protected habitats creates a coastal environment in which thermal-discharge impacts cannot be dismissed as negligible.

1.3. Research Objectives and Structure

Despite the strategic importance of cooling technology selection for Polish energy policy and Baltic environmental governance, published integrated assessments combining regulatory framework analysis with site-specific thermal plume modelling for coastal NPPs in shallow semi-enclosed seas are sparse. Existing discussions tend to address engineering performance, water demand, regulatory assessment or ecological effects as separate domains, while fewer studies integrate these dimensions into one site-specific framework for coastal NPP cooling selection in shallow semi-enclosed seas [10,11,19,20]. We pursue three objectives: (1) delineate the multi-layer regulatory framework applicable to the Lubiatowo–Kopalino site and extract specific numeric compliance thresholds; (2) provide a structured technical, economic, and ecological comparison of four cooling technology options against these criteria; (3) synthesise quantitative site-specific thermal plume modelling results to evaluate regulatory compliance margins and ecological risk under current and future climate scenarios.

The novelty of this work lies not only in integrating regulatory, engineering, and ecological perspectives, but also in demonstrating that regulatory compliance does not necessarily imply ecological acceptability in shallow, climate-sensitive coastal seas. This contribution is achieved through three complementary innovations. The first is a multi-instrument regulatory synthesis that systematises four overlapping legal frameworks (WFD, Polish standards, HELCOM, and IAEA) into an internally consistent set of numeric compliance targets. The second is a technology-specific ecological risk evaluation, showing that conventional compliance metrics (ΔT at the mixing-zone boundary) do not adequately capture ecosystem-scale chronic thermal stress associated with extensive far-field low-magnitude anomalies. The third is a site-specific thermal-plume modelling framework that links regulatory requirements with quantitative simulations accounting for seasonal stratification, wind forcing, and storm-driven mixing in the southern Baltic receiving environment. Together, these elements provide a transferable framework for evaluating cooling technologies in shallow, eutrophic, semi-enclosed coastal seas.

2. Regulatory Framework for Thermal Discharges in Baltic Coastal Waters

Thermal discharge from a coastal NPP in Poland is governed by a multi-layered set of instruments operating at different spatial and temporal scales. Regulatory assessment cannot be reduced to a single outfall temperature: it must also account for the ecological status of the receiving water body, the spatial extent and persistence of the thermal plume, and the sensitivity of the coastal ecosystem. This section examines four frameworks in turn and consolidates their requirements into a single set of compliance criteria (Table 1).

Table 1. Applicable thermal-discharge regulatory and guidance frameworks for coastal NPPs in the southern Baltic.

Framework	ΔT /Temperature Reference	Spatial Scope/Zone of Assessment	Legal Status in Poland
EU Water Framework Directive 2000/60/EC	No fixed numeric threshold; temperature assessed within the good-ecological-status framework	All surface waters, including coastal and transitional	Transposed into Polish law; legally binding
Polish regulations (2016 classification; 2019 discharge)	35 °C ceiling for cooling-water discharge, not applicable to territorial sea waters; classification-derived reference values $\Delta T \leq 1.5$ °C (cold-water)/3.0 °C (other) applied in site-specific assessment; no universal binding marine ΔT	Discharge point, permit-defined monitoring area, EIA impact zone	Binding national law and administrative permits
HELCOM Baltic Sea framework	No binding numeric ΔT ; precautionary, ecosystem-based assessment of cumulative pressure and effects on protected areas	Baltic Sea regional scale; sub-basins and coastal zones; Natura 2000 flagged	Regional convention; non-binding, adopted by contracting parties
IAEA guidance	No binding generic ΔT ; emphasis on site-specific modelling and monitoring. Stringent near-field design target $\Delta T \leq 1$ °C at 500–1000 m applied in the site-specific assessment	Plant site, cooling system, receiving environment	International guidance; not directly binding unless incorporated into national licensing

2.1. EU Water Framework Directive (2000/60/EC)

The WFD establishes a binding obligation for EU member states to achieve and maintain good ecological status, or good ecological potential, in all surface water bodies, including coastal and transitional waters, and to prevent their deterioration [21]. The WFD is used as the primary regulatory reference because it constitutes the overarching legal framework governing the ecological status of all EU surface waters, including coastal waters. National regulations, environmental permitting procedures, and project-specific environmental impact assessments are required to comply with its objectives, making it the principal legal benchmark for thermal-discharge assessment in Poland. It does not prescribe a fixed numeric temperature threshold for thermal discharges. Instead, temperature is treated as a physicochemical condition supporting ecological status. The acceptability of a discharge therefore depends not on a single emission value but on whether the resulting temperature change could compromise the ecological status of the receiving water body or contribute to deterioration. The Directive permits the designation of mixing zones, that is, areas adjacent to a discharge point within which environmental quality standards may be exceeded, provided the zone is explicitly delimited, does not affect the status of the wider water body, and does not impair compliance elsewhere. For coastal NPP cooling-water discharges in the Baltic, the WFD thus sets an overarching legal ceiling: no discharge may be licensed in a way that perpetuates poor ecological status in the broader coastal ecosystem, regardless of what is permitted within a site-specific mixing zone. This receptor-oriented logic provides the framework within which thermal plume modelling and ecological risk assessment are interpreted. For the Lubiatowo–Kopalino site, no fixed numeric mixing-zone extent is prescribed in advance. Under the receptor-oriented logic of the Directive, the spatial delimitation of any mixing zone is established case-by-case in the

water-law permit on the basis of the Environmental Impact Assessment and the predicted thermal field, rather than as a generic numeric allowance. The present modelling supports exactly this delineation, by quantifying the area over which the relevant ΔT reference values are exceeded.

2.2. Polish National Regulatory Framework

Polish regulations implement the EU water-protection framework through national classification rules, discharge conditions, and environmental permitting. Two instruments are relevant to thermal discharges. The Regulation of the Minister of the Environment of 21 July 2016 (Journal of Laws 2016, item 1187) established the national framework for classifying the ecological and chemical status of surface waters and, in this context, supports the interpretation of temperature as a physicochemical parameter relevant to ecological status [22]. The legal basis of this regulation has since been superseded, so it is treated here as a reference point for the Polish classification approach rather than as the current basis for thermal-discharge permitting.

The operative discharge condition is set by the Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 (Journal of Laws, item 1311), under which cooling waters from open and closed cooling systems may be introduced into waters or into the ground provided their temperature does not exceed 35 °C. This condition does not apply to the introduction of cooling waters into territorial sea waters [23]. For a coastal NPP discharging into the Baltic, this exception means that a simple 35 °C ceiling cannot by itself determine environmental acceptability in the marine receiving environment. Instead, the assessment rests on site-specific permit conditions, the environmental impact assessment, plume modelling, and monitoring obligations, interpreted in light of the WFD's ecological-status objectives. In the marine coastal context, Polish law therefore functions as a permit-based and receptor-sensitive framework rather than a purely threshold-based one. Because the 2019 Regulation provides no fixed end-of-pipe temperature ceiling for territorial sea waters, the maximum acceptable thermal load there is determined case-by-case through the water-law permit and the accompanying Environmental Impact Assessment, operating under the WFD's overarching obligation to maintain good ecological status and prevent deterioration. The classification-derived reference values introduced below then serve as the interpretive benchmarks against which the predicted temperature field at the boundary of the designated mixing zone is judged. The burden of demonstrating compliance thus shifts to the EIA and to the spatial delimitation of the mixing zone granted in the water permit, which makes site-specific thermal-plume modelling a legally determinative element of the plant's licensing rather than a purely academic exercise.

Within this classification logic, the temperature increase relative to the ambient baseline at the outer boundary of a designated mixing zone is commonly assessed against reference values on the order of $\Delta T \leq 1.5$ °C for cold-water-dominated ecosystems and $\Delta T \leq 3.0$ °C for other ecosystem types, with seasonal and ecosystem-type modulation. These values are used in the present analysis as classification-derived reference points for interpreting the modelled thermal field (Section 4), not as a binding marine permitting ceiling, which, as noted above, is set on a site-specific, permit-based basis.

2.3. HELCOM Baltic Sea Framework

HELCOM, the governing body of the Helsinki Convention, provides the regional environmental framework for the Baltic Sea. Unlike the WFD and national regulations, it does not issue directly applicable discharge permits. Its role is to set regional environmental objectives and coordinated measures, structured through the Baltic Sea Action Plan around eutrophication, biodiversity, hazardous substances, and sea-based activities [24]. For

thermal-discharge assessment, HELCOM situates a local pressure within the broader context of cumulative stress on the regional sea [16]. A precautionary, ecosystem-based logic applies: thermal discharges should not cause significant adverse effects on the marine environment, with particular attention to protected areas and migratory corridors, and any discharge sited within or adjacent to Natura 2000 areas requires explicit assessment of effects on protected species and habitats. HELCOM does not set a binding numeric ΔT for individual discharge permits. Instead, it serves as an ecosystem-based sustainability benchmark, under which a technology that reduces the cumulative marine heat load is more consistent with regional objectives, even where another option also meets formal discharge conditions.

2.4. IAEA International Guidance

IAEA guidance is relevant because NPP cooling systems are simultaneously environmental infrastructure and part of the plant's operational and safety framework, requiring reliable heat removal under normal, shutdown, and abnormal conditions. Guidance on water management in water-cooled reactors describes the principal cooling options and emphasises that technology selection depends on water availability, environmental requirements, techno-economic factors, and applicable regulations, with the required cooling-water flow governed by the allowable temperature rise and the maximum discharge temperature set by water-quality authorities [10]. For coastal and marine sites, IAEA guidance further recommends site-specific high-resolution thermal plume modelling and robust monitoring programmes with pre-defined trigger levels as conditions of operating licences, reflecting the chronic rather than episodic nature of forcing from systems that operate continuously over 60-year lifetimes [25]. Consistent with this guidance and with international best practice, the underlying site-specific assessment adopts a stringent near-field design target of $\Delta T \leq 1\text{ }^{\circ}\text{C}$ at 500 to 1000 m from the outfall. Where applied, this is the most demanding of the reference values considered here and effectively sets the engineering design target. Unlike national law, IAEA guidance does not impose a legally binding site-specific threshold. Its function is to support a multi-criteria evaluation of cooling options rather than a single-limit test.

2.5. Regulatory Synthesis

The four frameworks differ in legal force and technical specificity but converge on a single assessment logic. The WFD provides the overarching legal objective of good ecological status and non-deterioration. Polish regulations operationalise this through classification rules and permit-based discharge conditions which, for marine coastal waters, point to site-specific assessment rather than a universal numeric ceiling. HELCOM adds a regional, precautionary, cumulative-pressure perspective with particular attention to protected areas. IAEA guidance contributes a nuclear-sector emphasis on reliable heat removal, site-specific modelling, and monitoring. No single instrument is sufficient on its own: a discharge may satisfy a national condition yet still require broader ecological justification if it sustains a plume in a sensitive coastal zone. Table 1 consolidates these requirements into the criteria applied to the technology comparison in Section 3 and the ecological risk assessment in Section 4.

The stringent near-field design target of $\Delta T \leq 1\text{ }^{\circ}\text{C}$ at 500 m adopted in the site-specific assessment is the most demanding of these reference values. Meeting it ensures consistency with the less stringent classification-derived national reference values and with HELCOM's precautionary, ecosystem-based expectations, while the WFD provides the overarching legal obligation that the other instruments operationalise.

3. Cooling Technology Assessment

Four cooling configurations are technically and economically feasible for a large coastal NPP of the planned scale: once-through (open-loop) seawater cooling, closed-loop cooling with cooling towers, dry-air cooling, and hybrid systems. Each occupies a distinct position on a spectrum of trade-offs between marine thermal impact, water use, thermodynamic efficiency, capital cost, and regulatory compliance risk. Building on the criteria established in Section 2, the four options are compared here against five linked dimensions: thermal footprint in the receiving water, water withdrawal and consumption, energy efficiency, capital cost, and regulatory compatibility.

3.1. Once-Through (Open-Loop) Seawater Cooling

In a once-through system, seawater is continuously withdrawn from the coastal zone, circulated through the condenser to absorb waste heat, and returned to the sea at an elevated temperature. For a coastal NPP, this configuration benefits from direct access to a large and relatively stable heat sink, providing efficient heat removal with low parasitic energy demand and comparatively low system complexity [10,26]. For the planned AP1000 units, the adopted discharge parameters used in the thermal-plume model, including flow rate, discharge temperature, and outlet depth, were taken from the Lubiatowo–Kopalino Environmental Impact Assessment documentation and represent conservative design assumptions used for regulatory evaluation. The modelled discharge flow for all three units was parameterised as 500,000 m³/h, equivalent to 138.9 m³/s, or approximately 12.0 million m³/day, with a temperature elevation of roughly 10 °C across the condenser. Depending on seasonal ambient conditions, this corresponds to outfall temperatures on the order of 8 to 12 °C above ambient. Because the cooling water is continuously replaced by relatively cool seawater, condenser back-pressure, which directly governs electrical output, is minimised, so once-through cooling preserves thermodynamic efficiency better than recirculating or dry systems, particularly during warm periods [10]. The adopted discharge parameters (flow rate, discharge temperature, and outlet depth) were taken from the Lubiatowo–Kopalino Environmental Impact Assessment documentation and represent the conservative design assumptions used for regulatory evaluation.

These advantages are offset by the largest direct interaction with the marine environment. Two distinct concerns arise. First, acute near-field thermal stress: at and immediately around the outfall, ΔT may reach 8 to 12 °C, creating a zone of potential physiological stress for organisms unable to leave the plume. Second, entrainment and impingement: the large combined intake of roughly 138.9 m³/s for three units can entrain larval fish, zooplankton, and phytoplankton and impinge larger organisms on intake screens. In the Baltic, where commercially and ecologically important species such as Atlantic salmon, sea trout, and Baltic cod are cold-water adapted, these impacts are not negligible. The underlying mechanisms are examined in Section 4. The decisive regulatory question, given the criteria in Section 2, is whether a well-engineered once-through system, specifically one fitted with a multi-port submerged diffuser to enhance initial dilution, can consistently meet the stringent near-field design target across all seasonal and climatic conditions. This depends sensitively on site-specific hydrodynamics and is addressed by the modelling in Section 4.

3.2. Closed-Loop Cooling with Cooling Towers

In a closed-loop system, cooling water recirculates through the condenser and rejects its heat to the atmosphere through mechanical-draft or natural-draft cooling towers, primarily by evaporation. Only a small blowdown stream, typically 2 to 5% of the circulating flow, is discharged to the sea to limit salt accumulation, so the marine thermal discharge is one to

two orders of magnitude smaller than in a once-through system and generally falls well within applicable discharge conditions [10,11]. The principal trade-offs are higher capital expenditure (cooling towers and associated infrastructure typically increase cooling-system cost by a factor of about 2 to 3), a thermodynamic efficiency penalty of approximately 1 to 2% from elevated condenser back-pressure, additional evaporative water consumption, and visual and local atmospheric impacts of large towers in a coastal setting [26]. Although water withdrawal is much lower than for once-through cooling, consumptive use is higher because part of the circulating water is lost to the atmosphere [11]. From a regulatory standpoint, closed-loop cooling largely removes the marine thermal-discharge problem and shifts the assessment toward water consumption, blowdown quality, chemical use, and land requirements, making it more compatible with the WFD and HELCOM objectives set out in Section 2.

3.3. Dry-Air Cooling

Dry-air cooling rejects condenser heat directly to the atmosphere using air-cooled condensers, without a liquid-water heat sink. It imposes essentially no thermal load on the receiving water and eliminates the intake-related impingement and entrainment problem, so it is the most favourable option for marine protection and achieves compliance with water-body thermal-discharge objectives by design [10,11]. Its disadvantages are thermodynamic and economic, and both depend on air temperature. Because southern Baltic air temperatures range from roughly -10°C in winter to above $+30^{\circ}\text{C}$ during summer heatwaves, achievable condenser back-pressure, and therefore plant efficiency, varies strongly with ambient conditions. A plant sized for adequate summer performance requires substantially more heat-exchange surface, raising capital cost to roughly 3 to 4 times that of a once-through system. During high-temperature episodes, the efficiency penalty relative to a well-cooled once-through system can reach 4 to 5%, directly reducing output at the times of peak electricity demand. Because climate projections for the region anticipate more frequent and longer summer heatwaves (Section 1.2), this penalty is expected to grow over the facility's operational lifetime, which is a material constraint for a baseload nuclear plant.

3.4. Hybrid Cooling

Hybrid systems combine dry-air and wet-tower operation, switching between modes according to season, ambient conditions, water availability, and grid demand [10,27]. In the typical configuration, the plant operates predominantly in dry mode during cool periods and uses wet-assisted cooling during warm summer periods, maintaining acceptable efficiency and output year-round while substantially reducing marine thermal discharge and water consumption relative to once-through cooling. This suits the pronounced seasonal temperature range of the southern Baltic, where dry-mode efficiency penalties would be incurred only during a limited summer window. Capital cost is intermediate, typically about 2 to 2.5 times once-through cost, and the defining advantage is operational flexibility: the dry-to-wet ratio can be tuned in real time to ambient conditions, grid demand, and ecosystem status. This flexibility makes hybrid cooling well suited to a facility expected to operate for 60 years in a warming climate, and it aligns with the ecosystem-based, precautionary logic of HELCOM by allowing marine heat rejection to be minimised during the most ecologically sensitive periods. The trade-off is greater design and operational complexity, and the environmental benefit is realised only if permit conditions or operating rules actually require environmentally optimised operation.

3.5. Comparative Assessment

No single technology dominates across all five criteria. Once-through cooling is the most efficient and least capital-intensive option but carries the highest marine thermal footprint and the most demanding regulatory scrutiny, particularly under summer stratified conditions in the shallow Baltic. Dry-air cooling is the strongest option for marine protection but has the highest efficiency penalty and capital cost, and the penalty worsens precisely during summer heat extremes. Closed-loop cooling strongly reduces marine thermal impact but transfers part of the burden to evaporative water consumption, tower impacts, and a modest efficiency penalty. Hybrid cooling occupies a balanced position, reducing marine thermal pressure during sensitive periods while preserving efficiency and economic competitiveness, at the cost of higher complexity. Selection therefore requires multi-criteria evaluation rather than a single indicator, and in the Lubiatoŵo–Kopalino context the most relevant comparison is between once-through and hybrid or closed-loop configurations. A comparative summary of the four cooling configurations, including their technical characteristics, environmental implications, regulatory considerations, and long-term sustainability aspects, is presented in Table 2.

Table 2. Comparative assessment of cooling technologies for the Lubiatoŵo–Kopalino coastal site.

Cooling Technology	Marine Thermal Footprint	Water Withdrawal/Consumption	Energy Efficiency Penalty	Relative CAPEX	Regulatory Posture (per Section 2)
Once-through	Highest; continuous plume, ΔT 8–12 °C at outfall	Very high withdrawal (~100–200 m ³ /MWh); low consumptive use	None (baseline)	1.0× (baseline)	Conditional; requires site-specific modelling, EIA, and monitoring
Closed-loop (towers)	Low; blowdown only, much smaller plume	Lower withdrawal (~2–4 m ³ /MWh); higher consumptive use	~1–2%	~2–3×	Generally compliant; assessment shifts to consumption, blowdown, towers
Dry-air	None; no marine discharge	Negligible (~0 m ³ /MWh)	~2–5% (worst in summer heat)	~3–4×	Compliant by design; must demonstrate reliable heat removal in extreme heat
Hybrid	Variable and controllable; lower than once-through if optimised	Intermediate (~1–3 m ³ /MWh), mode-dependent	~1–3% (seasonal)	~2–2.5×	Strong adaptive option; supports seasonal, risk-based compliance

Note: water withdrawal and consumption ranges follow Macknick et al. while discharge flow and temperature parameters are based on the project-specific technological assumptions for the planned Lubiatoŵo–Kopalino nuclear power plant, as adopted in the thermal plume modelling framework [11]. Cost and efficiency impacts are treated as indicative because they are strongly site- and design-specific. Published estimates show that closed-cycle cooling retrofits may involve substantial capital costs, heat-rate penalties, auxiliary power demand and outage-related costs, while dry and hybrid cooling performance is strongly affected by ambient temperature and summer operating conditions [26–29].

4. Ecological Risk and Site-Specific Thermal Plume Assessment

Ecological risk in the southern Baltic cannot be judged by comparing peak ΔT with a single regulatory threshold. In a shallow, semi-enclosed, seasonally variable sea, the significance of a thermal plume depends on the interaction between the discharge, local hydrodynamics, background temperature, biological sensitivity, and pre-existing cumulative stressors [16]. This section sets out the mechanisms of thermal impact, draws on a domestic reference case, summarises the site-specific modelling that underpins the assessment, and interprets the results in terms of acute versus diffuse ecological forcing and its interaction with climate change.

4.1. Mechanisms of Thermal Impact

Elevated water temperature acts through interconnected physiological, chemical, and ecological pathways that are particularly important in nutrient-enriched systems. Although temperature is a naturally variable parameter, rapid or persistent deviations from background conditions affect both aquatic organisms and ecosystem functioning [30]. Warming increases metabolic and respiratory rates while reducing dissolved-oxygen solubility, resulting in simultaneous increases in oxygen demand and decreases in oxygen availability. This combined oxygen stress is particularly severe in eutrophic or weakly mixed waters during summer [16,30]. Baltic fish adapted to cold-water conditions may experience physiological stress, reduced growth, impaired reproduction, and weakened immune function under prolonged thermal exposure [31].

At the community level, thermal enrichment can alter species composition, accelerate primary production and nutrient cycling, and favour algal and cyanobacterial blooms, with subsequent oxygen depletion during biomass decay [32–34]. In eutrophic Baltic waters, even modest sustained warming of 0.5 to 1.0 °C may favour cyanobacterial blooms and is considered ecologically significant [35]. Long-term or repeated warming may also restructure benthic and fish communities and reduce local biodiversity [31,36,37]. Because the Lubiato–Kopalino site lies adjacent to Natura 2000 SACs, any detectable thermal anomaly within or near these areas requires assessment under Article 6(3) of the Habitats Directive, constraining operational flexibility [8,17,25]. Consequently, the ecological relevance of a thermal plume depends not only on its peak ΔT but also on its exposure duration, persistence, and spatial overlap with sensitive habitats [16,25].

4.2. Dolna Odra Power Plant as a Domestic Reference Case

A useful domestic reference is the Dolna Odra power plant, whose heated cooling-water discharge has been studied in the Polish context [32,38]. It is not a direct analogue of the planned NPP, since the receiving environment, hydrology, and dilution capacity differ, but it illustrates the mechanistic pathway by which thermal enrichment can raise primary production and shift water-quality conditions toward a more eutrophic state [30]. Two lessons carry over to Lubiato–Kopalino. First, compliance with a temperature threshold does not preclude local biological responses in the near-field. Second, thermal discharge must be read together with nutrient status, because added heat can amplify pre-existing eutrophication during warm, productive periods. The Dolna Odra case therefore supports a precautionary reading in which the decisive question is not only whether peak ΔT exceeds a limit, but whether the plume coincides with conditions that favour biological amplification.

4.3. Site-Specific Thermal Plume Model: Methodology

This section summarises only the model components needed to interpret the results, which are then applied to the regulatory and ecological assessment that is the focus of this article. A high-resolution 2D depth-averaged advection–diffusion model was developed for the Lubiato–Kopalino coastal zone on a 200 m $\times$ 200 m grid. The marine computational domain covered the southern Baltic Sea coastal sector between the Stilo and Rozewie capes, with a bounding box extending from 16.77389° E to 18.73175° E and from 54.56569° N to 55.34278° N. This corresponds to an approximate west–east, along-shore extent of 125.9 km and an approximate south–north, offshore extent of 84.6 km. The marine polygon used as the computational domain covered approximately 6857.5 km² (Figure 1).

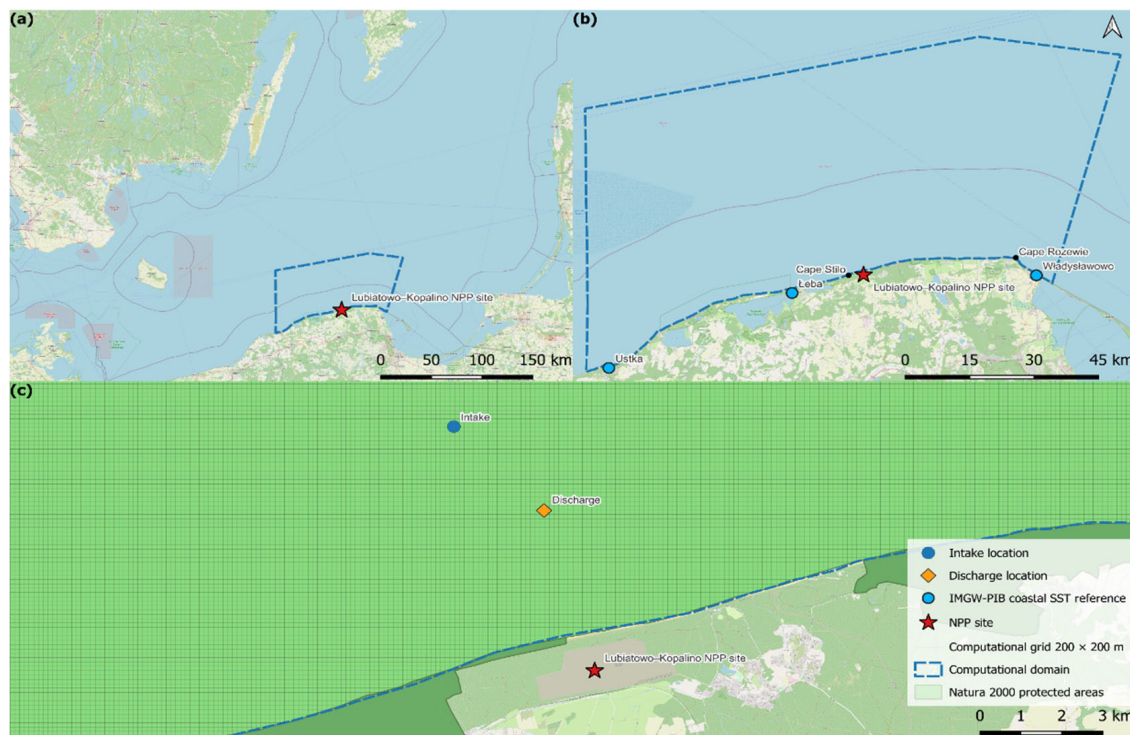


Figure 1. Study area and modelling domain. (a) Regional location of the Lubiatowo–Kopalino nuclear power plant site on the southern Baltic coast. (b) Marine computational domain extending between the Stilo and Rozewie capes, including the IMGW-PIB coastal SST reference locations used to construct the ambient sea surface temperature fields: Ustka, Łeba, and Władysławowo. (c) Detailed view of the model intake and discharge locations, the 200 m × 200 m computational grid, and adjacent Natura 2000 protected areas. Base map: © OpenStreetMap contributors. Natura 2000 boundaries: GDOŚ. Own elaboration.

The model was forced using hydrometeorological and ambient temperature data covering the period from 1 January to 31 August 2023. Winter conditions were represented by the January–April 2023 forcing window, whereas the summer 90th-percentile and storm scenarios were based on the June–August 2023 forcing window. Ambient sea surface temperature (SST) fields were constructed directly from observations recorded at the IMGW-PIB coastal stations of Ustka, Łeba, and Władysławowo using inverse distance weighting (IDW) interpolation. Additional forcing included surface circulation fields from the PM3D hydrodynamic reanalysis (ICM UW), significant wave height from the WAM spectral wave model, and 10 m wind fields from ERA5 (ECMWF). PM3D was used exclusively to provide the background surface-circulation fields and was not used to generate the ambient SST field. These forcing datasets were aggregated to the relevant scenario windows before being applied in the 2D depth-averaged advection–diffusion model. The governing depth-averaged heat-transport equation follows the classical advection–diffusion formulation widely used in surface-water quality and thermal transport modelling [39]:

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = D(x, y) \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + Q(x, y, t) \quad (1)$$

where T is water temperature, (u, v) are depth-averaged velocities combining ocean currents and wind-driven drift, D is the turbulent diffusion coefficient, and Q represents the heat input associated with condenser cooling-water discharge and constitutes the only internal heat source in the model domain. The baseline diffusion coefficient ($D_0 = 10 \text{ m}^2/\text{s}$, raised to $50 \text{ m}^2/\text{s}$ under storm conditions) follows representative values for shallow coastal seas [15].

The discharge flow rate was parametrised as $138.9 \text{ m}^3/\text{s}$ with a discharge temperature elevation of 10°C at 10 m depth, consistent with worst-case EIA assumptions. The 10 m discharge depth corresponds to the nominal submerged release depth of the multi-port diffuser introduced in Section 3.1, whose function is to discharge the effluent below the surface and enhance initial dilution before the plume reaches the surface layer. In the depth-averaged framework, this is represented as a sub-surface point release at that depth, while the detailed near-field jet and diffuser dynamics are addressed separately (Section 4.4). The domain was integrated with an explicit upwind and central finite-difference scheme satisfying the Courant and diffusive stability conditions.

The present modelling framework was developed to support comparative evaluation of cooling strategies during the pre-construction phase of the Lubiatowo–Kopalino nuclear power plant. Because the facility has not yet been commissioned, site-specific measurements of thermal discharge and near-field hydrodynamics are unavailable, precluding direct calibration and validation of the thermal plume model. Consequently, the model is intended as a screening-level decision-support tool for comparative assessment rather than as a predictive operational model. Table 3 contains numerical configuration and principal parameters of the model.

Table 3. Numerical configuration and principal parameters of the 2D thermal-plume model.

Parameter	Model Configuration
Model formulation	2D depth-averaged advection–diffusion model.
Computational domain	Marine sector between the Stilo and Rozewie capes; $16.77389\text{--}18.73175^\circ \text{ E}$ and $54.56569\text{--}55.34278^\circ \text{ N}$.
Domain extent	Approximately 125.9 km along-shore $\times$ 84.6 km offshore; marine area approximately 6857.5 km^2 .
Horizontal grid resolution	$200 \times 200 \text{ m}$.
Initial condition	Scenario-specific ambient sea surface temperature (SST) raster for the first day of each simulation, constructed from IMGW-PIB coastal observations by IDW interpolation and aggregated to the $200 \times 200 \text{ m}$ model grid. Land cells were identified from missing SST values and excluded from the marine calculation.
Boundary conditions	No horizontal heat flux was imposed across the land–sea boundary by treating land-neighbour cells as inactive in the finite-difference stencil and assigning them the temperature of the adjacent active sea cell. At the external raster/domain edges, a zero-gradient boundary condition was applied by repeating the nearest edge-cell values.
Ambient SST forcing	IMGW-PIB observations from Ustka, Łeba, and Władysławowo interpolated by inverse distance weighting (IDW).
Surface-current forcing	PM3D hydrodynamic reanalysis, represented by depth-averaged eastward and northward current components.
Atmospheric forcing	ERA5 10 m wind fields, used to estimate wind-driven surface drift.
Wave forcing	WAM significant wave height, used to parameterise wave-enhanced turbulent diffusion.
Baseline diffusion coefficient	$10 \text{ m}^2/\text{s}$.
Storm diffusion coefficient	$50 \text{ m}^2/\text{s}$.
Total discharge flow	$500,000 \text{ m}^3/\text{h} = 138.9 \text{ m}^3/\text{s}$ for all three units combined.
Discharge temperature elevation	10°C above ambient.
Discharge depth	10 m .

Table 3. Cont.

Parameter	Model Configuration
Numerical scheme	Explicit first-order upwind advection and central finite-difference diffusion.
Time step	Adaptive sub-time-step calculated internally from the Courant–Friedrichs–Lewy advection criterion and the explicit diffusion stability condition. Each 24 h simulation day was divided into the required number of stable sub-steps.
Simulation periods	Winter forcing window: January–April 2023; summer 90th-percentile and heatwave-and-calm scenarios: June–August 2023; storm scenario: 24 h enhanced-forcing simulation based on summer conditions.
Output/statistical processing	Seasonal fields sampled at 14-day intervals and summarised using the 90th-percentile thermal-anomaly envelope.
Computational platform	Custom R implementation using geospatial and NetCDF processing packages on a local Windows workstation.

4.4. Model Uncertainty

The principal outcomes are robust to $\pm 50\%$ variation in the diffusion coefficient and to grid resolution between 100 and 300 m. For the present purpose, three limitations matter for interpretation. The depth-averaged formulation does not resolve vertical plume structure, which is the most consequential simplification for surface-dwelling receptors. A two-dimensional depth-averaged approach was adopted deliberately because the assessment targets the relative spatial extent, seasonal contrast, and persistence of the plume across multiple multi-month scenarios, for which a depth-averaged screening model is computationally efficient and consistent with the resolution of the available forcing fields. Its structural cost is that heat released into the surface layer under summer stratification is mathematically distributed over the full water column, so the modelled depth-averaged anomaly is lower than the true sea-surface temperature anomaly during stratified periods. The surface-layer anomaly, and hence the exposure of surface-dwelling receptors such as cyanobacteria, is therefore systematically underestimated in the summer scenarios, and the reported summer ΔT values should be read as conservative lower bounds on the surface signal rather than as surface temperatures. Quantifying this underestimation and resolving the surface-trapped plume would require a three-dimensional, stratification-resolving model, which would also be needed to capture the interaction of the discharge with wind-driven upwelling fronts (Section 4.7) and is identified as a priority for the next stage of this work. A further consequence of the 200 m horizontal grid is that the model resolves the far-field and seasonal plume structure but not the near-field jet momentum and multi-port diffuser dynamics, which occur on scales of tens of meters. The grid therefore provides only a small number of cells within the 500 to 1000 m near-field zone and cannot by itself certify compliance with the stringent near-field design target. Near-field dilution and the associated $\Delta T \leq 1^\circ\text{C}$ target are accordingly assessed through the empirical dilution performance of the multi-port submerged diffuser rather than resolved directly by the grid model, while the grid results are used for the far-field extent, seasonal contrast, and persistence that govern the ecosystem-scale assessment. The constant horizontal diffusion coefficient simplifies turbulent mixing that varies with time and sea state. The depth-averaged formulation does not resolve vertical plume structure. The model is therefore best treated as a diagnostic tool for relative spatial distributions and seasonal variability rather than as a source of absolute ΔT at a single point.

No site-specific measurements of thermal discharge, plume evolution, or operational thermal conditions are presently available because the nuclear power plant has not yet been

constructed. Consequently, quantitative calibration of the thermal plume model against field observations could not be performed. This limitation primarily affects the prediction of absolute temperature values at individual locations but does not preclude comparative evaluation of plume morphology, seasonal variability, or the relative performance of alternative cooling strategies under a common set of environmental forcing conditions.

The principal sources of modelling uncertainty arise from the hydrodynamic forcing, meteorological variability, simplified representation of turbulent mixing, and the use of design discharge parameters representative of the planned facility rather than operational measurements. Additional uncertainty is associated with the depth-averaged formulation, which cannot explicitly resolve three-dimensional circulation, vertical thermal stratification, or transient coastal processes such as short-lived upwelling events. These uncertainties primarily influence the predicted magnitude and local distribution of temperature anomalies.

Despite these limitations, the principal conclusions of the study are based on relative rather than absolute model behaviour. In particular, the comparative differences between seasonal scenarios, the contrast between acute near-field warming and extensive far-field thermal anomalies, and the relative evaluation of alternative cooling strategies are considered comparatively robust because all simulations were performed using a consistent modelling framework, identical numerical assumptions, and common environmental forcing. Accordingly, the model is intended to support comparative environmental assessment and technology selection during the pre-construction stage of the project, rather than precise prediction of future operational temperatures at individual locations.

4.5. Thermal Plume Results: Seasonal Scenarios

Across four hydrodynamic scenarios, the model reveals a consistent contrast between a spatially confined acute zone and an extensive low-magnitude far-field anomaly (Table 4).

Table 4. Thermal-plume metrics from the 2D advection-diffusion model at the Lubiatoŵo–Kopalino discharge zone under four hydrodynamic scenarios.

Scenario	$\Delta T \geq 2\text{ }^{\circ}\text{C}$ Area (km ²)	$\Delta T \geq 0.1\text{ }^{\circ}\text{C}$ Area (km ²)	Max Reach $\Delta T \geq 2\text{ }^{\circ}\text{C}$ (km)	Plume Morphology and Driver
Winter (90th percentile)	0.12	42.9	0.6	Narrow eastward wedge, driven by a strong coastal current
Summer (90th percentile)	1.18	1886.6	4.0	Multi-directional spreading under stratification and variable winds
Heatwave and calm	0.27	~50	0.9	Compact footprint, residual current exports heat
Storm (24 h, 3× forcing)	0.017	~10	0.2	Radial pattern, turbulent mixing dismantles the plume

In winter, strong, persistent coastal currents advect heat into a narrow eastward wedge, confining the $\Delta T \geq 2\text{ }^{\circ}\text{C}$ zone to under 0.6 km, while the $\Delta T \geq 0.1\text{ }^{\circ}\text{C}$ anomaly reaches about 43 km² (Figures 2 and 3).

The closely spaced isotherms visible in the near-field confirm that strong alongshore advection constrains lateral plume expansion despite continuous heat discharge. This behaviour indicates that winter plume development is controlled primarily by advective transport rather than turbulent diffusion, resulting in rapid downstream export of heat while limiting lateral spreading.

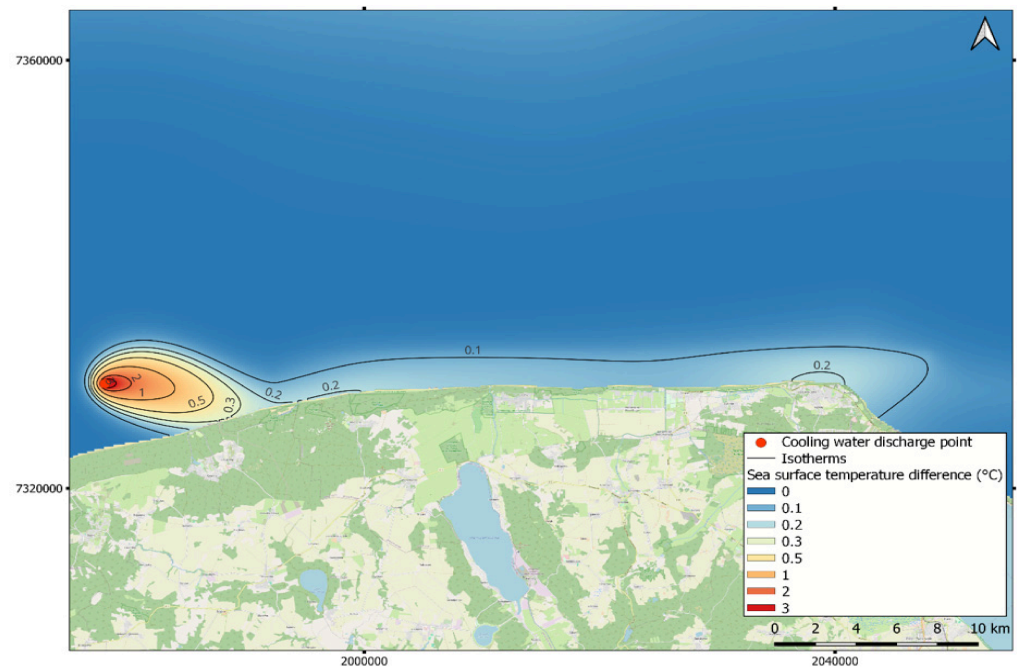


Figure 2. Winter 90th-percentile thermal plume, full domain (January to March 2023). Colours indicate simulated temperature differences relative to the ambient background temperature. Dominant forcing during this snapshot: the total model transport vector, combining the background surface current and wind-driven drift, was directed eastward (90.9°) with a vector-mean speed of 0.092 m/s. The background surface current was directed ESE (121.0°) with a vector-mean speed of 0.023 m/s, while the mean ERA5 10 m wind field was from W (259.6°) with a mean speed of 2.23 m/s. The mean significant wave height over the model domain was 1.20 m.

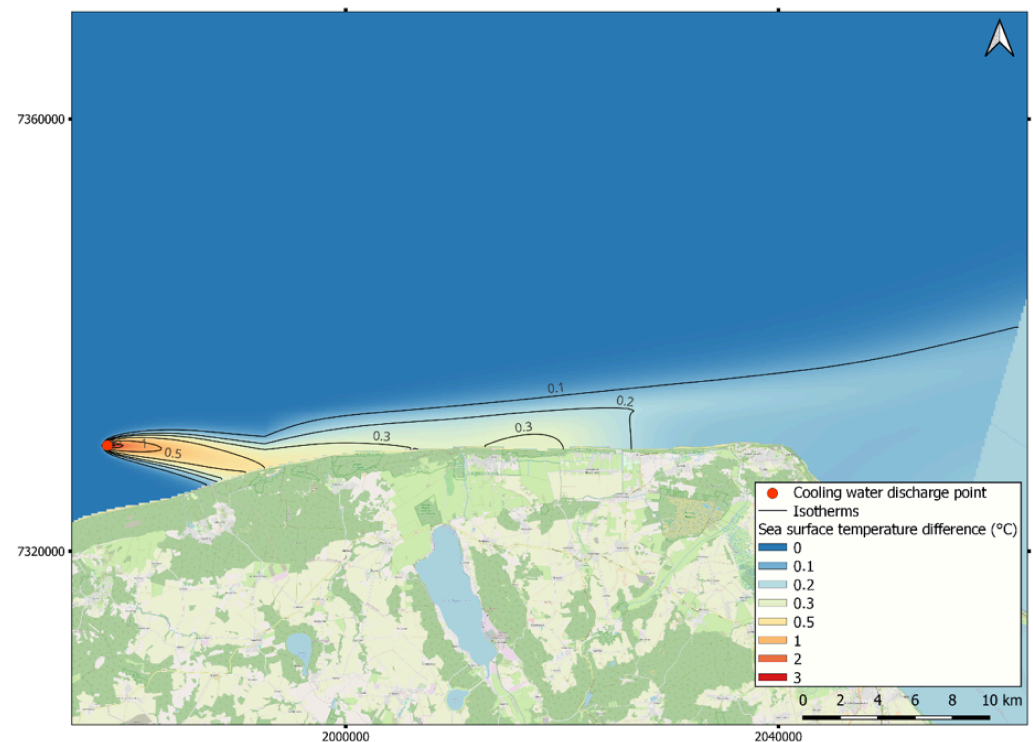


Figure 3. Winter 90th-percentile thermal plume, near-field detail. Elevated values (ΔT of 1 to 2 $^\circ\text{C}$) remain confined within about 500 m of the outfall, with isopleths closely spaced and aligned parallel to the coastline.

In summer, thermal stratification suppresses vertical mixing and confines the discharge to the surface layer, producing a multi-directional spreading pattern. Peak anomalies ($\Delta T \geq 2\text{ }^{\circ}\text{C}$) nonetheless remain localised at about 1.18 km^2 , which indicates that near-field dilution is governed mainly by discharge momentum, whereas low-magnitude anomalies ($\Delta T \geq 0.1\text{ }^{\circ}\text{C}$) extend to roughly 1886.6 km^2 (Figures 4 and 5).



Figure 4. Summer 90th-percentile thermal plume, full domain (June to August 2023). Summer 90th-percentile thermal plume, full domain. Colours indicate simulated temperature differences relative to the ambient background temperature, including the far-field $\Delta T \geq 0.1\text{ }^{\circ}\text{C}$ envelope. Dominant forcing during this snapshot: the total model transport vector, combining the background surface current and wind-driven drift, was directed eastward (80.4°) with a vector-mean speed of 0.049 m/s . The background surface current was directed WSW (244.1°) with a vector-mean speed of 0.011 m/s , while the mean ERA5 10 m wind field was from WSW (257.1°) with a mean speed of 1.75 m/s . The mean significant wave height over the model domain was 0.70 m .

The three distinct plume branches illustrate the sensitivity of the discharge to temporally varying near-surface circulation, which promotes broad spatial dispersion under stratified summer conditions. Unlike winter conditions, summer stratification suppresses vertical dilution without substantially increasing the near-field footprint, allowing weak thermal anomalies to persist over a much larger surface area. This explains why ecological exposure is governed primarily by plume persistence and spatial extent rather than by maximum temperature alone.

The heatwave-and-calm case yields a compact footprint (0.27 km^2) because a residual current continues to export heat. This indicates that current persistence can limit thermal accumulation even under otherwise unfavourable meteorological conditions. Conversely, a 24 h storm with tripled forcing compresses the $\Delta T \geq 2\text{ }^{\circ}\text{C}$ zone to about 0.017 km^2 as turbulent mixing rapidly dismantles the plume (Figure 6), demonstrating the dominant role of turbulent mixing in accelerating heat dissipation under energetic conditions.

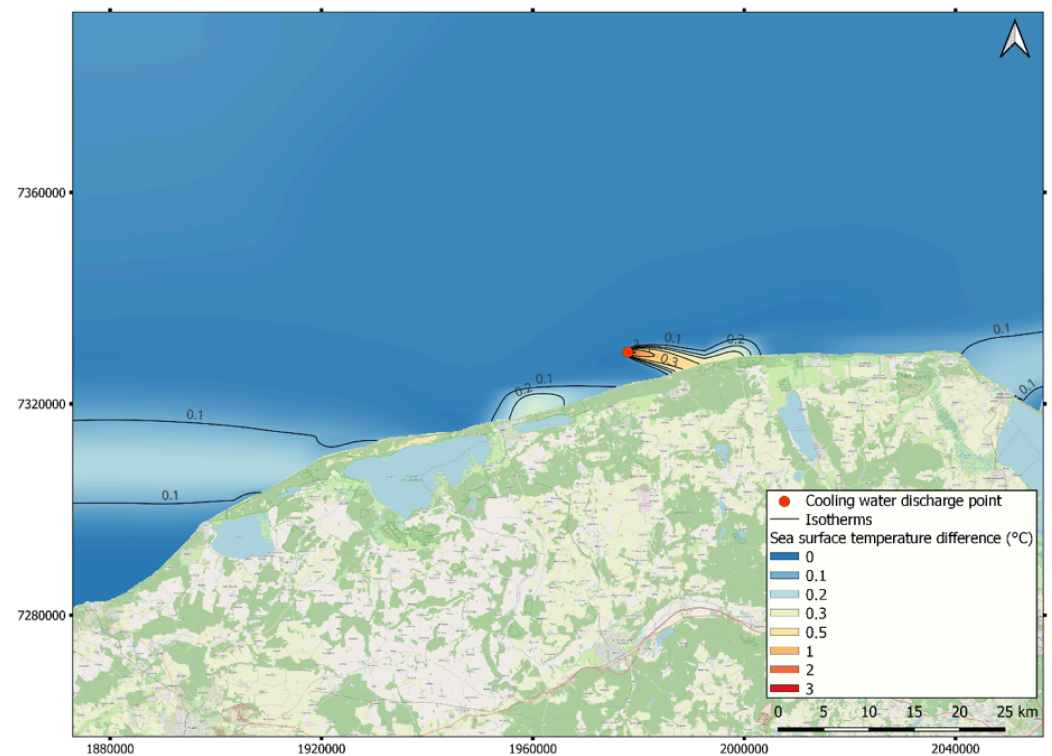


Figure 5. Summer 90th-percentile thermal plume, near-field detail. Three prominent branches extend eastward, westward, and northward from the discharge point.

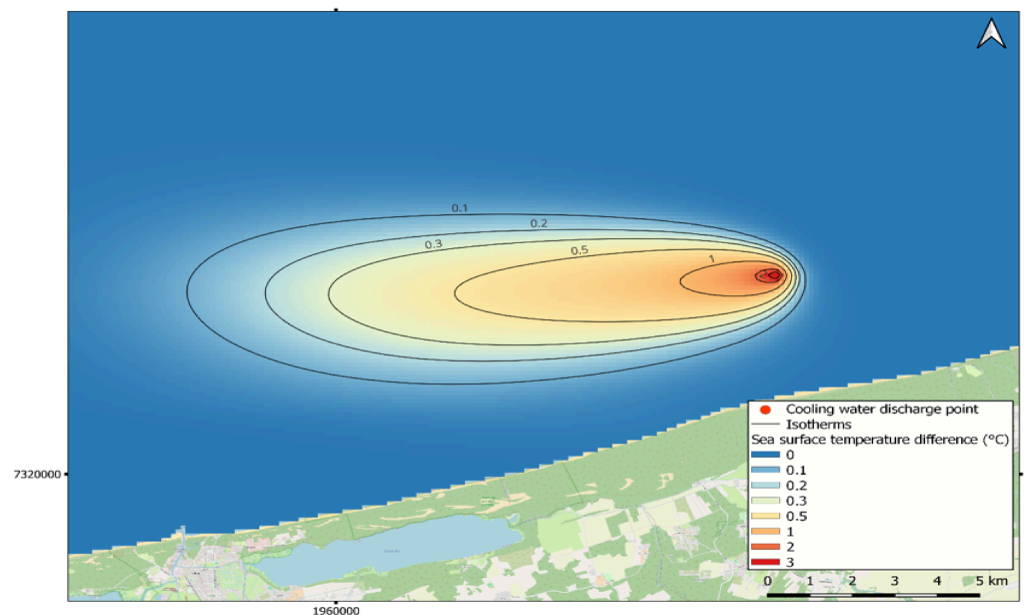


Figure 6. Storm-scenario thermal plume (24 h simulation with currents, wind, and wave forcing tripled). Intense turbulent mixing produces a radial, near-isotropic plume, with the $\Delta T \geq 2\text{ }^{\circ}\text{C}$ zone compressed to about 0.017 km^2 . Colours indicate simulated temperature differences relative to the ambient background temperature under enhanced hydrodynamic forcing. Dominant forcing during this snapshot: the total model transport vector, combining the background surface current and wind-driven drift, was directed eastward (80.4°) with a vector-mean speed of 0.146 m/s . The background surface current was directed WSW (244.1°) with a vector-mean speed of 0.033 m/s , while the mean ERA5 10 m wind field was from WSW (257.1°) with a mean speed of 5.25 m/s . The mean significant wave height over the model domain was 1.40 m . The storm scenario applied wave, wind, and current multipliers of 2, 3, and 3, respectively.

Within the assumptions of the present modelling framework, the simulations consistently indicate that the acute thermal zone remains spatially limited under all analysed scenarios, whereas the diffuse far-field anomaly becomes extensive during summer conditions. These results provide the basis for comparative evaluation of cooling technologies rather than prediction of exact future thermal conditions.

4.6. Ecological Implications: Acute Versus Diffuse Thermal Stress

The $\Delta T \geq 0.1$ °C threshold lies below the acute stress response of individual organisms, which is typically associated with temperature increases of ≥ 1 –2 °C for Baltic ectotherms. It is therefore used here not as an indicator of direct physiological stress or acute mortality, but as a conservative marker of chronic, ecosystem-scale forcing. The ecological relevance of this low-magnitude anomaly rests on its persistence, spatial extent, and overlap with an already brackish, eutrophic, low-exchange and warming basin.

First, temperature acts as a phenological cue for spawning, migration, feeding, and seasonal biological activity; therefore, persistent deviations of 0.1–0.5 °C may shift critical timing in sensitive species and life stages. Second, in nutrient-enriched waters, temperature influences phytoplankton and cyanobacterial bloom dynamics, so sustained sub-degree warming of already-warm surface layers may lower the effective bloom threshold when combined with eutrophication [34]. Third, the far-field $\Delta T \geq 0.1$ °C envelope overlaps with fished coastal zones and designated conservation areas, meaning that even weak thermal forcing can affect ecologically important regions over broad spatial scales.

Recent thermal-discharge studies support this interpretation. Power-plant thermal effluents have been shown to affect marine benthos by modifying benthic community structure, reducing biodiversity, and altering oxygen-related habitat conditions [20]. Thermal-discharge-induced seawater warming has also been shown to alter bacterioplankton richness, community composition, and inter-species interactions, indicating that microbial food-web components can respond to thermal perturbations even where the temperature increase is not acutely lethal [40]. In the southern Baltic, where low salinity, eutrophication, seasonal stratification, and recurrent cyanobacterial blooms already constrain ecosystem resilience, the far-field anomaly should therefore be interpreted as a chronic additive pressure rather than an acute mortality zone.

The modelling thus reveals a regulatory and ecological dichotomy. Acute thermal stress, represented by $\Delta T \geq 2$ –3 °C, remains spatially confined within approximately 0.6–4 km of the outfall and can be addressed through a designated mixing-zone approach. By contrast, the diffuse anomaly of $\Delta T = 0.1$ –0.5 °C extends over tens of square kilometres and reaches about 1886.6 km² in the summer scenario. Although this low-magnitude anomaly is unlikely to cause direct acute stress, it constitutes an additive pressure superimposed on existing eutrophication and ongoing warming, which standard mixing-zone compliance assessment does not fully capture [16]. The ecological implications discussed above should therefore be interpreted as evidence-based inferences rather than direct biological observations. The thermal-plume model quantifies the physical characteristics of thermal exposure, including its magnitude, spatial extent, and seasonal persistence, whereas the ecological responses are inferred from established relationships reported in the scientific literature for eutrophic, climate-sensitive coastal ecosystems. Accordingly, the present study does not predict specific biological responses but identifies environmental conditions under which an increased likelihood of ecological impacts may occur.

4.7. Integrated Ecological Risk Characterization

These impacts must be read against the Baltic's warming trajectory of about 0.06 to 0.08 °C per decade, with a further increase of 1.5 to 2.5 °C projected by 2070 [34]. Back-

ground warming interacts with the discharge in several ways. Rising baseline temperatures reduce the plume-to-ambient gradient and slow dilution. More frequent summer heatwaves coincide with low winds and stable stratification, producing the largest near-field anomalies. Warmer water also promotes cyanobacterial proliferation independently of the discharge, so that the discharge-derived anomaly synergistically lowers the bloom-initiation threshold [16,33,34]. The highest-risk situations therefore arise when elevated background temperature, weak mixing, high productivity, low oxygen, and the local plume coincide. Because the plume trajectory is hydrodynamically asymmetric, the relevant question for the adjacent Natura 2000 areas is not distance from the outfall alone but whether, under dominant or extreme conditions, the plume overlaps habitats of conservation concern [8,17]. Long-term monitoring should test these synergies directly by comparing phytoplankton composition, cyanobacterial cell counts, and chlorophyll-a concentration in the $\Delta T \geq 0.1$ °C zone against unaffected control stations.

The combined influence of these physical and ecological processes provides the basis for an integrated ecological risk characterization of thermal discharge in the southern Baltic Sea. A further high-stress situation arises from the interaction of the discharge with coastal upwelling. The southern Baltic coast in the vicinity of the Stilo and Rozewie capes is prone to wind-driven summer upwelling, in which easterly winds force surface water offshore and draw cold deep water toward the coast, lowering local sea-surface temperature by several degrees within days [15]. Because the condenser discharge raises temperature by a roughly fixed increment above the intake temperature, an upwelling event that abruptly depresses the ambient baseline widens the effective temperature contrast experienced by organisms in and around the plume, so the same discharge produces a larger thermal shock against a suddenly colder background. The rapid onset of such events also creates a steep transient gradient in space and time that differs physiologically from gradual seasonal warming. The present depth-averaged formulation cannot resolve the vertical shear and frontal structure of an upwelling event, so this interaction is not captured in the scenario results and is flagged here as an additional reason to favour a precautionary cooling strategy and to design monitoring able to detect short-lived, upwelling-coincident thermal extremes.

Taken together, the results presented in Sections 4.1–4.6 indicate that ecological risk cannot be evaluated solely on the basis of maximum temperature exceedance or compliance with regulatory mixing-zone criteria. Instead, risk arises from the interaction between the physical characteristics of the thermal plume (its spatial extent, persistence, and seasonal variability), the ecological sensitivity of the receiving environment, and the cumulative environmental pressures already affecting the southern Baltic Sea. Consequently, the present assessment adopts an integrated interpretation in which thermal-plume characteristics are evaluated together with ecosystem vulnerability rather than as isolated engineering performance indicators.

Under this integrated perspective, the acute thermal hazard remains spatially restricted and is largely confined to the immediate vicinity of the discharge outlet, where engineering measures such as a submerged multi-port diffuser effectively promote initial dilution. In contrast, the dominant ecological concern identified by the modelling is the extensive far-field anomaly developing during summer conditions. Although the predicted temperature increase is relatively small (typically 0.1–0.5 °C), its persistence over a broad coastal area coincides with periods of maximum biological activity, seasonal stratification, and enhanced susceptibility to eutrophication. The ecological significance therefore results from cumulative exposure rather than from isolated temperature peaks.

The present modelling therefore supports a qualitative ecological risk characterization in which regulatory compliance represents a necessary but not sufficient condition for

environmental sustainability. While the predicted thermal plume satisfies the applicable regulatory framework under the analysed scenarios, long-term ecosystem protection additionally requires consideration of chronic thermal exposure, climate-driven warming, and the cumulative interaction between multiple environmental stressors. This distinction provides the scientific basis for the cooling-technology recommendations developed in this study, demonstrating that environmentally sustainable cooling-system design requires consideration of both engineering performance and ecosystem vulnerability.

5. Discussion

5.1. Integrated Assessment: Regulatory, Ecological, and Climate Perspectives

The modelling results indicate that seasonal hydrodynamic conditions exert a stronger influence on plume behaviour than the discharge itself. During winter, strong alongshore currents rapidly advect heat away from the outfall, restricting the near-field thermal footprint despite the relatively large discharge-to-ambient temperature difference. In contrast, summer thermal stratification suppresses vertical mixing while variable surface circulation promotes extensive horizontal dispersion of weak thermal anomalies. Consequently, the ecological significance of the plume is determined primarily by its persistence and spatial extent rather than by peak temperature alone. This distinction is particularly important in shallow, semi-enclosed coastal seas such as the Baltic, where weak hydrodynamic flushing allows low-magnitude thermal anomalies to affect large areas over prolonged periods.

The once-through system with a multi-port diffuser is conditionally compliant with current requirements under present hydrodynamic conditions: the acute zone remains within a legally definable mixing zone and satisfies the permit-based national framework and HELCOM's precautionary expectations (Section 2). The compliance margin is not, however, demonstrably robust to future climate conditions or to the modelling uncertainties set out in Section 4.4. As shown in Section 4, the far-field low-magnitude anomaly ($\Delta T = 0.1$ to 0.5 °C, about 1886.6 km² in the summer 90th-percentile case) is an additive stressor on an ecosystem already eutrophic and warming, and standard mixing-zone compliance does not capture it. This gap between legal compliance and ecological sustainability is not specific to Lubiato–Kopalino. It is a structural feature of mixing-zone approaches applied to shallow, semi-enclosed seas, where low tidal energy and restricted flushing allow weak anomalies to persist over large areas [16].

Among the alternatives, closed-loop cooling removes the far-field risk and provides full regulatory assurance, at the cost of higher capital expenditure and a small efficiency penalty. Dry-air cooling eliminates marine loading entirely but incurs summer efficiency penalties that climate projections suggest will grow. Hybrid cooling substantially reduces marine discharge while retaining operational flexibility (Section 3). Over a 60-year horizon, and accounting for rising climate-related compliance risk and the likely tightening of environmental standards, the lifecycle cost difference between once-through and hybrid configurations may be considerably smaller than the upfront capital advantage of once-through suggests. The decision framework should therefore be explicitly forward-looking and risk-averse rather than anchored only in present-state compliance [25].

5.2. Study Limitations

Several limitations qualify these findings. The assessment rests on numerical modelling and published literature rather than on in situ measurements, because the discharge facility does not yet exist. The model has therefore not been validated against site temperature observations, and a pre-operational temperature-tracer survey should accompany the first years of operation (Section 4.4). The hydrodynamic forcing derives from reanalysis products that carry their own error, and the cost and efficiency figures in Section 3 are

indicative engineering estimates rather than site-specific costings. The depth-averaged formulation, in particular, distributes surface-trapped heat over the full water column and therefore underestimates the sea-surface temperature anomaly under summer stratification, so the summer surface signal is best regarded as a conservative lower bound pending a three-dimensional analysis (Section 4.4). Finally, the analysis treats thermal forcing largely in isolation from other discharge constituents and from interactions with neighbouring pressures, which a coupled hydrodynamic and ecological assessment would resolve.

The present study is subject to several limitations that should be considered when interpreting the results. First, the thermal-plume simulations were performed using a depth-averaged two-dimensional advection-diffusion model intended for comparative assessment during the pre-construction stage of the project. Consequently, the model does not explicitly resolve three-dimensional circulation, vertical density stratification, or transient hydrodynamic processes occurring at finer spatial and temporal scales. In addition, the absence of operational thermal-discharge data precludes direct calibration and validation of the simulated plume against field observations.

Second, the ecological assessment is based on the physical characteristics of thermal exposure rather than direct simulation of biological responses. The model does not include ecological process modules describing phytoplankton dynamics, dissolved oxygen, nutrient cycling, or species-specific physiological responses. Accordingly, the ecological implications presented in this study should be interpreted as evidence-based ecological inferences supported by the published literature rather than as direct biological predictions.

Future research should focus on validating the modelling framework using operational monitoring data following plant commissioning, extending the simulations to fully three-dimensional hydrodynamic models, and coupling thermal-plume simulations with ecosystem-process models to improve quantitative assessment of long-term ecological responses. Such developments would strengthen the predictive capability of the framework while preserving its value as a decision-support tool for environmentally sustainable cooling-system design.

5.3. Transferability to Other Shallow, Semi-Enclosed Marine Systems

The analytical framework developed in this study is transferable primarily at the level of screening logic rather than as a direct predictor of plume geometry. Its relevance is highest in aquatic systems where thermal discharge is superimposed on restricted water exchange, shallow or stratified morphology, eutrophication pressure, existing thermal stress, and climate-driven warming. To clarify this point, Table 5 compares the Baltic Sea with other semi-enclosed or weakly flushed basins where similar assessment questions may arise, while also highlighting the key differences that would require local recalibration of the model and regulatory thresholds.

Table 5. Comparative relevance of the proposed thermal-discharge assessment framework for selected semi-enclosed or weakly flushed aquatic systems.

Basin	Key Similarity to the Baltic Sea	Key Differences	Relevance for Framework Transferability
Baltic Sea	Brackish, semi-enclosed basin with slow water exchange of approximately 30 years, strong salinity gradients, stratification, eutrophication pressure, oxygen deficiency, and recurrent cyanobacterial blooms [16].	Reference case with low-salinity brackish biota and EU regulatory context.	Direct reference case for distinguishing near-field compliance from diffuse far-field ecosystem-scale thermal forcing.

Table 5. *Cont.*

Basin	Key Similarity to the Baltic Sea	Key Differences	Relevance for Framework Transferability
Black Sea	Semi-enclosed basin with restricted exchange, strong stratification, eutrophication history, and oxygen-depleted deep waters [41,42].	Much deeper than the Baltic Sea; thermal-plume relevance is mainly coastal and shelf-specific.	Transferable for coastal and shelf thermal-discharge screening, but requires local stratification, shelf-depth, circulation, and oxygen data.
Caspian Sea	Large enclosed brackish basin with no oceanic outflow, long effective pollutant retention, and regional eutrophication pressures [43,44].	Endorheic lake-sea system with strong water-level, salinity, and ecological gradients.	Transferable as a chronic-pressure and weak-exchange screening framework, but not as a direct marine-regulatory analogue.
Persian Gulf	Shallow, semi-enclosed, hypersaline and thermally stressed basin with restricted exchange and multi-year residence times in some areas [45,46].	Much warmer and more saline than the Baltic Sea, with different biological tolerances and strong desalination/coastal-effluent pressure.	Transferable for cumulative heat-load and restricted-exchange assessment, but thresholds must be recalibrated for warm, hypersaline ecosystems.
North American Great Lakes	Large, weakly flushed freshwater basins with long and variable retention times, stratification, eutrophication issues in some basins, and important fisheries and ecosystem services [47,48].	Freshwater rather than brackish or marine; lake-specific circulation, ice cover, and regulatory frameworks differ.	Transferable as a lake-based screening approach, especially where long retention time and eutrophication increase ecological sensitivity.
Yellow Sea	Shallow, semi-enclosed shelf sea with high productivity, riverine nutrient inputs, seasonal stratification, harmful algal bloom pressure, and an estimated hydraulic residence time of approximately 5–6 years [49,50].	Stronger tidal mixing, marine salinity, and monsoon-driven circulation compared with the Baltic Sea.	Transferable for shallow-shelf thermal-plume screening, but requires recalibration for tidal mixing, marine salinity, monsoon forcing, and local ecosystem sensitivity.

This comparison shows that the framework is most applicable where thermal discharge interacts with slow exchange, shallow or stratified water columns, eutrophication, and ecologically sensitive coastal zones. However, the numerical plume dimensions obtained for the southern Baltic should not be transferred directly to other basins. Local hydrodynamic forcing, salinity, residence time, water-column stratification, ecosystem sensitivity, and regulatory thresholds must be recalibrated for each site.

6. Conclusions

The cooling technology choice for Lubiato–Kopalino exemplifies a broader challenge facing coastal energy infrastructure in an era of climate change and strengthened environmental governance: reconciling reliable, low-carbon electricity generation with economic efficiency and the long-term ecological integrity of a sensitive receiving environment. By integrating a multi-instrument regulatory analysis, a structured technology comparison, and a site-specific thermal plume assessment, this study supports four main conclusions:

1. Thermal-discharge assessment should not be reduced to a single temperature threshold. The Water Framework Directive, Polish water regulations, the HELCOM framework, and IAEA guidance differ in legal force and detail but converge on a broader logic in which plume extent, duration, seasonal timing, and overlap with sensitive habitats matter alongside maximum ΔT .

2. Once-through cooling with a multi-port diffuser is conditionally compliant with current requirements under present hydrodynamic conditions, but it generates a spatially extensive low-magnitude anomaly ($\Delta T = 0.1$ to 0.5 °C over about 189 km^2 in the summer 90th-percentile case) that constitutes an additive stressor on an already eutrophic, warming ecosystem and that standard mixing-zone compliance does not capture. This dilution ratio is stated as a near-field engineering design target consistent with the performance achievable by multi-port submerged diffusers and with the stringent $\Delta T \leq 1$ °C objective adopted in Section 2, rather than as a quantity resolved by the depth-averaged grid model, which does not capture near-field jet and diffuser dynamics (Section 4.4). Verification of the achieved dilution belongs to detailed near-field diffuser design and pre-operational testing. This margin may erode as baseline temperatures rise and summer stratification intensifies, so robustness testing under projected Baltic warming would strengthen confidence in the assessment.
3. The four technologies represent distinct water, energy, and environment trade-offs, and no option is universally optimal. Closed-loop and hybrid systems eliminate or substantially mitigate the far-field thermal impact at acceptable economic and efficiency cost, whereas dry-air cooling removes marine loading entirely but at the highest efficiency penalty, which worsens during summer extremes.
4. A staged hybrid approach, with the first unit operating with validated once-through cooling and subsequent units fitted with hybrid systems, best balances empirical learning, risk management, and environmental stewardship over the facility's 60-year operational lifetime.

The analytical framework is transferable to other shallow, nutrient-enriched, microtidal basins where comparable thermoelectric facilities are planned or operational. Three directions would extend this work: a full life-cycle assessment of cooling technologies under Polish conditions, covering construction, operational energy penalty, water use, emissions, chemical use, and end-of-life; coupled hydrodynamic and ecological modelling linking plume behaviour to oxygen dynamics, eutrophication indicators, biological receptors, and Natura 2000 conservation objectives; and the incorporation of climate-change scenarios, extreme hydrometeorological conditions, and adaptive operating strategies, particularly for hybrid cooling. Together these would support a more robust and transparent selection of cooling technologies for nuclear power plants in environmentally sensitive coastal regions.

Should once-through cooling be selected, the outfall should be equipped with multi-port submerged diffusers achieving a near-field dilution ratio of at least 1:10 within 200 m, so that the stringent near-field design target is met across the full range of seasonal conditions identified by the modelling. Licensing should require seasonally differentiated, spatially distributed monitoring of water temperature, dissolved oxygen, and chlorophyll-a fluorescence along the three principal plume directions identified by the model (eastward, westward, and northward), with pre-defined trigger levels linked to operational responses such as reduced discharge temperature or flow adjustment during sensitive biological periods [16,25].

The direct modelling basis for this recommendation is the summer 90th-percentile result. Although the acute $\Delta T \geq 2$ °C zone remains spatially limited, the once-through scenario produces a diffuse $\Delta T = 0.1$ – 0.5 °C anomaly extending over approximately 1886.6 km^2 . Replicating the same once-through configuration for all three units would therefore retain the principal ecosystem-scale pressure identified by the model. By contrast, fitting Units 2 and 3 with hybrid systems would directly limit the cumulative far-field thermal load, while operation of the first unit would provide site-specific monitoring evidence under actual plant conditions.

As the preferable long-term solution, we therefore recommend a staged hybrid configuration. The first reactor unit would operate with once-through cooling during the early operational phase, while monitoring experience accumulates and climate scenarios become clearer, and subsequent units would be fitted with hybrid dry and wet systems from the outset. This sequence allows the operator to gather empirical data on plume behaviour under real conditions, which can inform decisions on whether and how to retrofit the first unit, recognising that such a retrofit would be a major undertaking rather than a routine upgrade, while signalling a clear trajectory toward reduced marine loading consistent with evolving EU standards. Converting an operating once-through unit to hybrid or closed-loop cooling is a capital-intensive intervention rather than an incremental modification: it requires additional intake and outfall structures together with extensive air-cooled condenser or hybrid-tower fields, with consequences for site spatial planning, the layout of safety-related ultimate heat sink (UHS) systems, and overall capital expenditure. For this reason, hybrid cooling should be planned from the outset for the later units, and the spatial and infrastructural provisions for any future retrofit of the first unit should be reserved during the initial site layout rather than deferred as an easy incremental upgrade. The proposed staged approach does not depend on a specific commissioning interval between reactor units. Rather, it assumes the sequential commissioning typical of multi-unit nuclear power projects, allowing operational monitoring data from the first unit to inform the implementation of cooling systems for subsequent units. The exact commissioning schedule remains subject to project implementation and regulatory approval and is therefore beyond the scope of the present study. The configuration is well matched to the southern Baltic's seasonal cycle: dry-mode operation avoids marine discharge during cool, well-mixed periods of high assimilative capacity, while wet-assisted operation preserves efficiency during warm, stratified summers, when the ecosystem is most vulnerable and atmospheric heat rejection alone would be most penalising.

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Abbreviations

NPP	Nuclear power plant
WFD	Water Framework Directive
HELCOM	Baltic Marine Environment Protection Commission
IAEA	International Atomic Energy Agency
EIA	Environmental Impact Assessment
SAC	Special Area of Conservation
SPA	Special Protection Area
SST	Sea Surface Temperature

Nomenclature

Symbols

T	Water temperature (°C)
ΔT	Temperature anomaly relative to ambient conditions (°C)
u, v	Depth-averaged horizontal velocity components (m s^{-1})
D	Turbulent diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)
Q	Heat-source term representing thermal input from the cooling-water discharge

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