

A desalination research agenda fit for the 21st century

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HIGHLIGHTS

- Research focused on desalination technology is necessary but insufficient.
- More research on the economic and social impacts of desalination is needed.
- Desalination research needs to embrace open science principles.

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ABSTRACT

Desalination is expanding exponentially across the world. Yet, there is little research on the economic, institutional, and social dimensions of desalination, as well as on policy-relevant lessons for managing the risks and opportunities from this technology, especially in low- and middle-income countries. This perspective article proposes a broad research agenda anchored in five key themes – energy and materials, institutions and regulations, social dynamics and perception, strategic planning, and financial sustainability – and grounded in the principles of open science to help steer the sustainable and equitable roll-out of desalination globally.

1. A new era of desalination?

Desalination is expanding exponentially across the world. Once a water technology for the energy rich and water-stressed Gulf Cooperation Countries (GCC), desalination has now gone – for want of a better word – mainstream. Across the world, countries such as Chile, China, Egypt, India, Mexico, Morocco, and Senegal, are investing in desalination to meet water demands and reduce urban water shortages. According to the International Desalination and Reuse Association (IDRA), the body that promotes desalination worldwide and that celebrated its 50th anniversary in 2023, the total global contracted desalination capacity is at least 109.2 million cubic meters per day [1] (around 4 % of global domestic water use [2]). Since 2010, the global installed capacity has grown at an average of 7 % per year [3]. Growing interest and investment in desalination respond to the growing demands for water, increasing awareness among policymakers and investors of the growing risk of ‘day zero’ events – when a city runs out of water - and preference to invest in supply-side solutions to reduce water shortages. The dramatic declines in the energy required to drive desalination over the past fifty years have also played a major role in this expansion.

This exponential growth in desalination investments has been accompanied by a spur of related innovations and research. Patenting

activity in desalination technologies quadrupled from 1990 to 2010 [4], and the number of academic publications has also increased from less than a 1000 in 1990 to more than 18,000 in 2020 [5]. Despite this growth in desalination technology development and application, there is little research examining the economic, institutional, and social dimensions of desalination and providing guidance for policy on managing the risks and opportunities from this technology, especially in low- and middle-income countries. The number of publications addressing the social and political dimensions of desalination and its economics aspects beyond energy consumption is increasing; however, it is still very low (about ten times less) compared to technology-focused research [5]. This Perspective article puts forward a broad research agenda anchored in five key themes and grounded in the principles of open science to help steer the sustainable and equitable roll-out of desalination around the world..

2. Research focused on technology is necessary but insufficient

Most desalination research to date has focused on technology, such as advances in membrane-based processes and new applications of nanomaterials to improve energy efficiency. This research is driving efficiency improvements in desalination and might further contribute to

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bringing down operational costs; however, energy consumption only accounts for about one quarter to one half of the costs of desalination, with other costs related to environmental permitting, capital, and other operating costs (e.g., membrane replacement) [6]. Hence, if desalination is to play a significant role in augmenting and diversifying the world’s water supplies, factors other than technological improvements are likely to affect its uptake and further expansion, requiring a broad research agenda to support 21st century water policy. This research agenda would complement ongoing industry-led and practitioner-oriented efforts – such as the ones spearheaded by IDRA - to collect data, convene stakeholders, and promote best-practices, and would also include other non-conventional water supply sources, notably wastewater. A comprehensive research agenda on desalination would cover at least five dimensions (Fig. 1).

2.1. Energy and materials nexus

Most desalination research to date has focused on the minimization of energy consumption, mostly through development of new materials for membranes. However, systematic reviews considering all three desalination mechanisms (pressure, thermal and electro-driven) show that technological innovation through novel materials will not deliver expected energy efficiency gains [7]. This confirms insights from the material science community suggesting that technological advances alone do not deliver resource-use efficiency [8].

This reality has important consequences for the membrane research community, which has benefitted from a large emphasis on membrane technology development, and for research funders, who have tended to support initiatives that promise to break free of desalination’s energy requirements through novel technologies alone. If we really want to support the sustainable roll out of desalination, we need to go beyond the emphasis on material development and focus on rigorous analysis of the scalability, manufacturability, and deployment challenges of desalination solutions.

Through a broader focus on technology deployment and scalability, researchers will also drive a shift in the political and corporate rhetoric and in the research funding landscape around material and energy technologies for desalination. Rather than waiting for the next, and perhaps unrealizable, technological breakthrough in materials manufacturing, desalination researchers should focus on (and funders

should support) research aimed at answering questions such as: which treatment technologies can succeed at speed and scale? What factors influence the system-level and life-cycle performance of desalination technologies? And how do costs of treatment vary and what are appropriate targets for cost reduction? Techno-economic approaches that couple process modelling and economic analysis [9,10] and life-cycle assessment frameworks incorporating both manufacturing- and use-phase environmental impacts [11] can help to effectively address these questions.

If desalination researchers focused less on membrane development and more on system-level questions, the community could also better assist decision-makers in understanding how desalination fits within the strategic challenge of delivering water services and clean energy under climate change. The clean energy boom will likely make desalination even more widespread, including to produce green hydrogen [12]. However, water is a local problem, and the extent to which renewable energy desalination for green hydrogen will become viable with respect to the local availability of clean energy and other natural resources remains unclear. Furthermore, system-level questions surrounding the energy and material implications of decentralized water service delivery models supported by desalination (i.e., small-scale plants for remote communities; desalination plants for mining) still need to be explored (i.e., trade-offs between technology choice and chemical usage).

A refocused research agenda on energy and materials would also pay more attention to the nexus of desalination with rare earth elements and minerals. Important dimensions include mineral recovery from brine [13], and the environmental impacts of desalination membranes and infrastructure [14], including opportunities for circularity. For example, applications of material flow accounting and scenario analysis could help understand any risks from material or energy bottlenecks in the large-scale deployment of desalination or any opportunities to reduce desalination’s energy and material footprint throughout its life cycle.

2.2. Institutions and regulations

Research on the governance of desalination, and particularly on institutional and regulatory models appropriate for low- and middle-income countries, is lacking. In most countries around the world, desalinated water is not formally included in water rights and water governance arrangements. As seen in Saudi Arabia and Israel, the

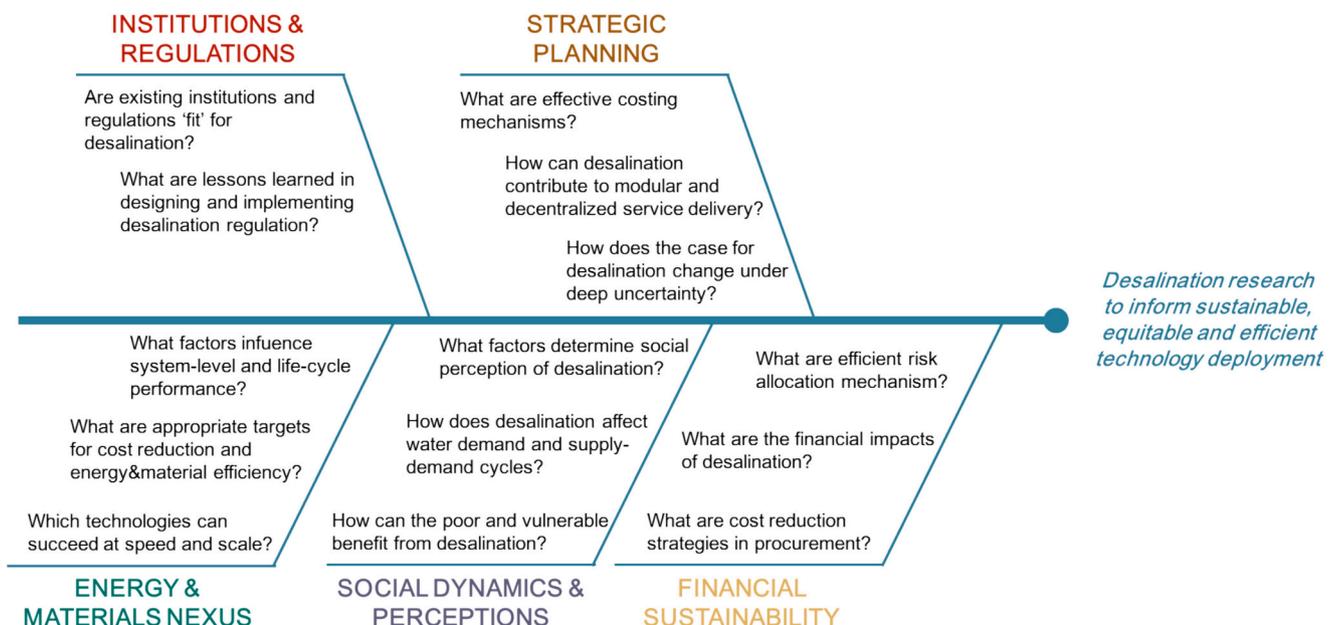


Fig. 1. A desalination research agenda for the 21st century.

expansion of desalination often leads to the creation of large-scale water infrastructure to transfer water around the country in a way that is detached from traditional water allocation regimes based on river basins. In some contexts, this extensive water transfer infrastructure might alter water allocation dynamics and priorities of use, at nested scales from the local to the transboundary, and might also shift the centre of gravity in water governance towards centralized institutional models. In other contexts, desalination infrastructure might enable a shift towards more decentralized models of water service delivery and governance [15].

In addition, existing water institutions – such as urban water utilities or river basin authorities that already struggle to keep pace with rapid technological and global change – typically do not have the capacity and know-how to manage desalination. These institutions rarely have: (i) established standards on desalinated water production, including water quality (e.g., boron concentrations) and management of desalination by-products such as brine [16]; (ii) capacity and standardized procedures to negotiate desalination projects with international technology providers and contractors; (iii) information sharing protocols with entities regulating related sectors such as coastal management, land zoning and environmental permitting.

The relevance of this point is demonstrated by the fact that one of the main drivers of Saudi Arabia's recent overhaul of its institutional model for water service delivery was the need to make it more suitable for the further scaling-up of desalination infrastructure [17]. Desalination initiatives typically involve many players (technology providers, operators, and financial partners), each covering a different aspect of the desalination value chain. Engaging with this vast array of actors can be potentially challenging for governments and utilities, especially in low-income settings, calling for researchers to help policymakers identify the most suitable institutional models in each context.

Alongside research on institutional models to support the roll-out of desalination, research should explore and compare the performance of alternative approaches for regulating desalination and related aspects of water service delivery. This ranges from environmental regulation, for which comparative analyses exist and identify room for improvements in several countries [18], to drinking water safety, energy and net-zero requirements, and economic regulation (i.e., tariff setting). Even in the high-income and high institutional capacity context of the GCC, the potential for regulation to enhance the sustainability of desalination, and notably brine management, remains underexplored [19].

2.3. Social dynamics and perception

Research on the social dynamics and perception of desalination is growing [20]; however, several policy-relevant questions remain unanswered. These include: (i) how does desalination affect water demand and supply-demand cycles? (ii) how can the poor and vulnerable benefit from desalination? and (iii) what factors influence social perception of desalination? These three questions are unpacked below.

The expansion of desalination might have the counterintuitive effect of enabling higher water demands, thus offsetting any initial benefits of desalination in reducing water shortages. This effect, known to economists as the paradox of supply and to engineers as the supply-demand cycle, arises when new water supply infrastructure is built without demand-side interventions to signal the cost of production and pumping – not just energy-related but also material and environmental – to water users. This gives users a false sense of abundance, enabling greater demands than initially projected and thus offsetting the benefits of the new infrastructure [21]. This effect is at play in the hyper-arid GCC countries, where large investments in desalination are accompanied by some of the highest levels of per capita water consumption in the world [22]. Policymakers should pay attention to this perverse outcome that might affect the long-term sustainability of desalination, and research should provide recommendations on opportunities to avoid it.

Social scientists also suggest that the benefits of desalination usually accrue to economically and socially better off water users who can afford

to pay for desalinated water [23]. It is important to identify ways to extend the benefits of desalination to disadvantaged communities, including in remote rural areas where brackish groundwater might be available. Political ecologists have identified the risks of overlooking these dynamics, and they have rightly called for more research on the equity dimensions of desalination [24].

Research also needs to better understand and predict public perception of desalination. Reviews of the socio-political factors impacting the adoption of desalination identify public perception as crucial in determining the success or failure of desalination projects [16]. Project developers are aware of the risk that public opposition poses to infrastructure projects. Despite this awareness, there is still very limited research addressing this issue [25]. Lack of research around perception undermines efforts to transparently identify and communicate the environmental impacts of desalination projects. Despite the availability of mitigation measures and the accepted view among desalination experts that the environmental impacts of desalination on marine ecosystems can be managed [26], public perception around the environmental impacts of desalination is still largely negative. For example, environmental damage was among the key aspects cited by stakeholders opposing the Huntington Beach desalination plant in Southern California, with the project not receiving approval and being abandoned in 2022 [27].

A focus on public perception raises fundamental questions for desalination research which are still largely unanswered. For example: what are predictors of local support or opposition to desalination projects? Does public attitude towards desalination change over time and depending on the location of the facility? What are the preferences and choices of communities when it comes to alternative options to achieve water supply resilience? What are effective and transparent communication strategies to increase public understanding of desalination, including of its environmental impacts?

Answering questions on public perception requires pursuing at least two avenues of research. The first one requires more development and application of non-market valuation studies to elicit user preferences for desalination. While there is a vast literature using non-market valuation to study household preferences and willingness to pay for improved drinking water services and also for protection of coastal resources, only a handful of studies focus on desalination [28–30]. The application of these methods helps understand the social feasibility of adopting desalination and can also inform the design of potential pricing mechanisms.

The second one requires scaling-up the use of social science methods and frameworks that can be applied to understanding societal technology choices, such as cultural theory [31,32] and risk perception theory [33]. Local perceptions of water scarcity, concerns around environmental impacts, and preferences for alternative water supply options are influenced by several factors (e.g., concern around privatization of water supplies; preference for 'natural' water), and do not typically respond to rational engineering and economic arguments alone.

Perceptions can prevent the public from realizing the full potential of desalination. For example, technologies that remove salt can also remove other contaminants, meaning that water agencies might end-up deploying desalination to comply with increasingly stringent drinking water quality standards even when source waters are not saline but heavily contaminated surface or groundwater. A small but growing number of publications in the field of desalination shows the potential for social science approaches to shed light on local perceptions, and the social and psychological variables that influence them [34–36]. For example, application of risk perception theory to case studies in Mexico and Chile shows that, despite desalination investments, consumers still tend to prefer bottled water because of distrust in public water supplies [37].

2.4. Strategic planning

Like all large-scale water infrastructure, desalination investments are

poised to be affected by mega-project risks, such as underestimated costs, long-term uncertainty in demands, and undervalued social and environmental impacts. Reviews of existing desalination infrastructure costing methodologies highlight the lack of harmonized and transparent approaches for mitigating these risks, with most policymakers relying on black box type tools that do not provide enough details on the sensitivities of plant design and costs – and therefore convenience of desalination vis-à-vis other supply sources – to a range of uncertainties [38].

Researchers should provide investment planning frameworks for objective assessments of the rationale for deploying desalination and to explore optimal placement and characteristics of desalination infrastructure, considering alternative configurations, impacts on the environment and robustness to uncertainty. Advances in strategic planning grounded in decision-making under deep uncertainty can help decision-makers transparently explore how the economic case for desalination changes under multiple climate, environmental management, social and cost scenarios, and identify strategies that reduce project risks [39]. Adoption of these frameworks would reduce the risk of idle plants and would also enable evidence-based discussions with the public regarding the need for desalination and options to manage its environmental impacts. It would also help decision-makers consider alternative approaches for delivery of desalinated water, which might include decentralized solutions phased over multiple construction stages [40]. In jurisdictions where water planning regulations already require strategic planning to justify desalination projects, such as California, researchers could examine project documents, economic analyses, and environmental impact reports to compare methodologies and identify opportunities to improve and standardize planning methodologies for individual desalination projects as well as national desalination strategies.

2.5. Financial sustainability

Policymakers should also be concerned about the impact of desalination investments on the overall financial sustainability of the water sector. This is particularly the case in low- and middle-income countries, where water service providers rarely achieve cost recovery and where the water tariff increases required to cover the costs of desalination might face backlash and might affect the poor more than the rich. In Jordan, where desalination is a major component of the country's water strategy, water tariffs increases often result in public backlash [41]. In Egypt, the World Bank estimates that operational expenditures in desalination increased operating costs for the state-owned water and wastewater company by 25 % [42]. Hence, research is urgently needed to advise policymakers on the financial impacts of desalination, and on approaches to sustainably finance this technology through equitable tariffs, budget transfers and international aid.

Under this area, research is needed to identify sustainable and equitable financing models for desalination. Research questions include: what are sustainable approaches for tariff setting and fiscal planning for large-scale desalination plants? And for decentralized systems? What are available financing models and what are lessons learned in their application? Given that the public sector is typically heavily involved in the planning and financing of desalination projects [43], research on financing could help reduce the impact of desalination on public budgeting, for example by identifying efficient procurement mechanisms, finance structuring, and risk allocation models. Research on the financial aspects of desalination can help identify financing strategies that reduce the burden of desalination infrastructure on already growing public debt, especially in the Global South.

3. Desalination research needs to embrace open science principles

To expand desalination research in the areas above, particular attention needs to be paid to open data. At present, most data on

desalination (and also wastewater reuse) infrastructure globally is provided through proprietary databases and software built with confidential methodologies. While this type of advanced services is clearly beneficial to the water industry and needs to continue, the research community needs to step up its game to create open-access databases to help policymakers and the public navigate information on desalination. This would include data on institutional and regulatory approaches, desalination plant characteristics (e.g., technology type, costs, installed vs utilized capacity, and water quality), results from environmental impact assessments, and social aspects (e.g., population served, social dynamics), among others. The Open Membrane Database [44] demonstrates the benefits that open-access data gives to desalination researchers and practitioners, and this open science approach should be adopted to increase access to other aspects of desalination research beyond membranes.

As with most technologies, many advances in desalination, including reverse osmosis, have their roots in publicly funded research and development programs [45], such as the ongoing National Alliance for Water Innovation (NAWI), funded by the United States Department of Energy [46]. As research funders across the world scale-up their support to desalination, they also need to promote the uptake of open science principles. This will ensure that the public benefits of this technology are optimized and fairly distributed and will also incentivize the private sector to join discussions about sustainably deploying desalination and promoting open desalination science.

CRedit authorship contribution statement

Term	Edoardo Borgomeo
Conceptualization	*
Methodology / Study design	*
Software	*
Validation	*
Formal analysis	*
Investigation	*
Resources	*
Data curation	*
Writing – original draft	*
Writing – review and editing	*
Visualization	*
Supervision	*
Project administration	*
Funding acquisition	*

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.

Data availability

No data was used for the research described in the article.

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References

- [1] International Desalination, Reuse Association, Impact in numbers created through Desalination and Water Reuse. <https://idadesal.org/>. (Accessed 5 March 2024).
- [2] Estimate based on AQUASTAT data for desalinated water produced and municipal withdrawals (accessed 5 March 2024).
- [3] J. Eke, A. Yusuf, A. Giwa, A. Sodiq, The global status of desalination: an assessment of current desalination technologies, plants and capacity, *Desalination* 495 (2020) 114633.
- [4] H. Van Der Vegt, I. Iliev, Q. Tannock, S. Helm, Patent Landscape Report on Desalination Technologies and Use of Alternative Energies for Desalination, World Intellectual Property Organization, Geneva, 2011.
- [5] E. Jones, M. Qadir, M.T. van Vliet, V. Smakhtin, S.M. Kang, The state of desalination and brine production: a global outlook, *Sci. Total Environ.* 657 (2019) 1343–1356.
- [6] M.S. Mauter, P.S. Fiske, Desalination for a circular water economy, *Energ. Environ. Sci.* 13 (10) (2020) 3180–3184.
- [7] S.K. Patel, C.L. Ritt, A. Deshmukh, Z. Wang, M. Qin, R. Epsztein, M. Elimelech, The relative insignificance of advanced materials in enhancing the energy efficiency of desalination technologies, *Energ. Environ. Sci.* 13 (6) (2020) 1694–1710.
- [8] J.M. Allwood, Unrealistic techno-optimism is holding back progress on resource efficiency, *Nat. Mater.* 17 (12) (2018) 1050–1051.
- [9] B. Lee, L. Wang, Z. Wang, N.J. Cooper, M. Elimelech, Directing the research agenda on water and energy technologies with process and economic analysis, *Energ. Environ. Sci.* 16 (3) (2023) 714–722.
- [10] J.R. McCutcheon, M.S. Mauter, Fixing the desalination membrane pipeline, *Science* 380 (6642) (2023) 242–244.
- [11] M.J. Eckelman, M.S. Mauter, J.A. Isaacs, M. Elimelech, New perspectives on nanomaterial aquatic ecotoxicity: production impacts exceed direct exposure impacts for carbon nanotubes, *Environ. Sci. Technol.* 46 (5) (2012) 2902–2910.
- [12] International Energy Agency, Clean Energy Can Help to Ease the Water Crisis, International Energy Agency, Paris, 2023.
- [13] R.M. DuChanois, N.J. Cooper, B. Lee, S.K. Patel, L. Mazurowski, T.E. Graedel, M. Elimelech, Prospects of metal recovery from wastewater and brine, *Nat. Water* 1 (1) (2023) 37–46.
- [14] K. Lee, W. Jepson, Environmental impact of desalination: a systematic review of life cycle assessment, *Desalination* 509 (2021) 115066.
- [15] J. Williams, Desalination in the 21st century: a critical review of trends and debates, *Water Altern.* 15 (2) (2022) 193–217.
- [16] Y. Ibrahim, R.A. Ismail, A. Ogungbenro, T. Pankratz, F. Banat, H.A. Arafat, The sociopolitical factors impacting the adoption and proliferation of desalination: a critical review, *Desalination* 498 (2021) 114798.
- [17] Arab News, 'Saudi Arabia transforms SWCC into water authority to boost security', *Arab News*, 8 May 2024, Available from: <https://arab.news/yq9dv>, 2024. (Accessed 17 June 2024).
- [18] I. Sola, C.A. Sáez, J.L. Sánchez-Lizaso, Evaluating environmental and socio-economic requirements for improving desalination development, *J. Clean. Prod.* 324 (2021) 129296.
- [19] M. Al-Saidi, A.K. Ellermann, M.F. Fittkow, T.R. Perillieux, I. Saadaoui, R. Ben-Hamadou, The perils of building big: desalination sustainability and brine regulation in the Arab gulf countries, *Water Resour. Ind.* 100259 (2024).
- [20] B.F. O'Neill, J. Williams, Progress in understanding the social dimensions of desalination and future research directions, *Glob. Environ. Chang.* 87 (2024) 102877.
- [21] G. Di Baldassarre, N. Wanders, A. AghaKouchak, L. Kuil, S. Rangelcroft, T. I. Veldkamp, A.F. Van Loon, Water shortages worsened by reservoir effects, *Nat. Sustain.* 1 (11) (2018) 617–622.
- [22] A. Jägerskog, S. Barghouti, Advancing Knowledge of the Water-energy Nexus in the GCC Countries, World Bank, Washington, D.C., 2022.
- [23] J. McEvoy, M. Wilder, Discourse and desalination: potential impacts of proposed climate change adaptation interventions in the Arizona–Sonora border region, *Glob. Environ. Chang.* 22 (2) (2012) 353–363.
- [24] B.F. O'Neill, J. Williams, Developments in desalination need a social sciences perspective, *Nat. Water* 1 (12) (2023) 994–995.
- [25] B. Haddad, N. Heck, A. Paytan, D. Potts, Social issues and public acceptance of seawater desalination plants, in: *Sustainable Desalination Handbook*, Butterworth-Heinemann, 2018, pp. 505–525.
- [26] M. Elimelech, W.A. Phillip, The future of seawater desalination: energy, technology, and the environment, *Science* 333 (6043) (2011) 712–717.
- [27] E.J. Patel, Debating desalination: stakeholder participation and decision-making in Southern California, *Water Altern.* 16 (2) (2023) 509–540.
- [28] N. Becker, D. Lavee, T. Tavor, Desalinate or divert? Coastal non-market values as a decision tool for an integrated water management policy: the case of the Jordan River basin, *Ocean Coast. Manag.* 64 (2012) 27–36.
- [29] H. Ben Brahim-Neji, S. Del Saz-Salazar, A. Besrou, F. González-Gómez, Estimating willingness to pay for desalinated seawater: the case of Djerba Island, Tunisia, *Int. J. Water Resour. Dev.* 35 (1) (2019) 126–144.
- [30] W.F. Vásquez, N. Raheem, D. Quiroga, V. Ochoa-Herrera, Valuing improved water services and negative environmental externalities from seawater desalination technology: a choice experiment from the Galápagos, *J. Environ. Manage.* 304 (2022) 114204.
- [31] M. Douglas, A. Wildavsky, Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers, Univ of California Press, Berkeley and Los Angeles, 1983.
- [32] J. Koehler, S. Rayner, J. Katuva, P. Thomson, R. Hope, A cultural theory of drinking water risks, values and institutional change, *Glob. Environ. Chang.* 50 (2018) 268–277.
- [33] P. Slovic, Perceived risk, trust, and democracy, *Risk Anal.* 13 (6) (1993) 675–682.
- [34] N. Heck, A. Paytan, D.C. Potts, B. Haddad, Predictors of local support for a seawater desalination plant in a small coastal community, *Environ. Sci. Policy* 66 (2016) 101–111.
- [35] N. Heck, A. Paytan, D.C. Potts, B. Haddad, Coastal residents' literacy about seawater desalination and its impacts on marine ecosystems in California, *Mar. Policy* 68 (2016) 178–186.
- [36] T.K. Liu, J.A. Ye, H.Y. Sheu, Exploring the social acceptability for the desalination plant project: perceptions from the stakeholders, *Desalination* 532 (2022) 115757.
- [37] M.C. Fragkou, J. McEvoy, Trust matters: why augmenting water supplies via desalination may not overcome perceptual water scarcity, *Desalination* 397 (2016) 1–8.
- [38] N. Ghaffour, T.M. Missimer, G.L. Amy, Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability, *Desalination* 309 (2013) 197–207.
- [39] E.H. Beh, F. Zheng, G.C. Dandy, H.R. Maier, Z. Kapelan, Robust optimization of water infrastructure planning under deep uncertainty using metamodels, *Environ. Model. Software* 93 (2017) 92–105.
- [40] M.P. Shahabi, A. McHugh, M. Anda, G. Ho, A framework for planning sustainable seawater desalination water supply, *Sci. Total Environ.* 575 (2017) 826–835.
- [41] Civil Society Knowledge Centre, Protesters stage a sit-in in Ma'an after the Friday prayer to protest against the privatisation of Ma'an water company and its fusion with Aqaba water company and to protest against the general increase in prices. The Centre for Social Sciences Research and Action. 17 June 2022, Available from: <https://civilsociety-centre.org/content/protesters-stage-sit-maan-after-friday-prayer-protest-against-privatisation-maan-water-3>, 2022. (Accessed 17 June 2024).
- [42] D. de Waal, S. Khemani, A. Barone, E. Borgomeo, The Economics of Water Scarcity in the Middle East and North Africa: Institutional Solutions, World Bank, Washington, D.C., 2023.
- [43] B. Montano, M. García-López, J. Melgarejo, The financial and legal feasibility of a desalination project, *Desalination* 517 (2021) 115238.
- [44] C.L. Ritt, T. Stassin, D.M. Davenport, R.M. DuChanois, I. Nulenz, Z. Yang, R. Verbeke, The open membrane database: synthesis–structure–performance relationships of reverse osmosis membranes, *J. Membr. Sci.* 641 (2022) 119927.
- [45] H. Cooley, P.H. Gleick, G. Wolff, G., Desalination, with a Grain of Salt. A California Perspective, Pacific Institute for Studies in Development, Environment and Security, Oakland, 2006.
- [46] David Sedlak, Meagan Mauter, Jordan Macknick, Jennifer Stokes-Draut, Peter Fiske, Deborah Agarwal, Thomas Borch, Richard Breckenridge, Tzahi Cath, Shankar Chellam, Amy Childress, Dion D. Dionysiou, Daniel Giammar, Eric Hoek, Sunny Jiang, Lynn Katz, Jaehong Kim, Robert Kostecki, Jeffrey McCutcheon, Yarom Polsky, Zachary Stoll, Pei Xu, National Alliance for Water Innovation (NAWI) Master Technology Roadmap. United States, 2021, <https://doi.org/10.2172/1818076>.