



## Original Research Articles

## Analysis of the success and failure aspects of cross-border renewable energy powered water desalination plants in conflict zones

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## ABSTRACT

Cross-border renewable energy powered desalination offers a potential response to water scarcity in conflict-affected regions, but its implementation is constrained by interconnected technical, political, institutional, environmental, financial, and social challenges. This study identifies and prioritizes the critical success factors affecting such projects using the Analytic Hierarchy Process. A multidimensional framework comprising seven main dimensions and 58 sub-criteria was evaluated through structured expert judgments. The results show a balanced distribution among the seven main dimensions, with weights ranging from 0.136 for social and community aspects to 0.146 for environmental and ecological aspects, indicating that no single dimension independently determines project success. At the sub-criterion level, the five highest global weights were obtained for the reliability and efficiency of desalination technology (0.0221), the use of renewable energy to reduce carbon emissions (0.0210), technical compatibility between participating countries' infrastructure (0.0207), perceived fairness in benefit allocation (0.0203), and clarity of legal frameworks (0.0203). Under a +20% perturbation of each main-criterion weight, 5–7 of the original top ten sub-criteria remained in the top ten, demonstrating reasonable ranking stability. The findings indicate that successful cross-border desalination requires an integrated socio-technical approach combining operational reliability, environmental sustainability, compatible infrastructure, legal clarity, and equitable cooperation.

## 1. Introduction

Water scarcity is increasingly emerging as a major challenge in politically unstable and resource-constrained regions worldwide. In many arid and semi-arid areas, growing populations, climate change, and limited freshwater resources are intensifying pressure on shared water supplies. Competition over transboundary water resources has often been associated with increased interstate tensions and disputes (Walschot and Katz, 2024; Gleditsch et al., 2006). However, the relationship between water scarcity and conflict is not always straightforward. Brochmann and Gleditsch (2012) argue that outcomes in shared basins depend not only on water availability itself, but also on governance structures, institutional arrangements, and the distribution of power among stakeholders. Recent evidence further indicates a growing trend of water-related conflicts, particularly in environmentally stressed regions (Kåresdotter et al., 2023), highlighting the urgent need for sustainable and cooperative water management strategies.

Despite these challenges, shared water resources can also promote cooperation when effective governance mechanisms are established. Gleditsch et al. (2006) emphasize that cooperation becomes possible when institutions exist to manage shared resources effectively, while Walschot and Katz (2024) highlight the importance of joint monitoring systems and data-sharing frameworks in facilitating collaboration. Within this context, cross-border desalination has emerged as a promising solution capable of reducing dependence on finite shared water resources such as rivers and aquifers. By introducing additional freshwater into the system, desalination can mitigate zero-sum competition and contribute to regional water security (Drieschova et al., 2008).

The integration of renewable energy into desalination systems further strengthens the potential for regional cooperation within the water-energy nexus. Renewable energy-powered desalination systems reduce dependence on fossil fuels and enhance environmental sustainability. According to Chenoweth and Al-Masri (2021), renewable energy integration creates additional opportunities for international

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cooperation and sustainable development. Similarly, Fischhendler and Tenenboim-Weinblatt (2019) argue that cooperation on environmental challenges can strengthen trust and interdependence between neighboring states. Katz (2021) further notes that technical coordination on water issues may continue even in the absence of formal political agreements, maintaining a minimum level of functional interaction. Moreover, water negotiations are often linked to broader political and economic issues such as trade and security, thereby expanding opportunities for cooperation (Katz and Fischhendler, 2011).

Empirical evidence indicates that the relationship between desalination and transboundary cooperation is conditional rather than automatic. In a comparative analysis of seven transboundary settings, Walschot and Katz (2022) found that the introduction of large-scale desalination was associated with increased cooperation and reduced conflict in the Israel-Jordan, United States-Mexico, and Saudi Arabia-Jordan cases. In these settings, additional desalinated supply increased flexibility in fulfilling water-sharing commitments and reduced pressure on contested conventional resources. However, the same study found that desalination facilitated unilateral action or reduced incentives for cooperation in cases including Israel-Palestine and Singapore-Malaysia. More recent analysis of Cyprus and the Arab-Israeli conflict similarly concluded that desalination alters hydro-political relations, but that the direction of change largely reflects the existing geopolitical and institutional context rather than the technology itself (Walschot and Katz, 2024).

Desalination may reduce tensions through several connected mechanisms. First, producing an additional water source can ease zero-sum bargaining over rivers and aquifers and provide a buffer against drought and supply variability. Second, water-energy exchanges can create reciprocal benefits when one state supplies renewable electricity while another produces or transfers desalinated water. Third, jointly governed infrastructure can institutionalize repeated interaction through technical committees, shared monitoring, data exchange, operating protocols, and dispute-resolution procedures. The proposed Red Sea-Dead Sea initiative involving Israel, Jordan, and Palestine illustrates this logic by linking desalination and water exchange to broader regional cooperation, although its difficulties also demonstrate the vulnerability of such projects to political disruption (Walschot, 2018). Therefore, desalination should be understood as a cooperation-enabling platform rather than a technological guarantee of peace. Its positive effects depend on equitable benefit allocation, protection against asymmetric dependency, transparent governance, environmental safeguards, and credible long-term agreements.

Nevertheless, the implementation of cross-border renewable energy-powered desalination projects remains highly complex. Project success depends not only on technical performance but also on political, financial, institutional, environmental, and social factors (Bernauer & Böhmelt, 2020). Technical challenges include renewable energy variability, infrastructure compatibility, operational reliability, and the need for advanced energy storage and monitoring systems (Curto et al., 2021; Cipollina et al., 2015). In addition, desalination systems may generate environmental concerns related to energy consumption and brine disposal if not properly managed (Walschot and Katz, 2022). Economic and governance-related challenges such as high investment costs, financing uncertainties, institutional instability, and lack of trust can further undermine long-term sustainability (Ghaffour et al., 2013; Madani, 2010).

Existing research can broadly be divided into two streams. The first applies multi-criteria decision-making methods to desalination technology selection, plant configuration, site suitability, renewable-energy integration, and techno-economic or environmental performance. Although these studies provide valuable engineering decision support, their criteria generally remain concentrated on cost, energy use, technical efficiency, and environmental impacts, with limited representation of power asymmetry, institutional legitimacy, social acceptance, legal enforceability, and peacebuilding. The second stream examines

transboundary water governance and hydropolitics, emphasizing treaties, power relations, trust, conflict, and cooperation. However, these studies are predominantly qualitative, conceptual, or case-specific and do not provide a structured quantitative prioritization of the conditions affecting cross-border desalination projects. Thus, an important methodological gap remains between engineering-oriented desalination assessment and conflict-sensitive transboundary-governance analysis.

This study bridges these two streams through a conflict-sensitive AHP framework comprising seven main dimensions and 58 sub-criteria. The framework does not propose a new variant of the AHP algorithm; rather, its methodological contribution lies in operationalizing technical, financial, political, governance, social, environmental, and peacebuilding considerations within a common hierarchical structure. It produces local weights within each dimension and global weights that permit comparison across dimensions, thereby identifying which conditions should receive priority during project planning. A sensitivity analysis is additionally used to examine whether the resulting priorities remain stable under changes in the main-criterion weights. The framework therefore extends conventional desalination MCDM applications from selecting technical alternatives toward evaluating the broader institutional and cooperation conditions required for shared infrastructure in conflict-affected settings.

Accordingly, the proposed framework integrates seven complementary dimensions. The technical and scientific dimension assesses technological reliability, renewable-energy integration, infrastructure compatibility, monitoring, and engineering capacity, which determine whether the system can operate safely and continuously. The financial and economic dimension considers investment availability, cost allocation, tariff affordability, operational expenditure, and the distribution of economic benefits required for long-term viability. The political and geopolitical dimension captures interstate stability, power asymmetry, diplomatic relations, strategic alignment, and willingness to share control. The governance, institutional, and legal dimension evaluates the formal arrangements through which responsibilities, data exchange, compliance, dispute resolution, and transboundary allocation are defined and enforced. The social and community dimension addresses public acceptance, stakeholder participation, social equity, institutional trust, and local socioeconomic effects, which shape the project's domestic legitimacy. The environmental and ecological dimension considers renewable-energy benefits, brine disposal, marine impacts, climate resilience, and compliance with environmental standards. Finally, the peacebuilding and cooperation dimension assesses whether the project fosters cross-border trust, hydrodiplomacy, fair benefit allocation, non-coercive interdependence, and continued collaboration during political tensions. This final dimension differs from governance, which concerns formal rules and institutions, and from social criteria, which concern community-level legitimacy; peacebuilding focuses specifically on changes in relationships, trust, and cooperative behavior between the participating parties. Specifically, the study aims to: (1) identify and organize the relevant success and failure factors within a seven-dimensional hierarchy; (2) calculate and rank their local and global priority weights using aggregated expert assessments; (3) verify the arithmetic consistency of the derived comparison matrices; (4) evaluate the robustness of the resulting rankings through sensitivity analysis; and (5) translate the prioritized factors into practical implications for policymakers, project developers, and transboundary institutions.

## 2. Success and failure aspects of cross-border renewable-energy-powered water desalination projects

This section examines the success and failure conditions of cross-border renewable energy-powered desalination projects across seven interrelated dimensions: technical, financial, political, governance, social, environmental, and peacebuilding aspects.

## 2.1. Technical and scientific aspects

The performance of cross-border desalination systems depends on several operational and engineering factors. According to [Curto et al. \(2021\)](#), system reliability is influenced not only by plant design but also by operator expertise, maintenance quality, and the availability of real-time monitoring systems for parameters such as salinity, membrane performance, flow rates, and energy supply. The integration of renewable energy technologies such as solar and wind can reduce operational costs and environmental impacts. However, renewable energy variability introduces additional operational challenges that require hybrid configurations and energy storage systems to maintain stable operation ([Cipollina et al., 2015](#)). Moreover, differences in infrastructure standards and operating conditions between countries may create technical bottlenecks and coordination difficulties ([Ghaffour et al., 2013](#)). In cross-border contexts, technical failures may also carry political implications, particularly in unstable regions.

## 2.2. Financial and economic aspects

Financial and economic factors are central to project viability and sustainability. Desalination remains a capital-intensive and energy-demanding process requiring substantial investments and long-term operational commitments ([Ghaffour et al., 2013](#)). [Dinar et al. \(2015\)](#) emphasize that disputes may arise when financial responsibilities and cost-sharing mechanisms are perceived as unequal or unclear. Projects that disproportionately benefit one party often face resistance, while transparent and equitable financial arrangements can strengthen trust and cooperation. In addition, fluctuations in operational costs, unstable funding mechanisms, and energy price uncertainty represent significant risks to project continuity ([Cipollina et al., 2015](#)). Public acceptance is also closely linked to tariff affordability and perceptions of economic fairness ([Curto et al., 2021](#)).

## 2.3. Political and geopolitical aspects

Cross-border desalination projects operate within politically sensitive environments shaped by regional tensions, governance challenges, and asymmetric power relations. [Bernauer and Böhmelt \(2020\)](#) argue that responses to water scarcity are influenced by political stability and institutional capacity as much as by physical resource availability. In some cases, desalination projects may facilitate cooperation, while in others they may intensify existing tensions. [Madani \(2010\)](#) notes that states may avoid cooperation when they perceive risks of dependence or exploitation, favoring unilateral approaches despite potential long-term benefits. Furthermore, dominant actors may influence governance arrangements and allocation mechanisms through political and economic leverage ([Zeitoun and Warner, 2006](#); [Zeitoun and Mirumachi, 2008](#)). Therefore, successful cooperation requires transparent agreements, negotiation mechanisms, and trust-building measures ([Mirzaei-Nodoushan et al., 2022](#)).

## 2.4. Governance, institutional, and legal aspects

Governance and institutional frameworks play a critical role in determining project outcomes. Cross-border water cooperation involves legal, political, economic, and social dimensions, making governance systems highly context-dependent ([Mirzaei-Nodoushan et al., 2022](#)). Formal agreements and treaties can reduce uncertainty and increase the likelihood of resolving disputes through negotiation rather than escalation ([Drieschova et al., 2008](#); [Dinar et al., 2015](#)). Effective governance systems generally include joint monitoring mechanisms, data-sharing procedures, enforcement provisions, and clearly defined institutional responsibilities ([Bernauer and Böhmelt, 2020](#)). Conversely, weak institutional frameworks may undermine cooperation and intensify tensions. Governance systems must also remain flexible and capable of adapting

to changing environmental and political conditions ([Madani, 2010](#)).

## 2.5. Social and community aspects

Social acceptance is a major determinant of project legitimacy and sustainability. [Katz \(2021\)](#) and [Walschot and Katz \(2022\)](#) indicate that opposition to large-scale water projects is often driven less by technical concerns and more by perceptions of fairness, transparency, and responsiveness to local needs. [Fischhendler and Tenenboim-Weinblatt \(2019\)](#) further emphasize that public acceptance depends on how communities perceive the distribution of benefits, financial responsibilities, and environmental risks. In cross-border settings, these concerns are often amplified by historical grievances and political tensions, making social legitimacy both critical and complex.

## 2.6. Environmental and ecological aspects

Environmental considerations strongly influence the sustainability of desalination projects. One of the most important environmental challenges is brine disposal and its impact on marine ecosystems. [Chenoweth and Al-Masri \(2021\)](#) note that concentrated brine discharge may increase salinity levels in areas with limited water circulation, potentially causing ecological degradation. Renewable energy integration can reduce environmental impacts by lowering dependence on fossil fuels; however, large-scale renewable energy systems may also generate land-use conflicts ([Alkaisi et al., 2017](#)). In addition, the high energy demand of desalination systems may still impose significant economic and environmental burdens despite renewable energy adoption ([Yechiel and Shevah, 2012](#)).

## 2.7. Peacebuilding and cooperation dynamics

Peacebuilding considerations remain central to cross-border desalination initiatives. [Walschot and Katz \(2024; 2022\)](#) argue that desalination projects may either strengthen cooperation or reinforce unilateral behavior depending on the surrounding political environment. Technical cooperation on shared infrastructure can support broader hydrodiplomacy efforts and facilitate communication between stakeholders ([Katz, 2021](#); [Bernauer and Böhmelt, 2020](#)). However, technical cooperation does not automatically lead to political reconciliation or trust-building. The peacebuilding potential of desalination projects therefore depends on the credibility of agreements, equitable benefit-sharing mechanisms, and the degree to which cooperation is institutionalized and perceived as fair by all parties involved ([Vij et al., 2020](#)).

Based on the conducted literature, a set of success and failure criteria in cross-border water desalination project contexts was organized into seven categories, as summarized in [Table 1](#).

The variables used in this study are treated as decision criteria rather than statistical predictors. Their selection followed a structured process combining theoretical relevance and expert validation. Candidate criteria were first extracted from research on desalination technology, renewable-energy integration, project finance, transboundary water governance, environmental management, stakeholder participation, hydrodiplomacy, and peacebuilding. A criterion was retained only when it: (1) had a direct and conceptually supported influence on project implementation, sustainability, or cooperation outcomes; (2) was applicable to cross-border renewable-energy-powered desalination; (3) was sufficiently distinct from the other criteria to minimize conceptual duplication; and (4) could be clearly evaluated by experts and translated into practical project or institutional action. The technical and financial criteria represent the operational and economic viability of the infrastructure; political and governance criteria capture interstate relations, power asymmetry, legal arrangements, and institutional capacity; social criteria reflect legitimacy, participation, and distributive equity; environmental criteria address ecological impacts and long-term resource

**Table 1**

Criteria related to the success and failure of cross-border renewable-energy powered desalination projects.

| Criterion                                 | Indicators (sub-criteria)                                                                                                                                                                                                                                                                                                                                                                                                                                            | Code             | Reference                                                                                                                              |
|-------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Technical & Scientific Aspects            | Reliability and efficiency of desalination technology.<br>Integration of renewable energy systems to power desalination.<br>Technical compatibility between countries' infrastructure.<br>Availability of engineering capacity and trained technical staff.<br>Joint monitoring systems.<br>Availability of shared technical data.<br>Incorporating adaptive engineering measures.<br>Scientific accuracy of demand forecasting and climate-related risk assessment. | TEC 1 -<br>TEC 8 | (Curto et al., 2021; Cipollina, et al., 2015; Ghaffour et al., 2013; Walschot and Katz, 2022; Chenoweth and Al-Masri, 2021;).          |
| Financial & Economic Aspects              | Equitable cost-sharing mechanisms.<br>Availability of stable long-term financing.<br>Transparency of financial arrangements and procurement processes.<br>Predictability of operation and maintenance (O&M) costs.<br>Economic benefits for all parties.<br>Effect of fluctuating energy prices.<br>Donor support to reduce political sensitivity over direct financing.<br>Incentives for using renewable-powered desalination.<br>Affordability of water tariffs.  | FIN 1 -<br>FIN 9 | (Ghaffour, et al., 2013; Cipollina, et al., 2015; Curto, et al., 2021; Dinar, et al., 2015; Bernauer & Böhmelt, 2020).                 |
| Political & Geopolitical Aspects          | Political stability among the participating countries.<br>Strength of diplomatic relations and trust.<br>Existence of formal agreements or treaties.<br>Commitment to long-term cooperation.<br>Transparency in cross-border negotiations and decision-making.<br>Prevention of unilateral actions or dominance.<br>Alignment of national strategies with regional integration.<br>Third-party mediation to reduce tensions.<br>Willingness to share control.        | POL 1 -<br>POL 9 | (Madani, 2010; Bernauer & Böhmelt, 2020; Mirzaei-Nodoushan, et al., 2022; Walschot & Katz, 2024; Katz, 2021).                          |
| Governance, Institutional & Legal Aspects | Strength of joint water-energy institutions.<br>Clarity of legal frameworks.<br>Flexibility clauses for climate variability or emergencies.<br>Effective dispute-resolution mechanisms.<br>Transparency of data-sharing protocols.<br>Inclusion of environmental and social safeguards.<br>Multi-sectoral coordination.<br>Long-term institutional stability and independence.                                                                                       | GOV 1 -<br>GOV 8 | (Drieschova, et al., 2008; Dinar, et al., 2015; Mirzaei-Nodoushan, et al., 2022; Bernauer & Böhmelt, 2020; Chenoweth & Al-Masri, 2021) |
| Social & Community Aspects                | Public acceptance.<br>Participation of affected or marginalized groups.<br>Social equity in benefit distribution.<br>Impacts on job creation and local economic development.<br>Public trust in government and institutions.<br>Awareness campaigns on environmental and economic impacts.<br>Inclusion of NGOs, CSOs, and experts.<br>Consideration of cultural and identity sensitivities.                                                                         | SOC 1 -<br>SOC 8 | (Katz, 2021; Fischhendler and Tenenboim-Weinblatt, 2019; Katz and Fischhendler, 2011; Walschot and Katz, 2022;)                        |
| Environmental & Ecological Aspects        | Environmental impacts.<br>Use of renewable energy to reduce carbon footprint.<br>Monitoring environmental indicators.<br>Minimizing ecological disruption during construction.<br>Shared environmental protection.<br>Climate resilience.<br>Compliance with international environmental standards.<br>Long-term sustainability.                                                                                                                                     | ENV 1 -<br>ENV 8 | (Alkaisi et al., 2017; Chenoweth and Al-Masri, 2021; Yechiel and Shevah, 2012; Cipollina, et al., 2015; Ghaffour et al., 2013)         |
| Peacebuilding & Cooperation Dynamics      | Cross-border trust-building.<br>Hydrodiplomacy efforts.<br>Fairness in benefit allocation.                                                                                                                                                                                                                                                                                                                                                                           | PBC 1 -<br>PBC 8 | (Fischhendler and Tenenboim-Weinblatt, 2019; Dinar, et al., 2015; Bernauer and Böhmelt, 2020; Katz, 2021; Walschot and Katz, 2024;)    |

(continued on next page)

Table 1 (continued)

| Criterion | Indicators (sub-criteria)                                                                                                                                                                       | Code | Reference |
|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|-----------|
|           | Dependency Avoidance.<br>Role of international organizations.<br>Issue-linkage strategies.<br>Incentives for cooperation during tension.<br>Involvement of academic and scientific communities. |      |           |

sustainability; and peacebuilding criteria assess trust, fairness, non-coercive interdependence, and continuity of cooperation during political tensions. The preliminary criteria were subsequently reviewed by senior scholars and practitioners and refined through pilot testing. This process resulted in the 58 sub-criteria organized under the seven dimensions presented in Table 1.

3. Research methodology

Following the identification of the major success and failure factors of cross-border renewable energy-powered desalination projects, a three-layer conceptual framework was developed (Fig. 1). The inner layer represents the overall objective of assessing project sustainability and cooperation outcomes. The intermediate layer includes four core system conditions: technical and scientific, environmental and ecological, governance and legal, and financial and economic aspects. The outer layer represents broader contextual dimensions, including political and geopolitical, social and community, and peacebuilding and cooperation dynamics. Based on this framework, a structured research

methodology was developed, as illustrated in Fig. 2.

An extensive literature review was conducted to identify the conditions influencing the planning, implementation, operation, sustainability, and cooperation outcomes of cross-border renewable-energy-powered desalination projects. The review covered desalination technologies, renewable-energy integration, project finance, transboundary water governance, international law, stakeholder participation, environmental management, hydrodiplomacy, and peacebuilding. Candidate indicators were screened for conceptual relevance, clarity, non-duplication, and applicability to politically sensitive cross-border infrastructure.

The retained indicators were organized into a three-level hierarchy. The first level represented the overall objective: prioritizing the success and failure factors of cross-border renewable-energy-powered desalination projects. The second level comprised seven main dimensions: technical and scientific; financial and economic; political and geopolitical; governance, institutional and legal; social and community; environmental and ecological; and peacebuilding and cooperation. The third level comprised 58 sub-criteria distributed across these dimensions, as

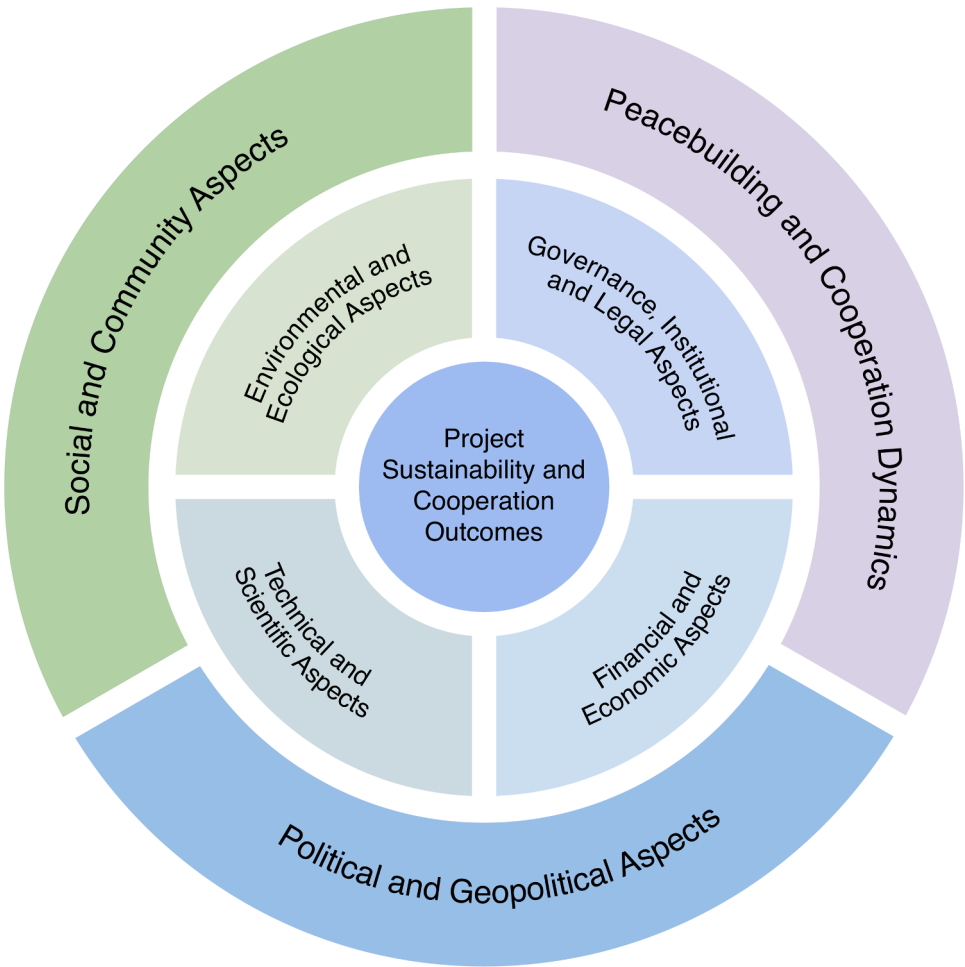


Fig. 1. Multi-dimensional framework of success and failure aspects in cross-border renewable-energy powered desalination projects.

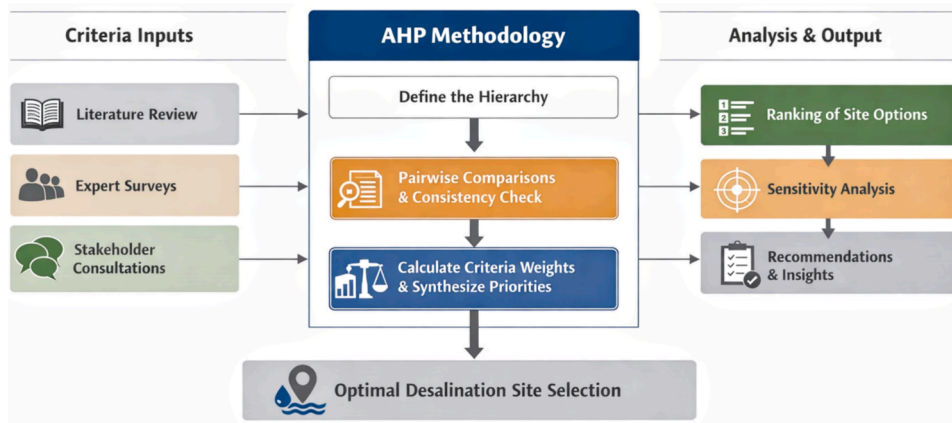


Fig. 2. Overview of research methodology and phases.

reported in Table 1.

The hierarchy separates formal governance arrangements from peacebuilding outcomes: governance concerns rules, institutions, responsibilities, compliance, and dispute resolution, whereas peacebuilding concerns cross-border trust, fairness, non-coercive interdependence, hydrodiplomacy, and the continuity of cooperation during political tensions.

A structured questionnaire was developed to obtain expert assessments of the relative importance of the identified factors. The first section recorded respondents' professional affiliation, disciplinary expertise, geographical experience, and years of experience. Sections A–G addressed the seven main dimensions and their associated sub-criteria. Respondents rated the importance of every item using a five-point Likert scale, where 1 indicated “least important,” 2 “less important,” 3 “moderately important,” 4 “important,” and 5 “very important.” The questionnaire requested importance ratings rather than direct pairwise judgments; the reciprocal comparison matrices were subsequently derived from the aggregated ratings.

Content validity was assessed in two stages. First, the draft questionnaire was reviewed by senior scholars and practitioners with expertise in desalination, renewable energy, water governance, environmental management, and conflict resolution. Items judged unclear, repetitive, or outside the scope of the research objective were revised or removed. Second, a pilot test was conducted to verify wording, scale interpretation, completion time, and the logical grouping of criteria. Feedback from both stages was incorporated before the questionnaire was distributed to the final expert sample.

Participants were selected purposively because the research required informed judgments spanning engineering and hydropolitical domains. Eligibility required demonstrated academic, professional, policy, or institutional experience in at least one of the following areas: desalination, renewable energy, water-resource management, environmental assessment, project finance, international relations, transboundary governance, or conflict resolution. To reduce disciplinary dominance, the sample was constructed to include both technical and non-technical expertise.

A total of 28 experts were invited to participate, of whom 24 provided complete and valid responses, corresponding to a response rate of 85.7%. Data were collected between March 2026 and April 2026. The final sample included 66.7% experts from technical disciplines and 33.3% from governance, policy, environmental, financial, and conflict-resolution fields. Respondents represented Germany, Italy, Austria, Greece, Morocco, Saudi Arabia, Palestine, Israel, Jordan, Portugal, Spain, Algeria, Oman, Turkey, Lebanon and Libya and had between 10 and 40 years of relevant professional experience. The questionnaire was pilot-tested with five participants who were included in the final sample.

The sample included participants from universities and research

institutions, governmental and regulatory bodies, private-sector organizations, international organizations, and/or civil-society organizations. Because the study relied on specialized expert judgment rather than population-level statistical inference, sample adequacy was determined based on participants' relevant professional experience, disciplinary diversity, geographical representation, and coverage of the seven dimensions of the proposed framework rather than through conventional probabilistic sample-size calculations. Potential respondent bias was minimized through the use of standardized questions, neutral criterion descriptions, a uniform rating scale, pilot testing, and the recruitment of experts from diverse disciplinary, institutional, and geographical backgrounds. All complete and valid responses were assigned equal weight in the AHP analysis. Professional experience, institutional seniority, and disciplinary background were not used to assign differential weights because doing so would introduce an additional subjective weighting assumption. Accordingly, differences in expertise were addressed through sample diversification rather than respondent-specific weighting; the absence of subgroup-specific weighting is acknowledged as a methodological limitation.

The collected Likert ratings were not directly converted into the discrete 1–9 Saaty scale. Instead, they were aggregated and transformed into positive reciprocal comparison values using ratios of mean importance scores. This approach preserves the relative differences in the expert ratings and makes the calculation reproducible.

For criterion or sub-criterion  $i$ , the aggregated mean importance score was calculated across  $K$  experts as:

$$\bar{x}_i = \frac{1}{K} \sum_{k=1}^K x_{ik} \quad (1)$$

where  $x_{ik}$  is the rating assigned to item  $i$  by expert  $k$ ,  $K$  is the number of valid expert responses, and  $\bar{x}_i$  is the aggregated mean importance score of item  $i$ .

The relative importance of items  $i$  and  $j$  was then calculated as:

$$a_{ij} = \frac{\bar{x}_i}{\bar{x}_j} \quad (2)$$

Reciprocity and the diagonal condition were imposed as follows:

$$a_{ji} = \frac{1}{a_{ij}} = \frac{\bar{x}_j}{\bar{x}_i}, \quad a_{ii} = 1 \quad (3)$$

For example, if two items received mean ratings of 4.5 and 3.0, their comparison values were 1.50 and 0.667 in the forward and reciprocal directions, respectively. The resulting  $n \times n$  comparison matrix was:

$$A = (a_{ij})_{n \times n} \quad (4)$$

where  $A$  is a positive reciprocal matrix,  $a_{ij} > 0$ ,  $a_{ii} = 1$ , and  $a_{ij} = 1/a_{ji}$ .

Separate matrices were constructed for the seven main dimensions and for the sub-criteria belonging to each parent dimension.

For each column  $j$ , the column sum was calculated as:

$$s_j = \sum_{i=1}^n a_{ij} \quad (5)$$

Each matrix element was normalized by its column sum:

$$b_{ij} = \frac{a_{ij}}{s_j} \quad (6)$$

The local priority weight of item  $i$  was obtained as the arithmetic mean of its normalized row:

$$w_i = \frac{1}{n} \sum_{j=1}^n b_{ij} \quad (7)$$

The local priority vector was therefore expressed as:

$$w = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \quad (8)$$

Global priority weights were calculated to permit comparison of sub-criteria belonging to different dimensions. For sub-criterion  $q$  under main dimension  $p$ , the global weight was:

$$g_{pq} = W_p w_{pq} \quad (9)$$

where  $W_p$  is the weight of main dimension  $p$ ,  $w_{pq}$  is the local weight of sub-criterion  $q$  within dimension  $p$ , and  $g_{pq}$  is its global weight relative to the overall objective. All global weights were ranked in descending order.

For completeness, the conventional AHP consistency calculations were applied. The weighted-sum vector was obtained as:

$$v = Aw \quad (10)$$

An element-wise estimate of the principal eigenvalue was then calculated as:

$$\lambda_i = \frac{v_i}{w_i} \quad (11)$$

The maximum eigenvalue estimate, consistency index, and consistency ratio were calculated as:

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \lambda_i \quad (12)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (13)$$

$$CR = \frac{CI}{RI} \quad (14)$$

where  $RI$  is Saaty's random index for a matrix of order  $n$ . Because every comparison value in this study was generated from a single ratio vector,  $a_{ij} = \bar{x}_i / \bar{x}_j$ , the matrices are structurally consistent:  $\lambda_{max} = n$  and  $CI = CR = 0$ , apart from rounding. Accordingly, the consistency ratio verifies arithmetic construction but should not be interpreted as an independent test of inconsistency among the original expert ratings. This limitation is acknowledged explicitly.

A one-at-a-time sensitivity analysis was conducted to examine the robustness of the global ranking. In each scenario, the weight of one main dimension  $c$  was increased by 20%, while the remaining main-dimension weights were renormalized so that their total remained equal to one. Local sub-criterion weights were held constant. The adjusted main-dimension weights were calculated as:

$$W_j^* = \frac{\alpha_j W_j}{\sum_{j=1}^7 \alpha_j W_j} \quad (15)$$

In Eq. (15),  $\alpha_j = 1.2$  for the perturbed dimension ( $j = c$ ) and  $\alpha_j = 1.0$  for all other dimensions.

New global weights were then obtained using:

$$g_{jq}^* = W_j^* w_{jq} \quad (16)$$

For each of the seven perturbation scenarios, all sub-criteria were reranked and compared with the base-case ranking. Robustness was assessed using three complementary indicators: the number of base-case top-ten factors retained in the perturbed top ten, the relative changes in the global weights of the five highest-ranked factors, and the maximum rank displacement of the leading factors. This procedure evaluates whether the principal conclusions depend disproportionately on any single main dimension (Saaty, 2008). The methodology of the sensitivity analysis followed in this research is shown in Fig. 3.

#### 4. Results and discussion

After collecting expert responses, pairwise comparison matrices were developed for the seven main criteria and for each sub-criterion. Expert judgements were then aggregated, and final weights were calculated for all levels of the hierarchy.

Results obtained from the analysis include the weight of the main criteria, which reflect the relative importance of each main dimension relative to the overall objective of this study. The results show that the seven main criteria are of relatively similar importance to each other, as shown in Fig. 4. The weights for the main criteria vary between approximately 0.136 for Social and Community Aspects and 0.146 for Environmental and Ecological Aspects.

These results indicate that all main dimensions are important, and none of them can be neglected. The narrow range of weights also suggests that the issue being studied is not controlled by a single, dominant factor. This is consistent with (Dinar, et al., 2015), which highlights that cooperation outcomes are shaped by interacting technical, institutional, and political dimensions rather than being driven by a single factor.

The main-dimension weights were closely distributed, ranging from 0.1360 to 0.1459, confirming that no single dimension independently determines project success. Environmental and ecological aspects ranked first (0.1459), followed closely by technical and scientific (0.1456), political and geopolitical (0.1454), financial and economic (0.1450), peacebuilding and cooperation (0.1433), governance, institutional and legal (0.1387), and social and community aspects (0.1360). This narrow range demonstrates the multidimensional character of cross-border desalination and indicates that technical feasibility must be supported by political commitment, effective institutions, environmental protection, financial stability, and social legitimacy.

Greater differentiation appeared at the sub-criterion level. The highest global priority was assigned to the reliability and efficiency of desalination technology (0.0221), followed by the use of renewable energy to reduce the carbon footprint (0.0210), technical compatibility between participating countries' infrastructure (0.0207), perceived fairness in benefit distribution (0.0203), clarity of legal frameworks (0.0203), environmental impacts of brine disposal (0.0200), and trust-building between technical teams (0.0198). These findings identify five central implementation priorities: reliable infrastructure, environmental sustainability, cross-border technical compatibility, equitable allocation of benefits, and clear institutional arrangements. The importance of technical reliability supports the view that stable system performance reduces the risk of disputes caused by service interruptions, while the high rankings of fairness and legal clarity confirm that cooperation depends on credible and equitable governance arrangements (Dinar et al., 2015; Walschot and Katz, 2022).

Within the individual dimensions, experts prioritized predictable

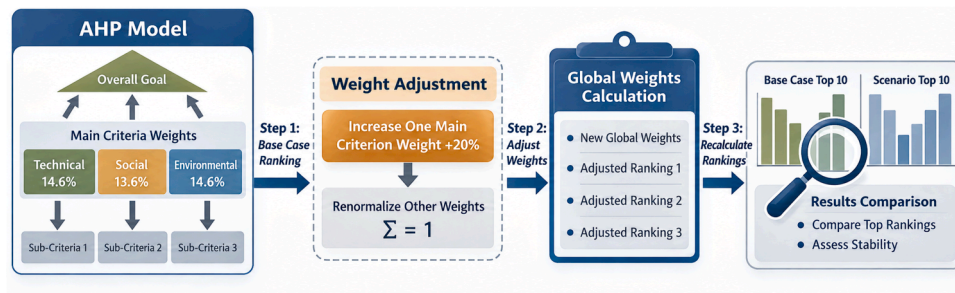


Fig. 3. Methodology of sensitivity analysis developed in this research.

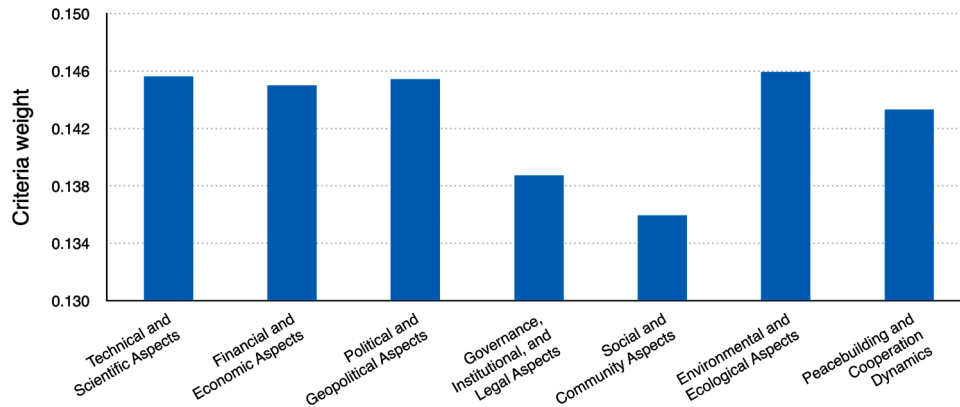


Fig. 4. Relative weights of the main criteria influencing transboundary desalination systems.

operation and maintenance costs and mutual economic benefits in the financial category; formal agreements and safeguards against unilateral control in the political category; legal clarity, dispute resolution, and transparent data sharing in governance; public trust, participation, and equitable benefit distribution in the social category; renewable-energy integration, responsible brine disposal, and sustainable water-intake systems in the environmental category; and fairness, technical-team trust, and hydrodiplomacy in the peacebuilding category. Conversely, mechanisms dependent primarily on external actors—including donor support, third-party mediation, and external facilitation—generally received lower priority. The overall pattern therefore indicates that respondents placed greater confidence in internally institutionalized cooperation, enforceable arrangements, operational reliability, and locally perceived fairness than in temporary external interventions. This finding supports previous research emphasizing that the sustainability of transboundary cooperation depends on institutional design, transparency, and perceptions of distributive justice (Dinar et al., 2015; Fischhendler and Tenenboim-Weinblatt, 2019).

These finding support Fischhendler and Tenenboim-Weinblatt (2019), who argued that the peacebuilding potential of shared infrastructure depends largely on how benefits are perceived and justified among participating parties. The findings therefore challenge the assumption that shared infrastructure automatically generates peace, suggesting instead that sustainable peacebuilding depends on equitable benefit-sharing, mutual trust, and continuous engagement between stakeholders over time (See Table 2).

The results presented in Table 2 indicate that technical performance, environmental sustainability, legal clarity, and fairness are generally more influential in transboundary settings, while external support mechanisms generally play a smaller role in determining the success or failure of desalination systems in such settings. This is consistent with (Dinar, et al., 2015), where institutional design and governance structures are considered key determinants of effective transboundary cooperation, and (Fischhendler and Tenenboim-Weinblatt, 2019),

Table 2

Highest-ranked sub-criteria based on their global weights.

| Sub Criterion                                       | Global Weight | Scenario Group |
|-----------------------------------------------------|---------------|----------------|
| Reliability & efficiency of desalination technology | 0.022,121     | Technical      |
| Use of renewable energy to reduce carbon footprint  | 0.021         | Environmental  |
| Technical compatibility between infrastructures     | 0.020,738     | Technical      |
| Perceived fairness of benefits                      | 0.020,281     | Peacebuilding  |
| Clarity of legal frameworks                         | 0.02,028      | Governance     |
| Environmental impact of brine disposal              | 0.019,964     | Environmental  |
| Trust-building between technical teams              | 0.019,822     | Peacebuilding  |
| Long-term sustainability of water intake systems    | 0.019,453     | Environmental  |
| Integration of renewable energy systems             | 0.019,356     | Technical      |
| Effective dispute-resolution mechanisms             | 0.019,351     | Governance     |
| Monitoring environmental indicators                 | 0.018,943     | Environmental  |
| Hydrodiplomacy efforts                              | 0.01,889      | Peacebuilding  |
| Public trust in institutions                        | 0.018,435     | Social         |
| Incentives for cooperation during tension           | 0.018,432     | Peacebuilding  |
| Formal agreements or treaties                       | 0.018,024     | Political      |
| Transparency of data-sharing protocols              | 0.017,978     | Governance     |
| Academic/scientific communities in data disputes    | 0.017,973     | Peacebuilding  |
| Shared environmental protections                    | 0.017,921     | Environmental  |
| Preventing unilateral actions/dominance             | 0.017,615     | Political      |
| Economic benefits for all parties                   | 0.017,615     | Financial      |

where perceived fairness and distribution of benefits are considered critical to sustaining long-term cooperation. Results suggest that countries should first ensure technical reliability, environmental compliance and legal clarity, and then reinforce trust, fairness, and long-term institutional arrangements to allow governments in transboundary settings to build confidence while gradually strengthening broader cooperation (Fig. 5).

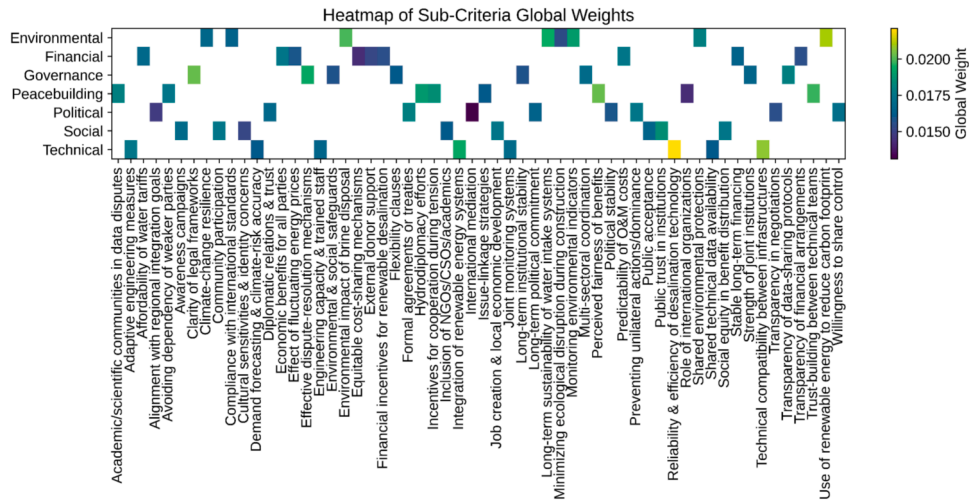


Fig. 5. Local weights Heatmap representation of the global priority weights of all sub-criteria derived from the AHP analysis.

#### 4.1. Sensitivity analysis results

The developed sensitivity analysis indicates that the obtained ranking is reasonably robust to moderate variations in the weights of the main criteria. When the weight of each main criterion was increased by 20% individually, between 5 and 7 of the base-case top 10 sub-criteria remained within the top 10 positions. The most stable factors across scenarios included the reliability and efficiency of desalination technology, the use of renewable energy to reduce carbon footprint, technical compatibility between participating countries' infrastructure, perceived fairness in benefit allocation, and clarity of legal frameworks. Although some reordering was observed among mid-ranked factors, the overall ranking pattern remained broadly consistent, confirming that the model's main conclusions are not driven by a single criterion alone.

The robustness of the obtained AHP-based prioritization was evaluated through a one-at-a-time sensitivity analysis, the results of which are presented in Figs. 6–8.

As shown in Fig. 6, which illustrates the retention of the base-case top ten sub-criteria under +20% perturbations of each main criterion,

between 5 and 7 out of the original top 10 factors (i.e., 50%–70%) remained within the top 10 across all scenarios. The highest stability was observed under Technical, Financial, Governance, and Environmental perturbations (7/10 retained), while slightly lower stability was observed under Political and Peacebuilding scenarios (6/10 retained), and the lowest under the Social scenario (5/10 retained). Despite these variations, the absence of any drastic reduction in retention confirms that the ranking structure is not highly sensitive to moderate changes in the weighting scheme.

Further insight into the robustness of the most influential factors is provided in Fig. 7, which presents a radar-based comparison of the global weights of the top five sub-criteria under selected scenarios. The results show that the global weights of these factors exhibit only minor deviations across scenarios, with variations generally remaining within a narrow band of approximately  $\pm 5\%$ – $10\%$  relative change from their base-case values. In particular, the highest-ranked factor, reliability and efficiency of desalination technology, consistently maintained a global weight close to 0.022, while other top factors, including renewable energy utilization, technical compatibility, perceived fairness, and legal

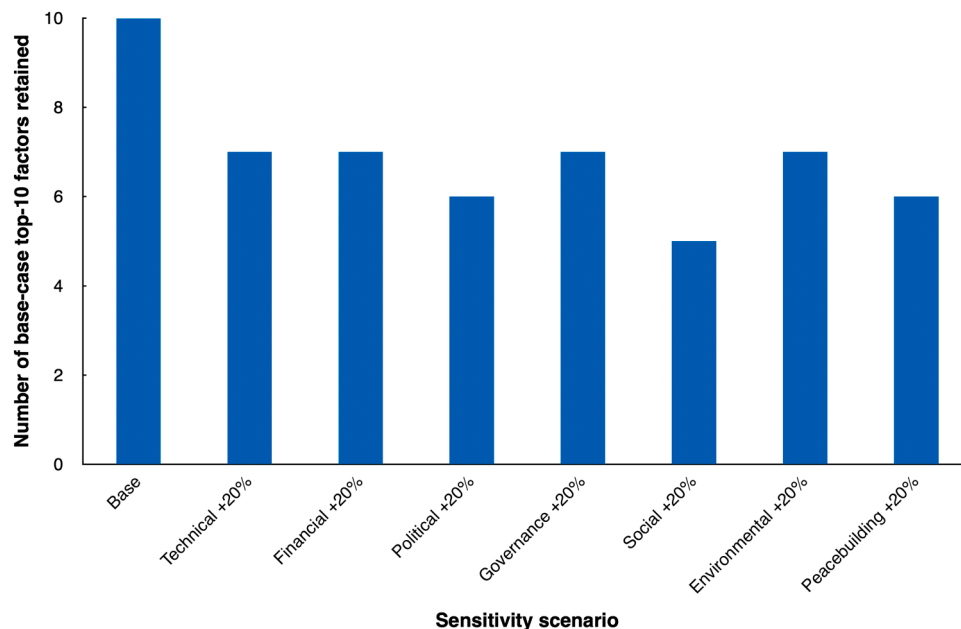


Fig. 6. Sensitivity analysis: Retention of the base case top 10.

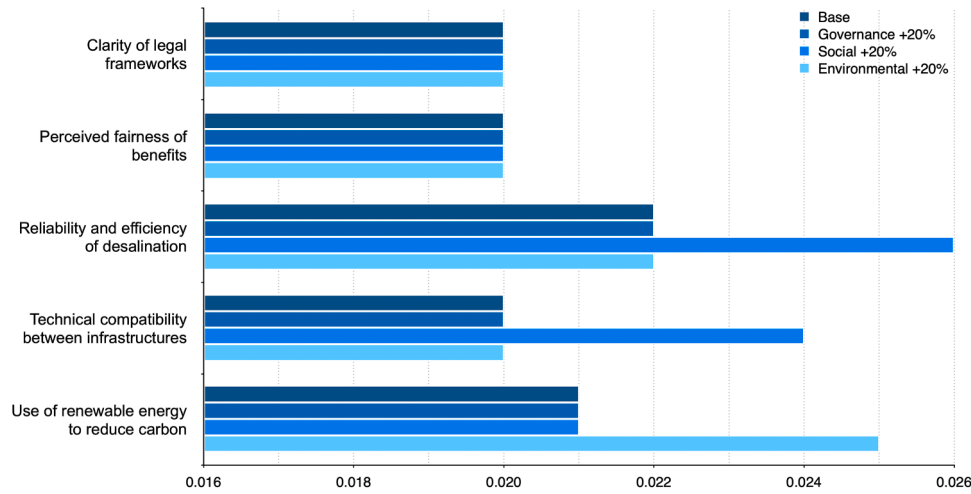


Fig. 7. Sensitivity analysis of top factors.

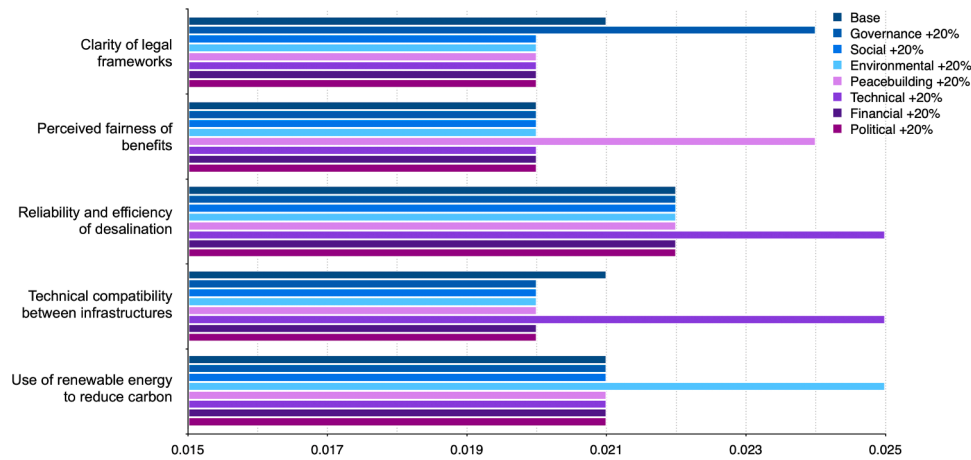


Fig. 8. Sensitivity analysis of top factors (all scenarios).

clarity, remained clustered within the range of approximately 0.020–0.021. This indicates that these factors are structurally dominant and largely unaffected by moderate shifts in decision-maker preferences.

Fig. 8 extends this analysis by presenting the radar chart for all sensitivity scenarios, confirming that no significant reordering occurs among the top-ranked sub-criteria. Although minor rank shifts are observed, particularly among mid-ranked factors, the maximum observed rank deviation for the top-tier factors does not exceed 2–3 positions, indicating limited sensitivity. Moreover, the relative proximity of the main criteria weights in the base case (ranging approximately from 0.136 to 0.146) contributes to this behavior, as moderate perturbations do not substantially distort the overall balance of the model.

Overall, the combined results from Figs. 6–8 demonstrate that the proposed framework exhibits a high degree of robustness, with stable identification of key success factors under varying assumptions. The findings confirm that the prioritization is not driven by a single dominant dimension, but rather reflects a balanced and resilient interaction between technical performance, environmental sustainability, governance structures, and cooperation dynamics in cross-border desalination systems.

#### 4.2. Peacebuilding implications of the results

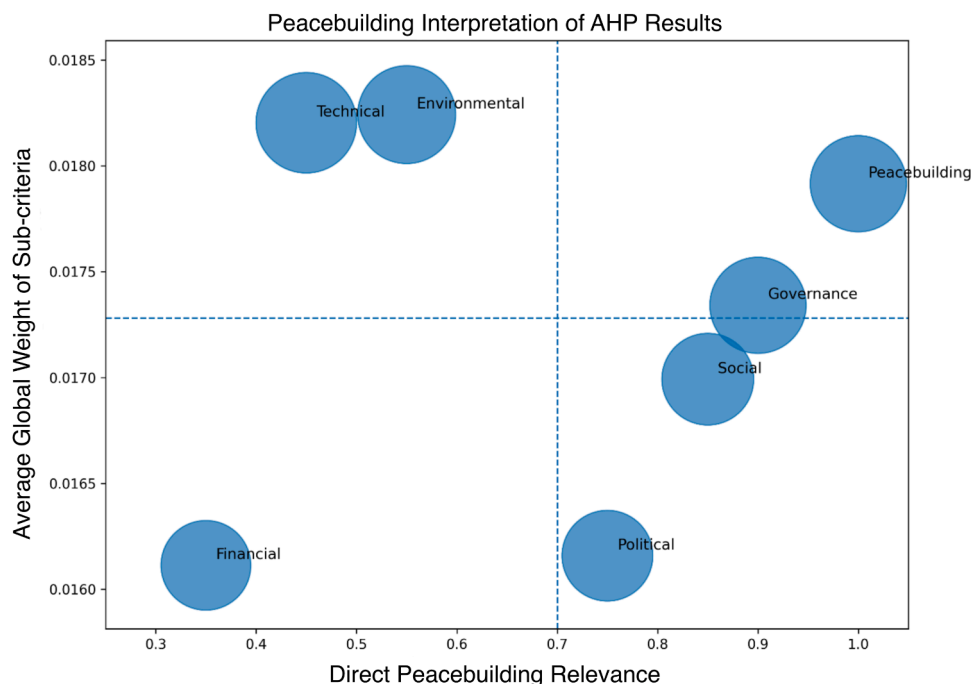
The quantitative results obtained from the AHP analysis provide

important insights into the conditions under which cross-border desalination projects may contribute to peacebuilding and long-term cooperation as shown in Fig. 9.

The global weights indicate that no single factor dominates the decision-making process. Instead, cooperation outcomes emerge from the interaction of technical, governance, social, political, and environmental dimensions. The highest-ranked sub-criteria are concentrated within a narrow range of approximately 0.020–0.022 in global weight, suggesting a balanced distribution of influence among the major factors affecting project sustainability and cooperation outcomes.

Among the evaluated dimensions, governance-related factors and technical reliability occupy the upper range of the ranking. Governance criteria associated with institutional clarity, transparency, and fairness in benefit distribution demonstrate both high importance and direct relevance to cooperation dynamics. This finding aligns with Dinar et al. (2015), who emphasized that equitable governance arrangements are essential for sustaining long-term cooperation in transboundary settings. Similarly, technical reliability remains an important enabling condition, as stable system performance reduces the likelihood of disputes related to operational failures and infrastructure disruptions (Walschot and Katz, 2022). However, technical factors contribute indirectly to peacebuilding by supporting operational stability rather than directly strengthening trust.

Social dimensions also show strong importance, particularly factors related to fairness, inclusiveness, and social legitimacy. These findings



**Fig. 9.** Quadrant-style bubble representation of the peacebuilding implications of the AHP results. The vertical axis shows the average global weight of sub-criteria within each dimension, while the horizontal axis represents their direct relevance to peacebuilding. Bubble size reflects the highest-ranked sub-criterion within each dimension.

support Fischhendler and Tenenboim-Weinblatt (2019), who argued that perceptions of justice strongly influence the sustainability of cross-border initiatives. By contrast, purely economic variables appear slightly lower in the ranking, suggesting that financial feasibility alone is insufficient to generate peacebuilding outcomes. Overall, the results indicate that peacebuilding potential depends primarily on governance quality, social legitimacy, and perceptions of fairness rather than technical or economic performance alone.

The close distribution of the seven main-dimension weights indicates that cross-border renewable-energy-powered desalination should not be managed as a sequence in which technical feasibility is addressed first and political, social, or environmental concerns are considered later. Instead, project preparation should proceed through parallel technical, institutional, environmental, financial, and peacebuilding workstreams. Nevertheless, the highest-ranked sub-criteria identify several priority safeguards that should be established at an early stage, particularly technological reliability, renewable-energy integration, infrastructure compatibility, fairness in benefit distribution, legal clarity, responsible brine management, and trust between technical teams.

For policymakers and transboundary institutions, these findings support the establishment of a joint governing body before major infrastructure commitments are made. Its mandate should define decision-making authority, water-allocation rules, financial responsibilities, data-sharing requirements, performance-monitoring procedures, and enforceable dispute-resolution mechanisms. Agreements should also prevent unilateral control by establishing balanced voting arrangements, independent verification, emergency procedures, and clearly specified conditions for modifying or suspending project operations. Benefit-sharing arrangements should transparently determine how water, costs, revenues, employment opportunities, environmental risks, and long-term economic benefits are distributed among participating countries and affected communities. Because perceived fairness ranked among the leading factors, distributional arrangements should be publicly explained and periodically reviewed rather than treated solely as intergovernmental financial provisions.

For project developers and operators, technical coordination should

include common design and performance standards, compatible monitoring and communication systems, shared operational protocols, coordinated maintenance planning, adequate redundancy, and joint training of technical personnel. Environmental safeguards should incorporate harmonized impact-assessment procedures, continuous monitoring of seawater intake and brine discharge, shared ecological thresholds, and publicly accessible compliance reports. Trust-building can be supported through permanent joint technical committees, routine exchange of operational data, independent performance audits, stakeholder consultation, accessible grievance procedures, and phased implementation beginning with pilot-scale cooperation. The relatively lower priority assigned to external donor support and third-party facilitation suggests that international actors should reinforce locally owned governance and technical capacity rather than substitute for them. Collectively, these measures convert the AHP rankings into an actionable framework for project planning, institutional design, risk reduction, and long-term cross-border cooperation.

## 5. Conclusion

This study developed a multidimensional AHP framework to identify and prioritize the factors influencing the implementation and sustainability of cross-border renewable-energy-powered desalination projects in conflict-affected settings. The framework integrates technical, financial, political, governance, social, environmental, and peacebuilding considerations within a common decision structure. The seven main dimensions received closely distributed weights: environmental and ecological aspects ranked first (0.1459), followed by technical and scientific (0.1456), political and geopolitical (0.1454), financial and economic (0.1450), peacebuilding and cooperation (0.1433), governance, institutional and legal (0.1387), and social and community aspects (0.1360). This narrow range confirms that project success cannot be attributed to a single dominant dimension and instead depends on the interaction of technical performance, institutional arrangements, political conditions, environmental protection, financial viability, and social legitimacy.

At the sub-criterion level, the reliability and efficiency of desalination technology achieved the highest global weight (0.0221), followed by the use of renewable energy to reduce the carbon footprint (0.0210), technical compatibility between participating countries' infrastructure (0.0207), perceived fairness in benefit distribution (0.0203), clarity of legal frameworks (0.0203), environmental impacts of brine disposal (0.0200), and trust-building between technical teams (0.0198). These findings demonstrate that reliable infrastructure and environmental performance must be accompanied by compatible technical systems, equitable benefit allocation, legal certainty, and sustained cross-border trust. The ratio-derived comparison matrices were structurally consistent by construction, with  $\lambda_{\max} = n$  and  $CI = CR = 0$ , apart from numerical rounding. Moreover, the sensitivity analysis showed that 5–7 of the base-case top 10 sub-criteria remained within the top 10 following a 20% increase in each main-dimension weight, indicating that the principal priorities are reasonably robust to moderate changes in decision-maker preferences.

The results provide a practical basis for project planning and institutional design. Policymakers and transboundary institutions should establish joint governance bodies, transparent benefit-sharing arrangements, enforceable dispute-resolution procedures, shared environmental safeguards, and protections against unilateral control. Project developers should prioritize interoperable technical standards, reliable renewable-energy and desalination technologies, joint monitoring systems, coordinated maintenance, and agreed emergency-response procedures. Trust should be strengthened through permanent joint technical committees, routine data exchange, independent performance verification, stakeholder participation, and phased implementation. These actions should be pursued as interconnected workstreams rather than sequential requirements because the closely distributed dimension weights demonstrate that technical, political, environmental, institutional, and social conditions are mutually reinforcing.

#### Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author used ChatGPT in order to generate the graphical abstract, Figs. 2 and 3. After using this tool, the author reviewed the content of the graphical abstract and takes full responsibility for the content of the published article.

#### CRedit authorship contribution statement

**Hala Qzaih:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – review & editing. **Tamer Khatib:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Supervision, Writing – review & editing. **Ahmed Beshtawi:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Supervision, Writing – review & editing.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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