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Complementarity of renewable energy generation and its storage in desalination processes

Michał Kaczmarczyk[a,*], Michał Bodzek[b], Barbara Tomaszewska[a]

[a] *Faculty of Geology, Geophysics and Environmental Protection, Department of Energy Resources, AGH University of Krakow, Mickiewicza 30 Av., 30-059 Kraków, Poland, emails: mkz@agh.edu.pl (M. Kaczmarczyk), bts@agh,edu.pl (B. Tomaszewska)*
[b] *Institute of Environmental Engineering, Polish Academy of Sciences, 41-819 Zabrze, M. Skłodowskiej-Curie 34 Street, Poland, email: michal.bodzek@ipispan.edu.pl (M. Bodzek)*

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ABSTRACT

Addressing the variability of renewable energy sources (RES) remains a fundamental challenge in the establishment of stable and sustainable energy grids. This review emphasises the significance of integrating various RES, such as solar, wind, and hydropower, to mitigate intermittency. Technological advances, including energy storage solutions and smart grid systems, play crucial roles in balancing energy distribution. Cooperative game theory and interregional collaboration show potential for optimising multi-energy complementarity. In particular, the integration of large-scale energy storage technologies, especially in desalination plants, demonstrates promising cost reduction and emission reduction. Furthermore, the strategic selection of energy storage technologies aligned with specific RES characteristics proves essential to achieve a stable and efficient energy mix. These insights provide a roadmap for a more sustainable, reliable energy system supported by renewable energy sources.

Keywords: Desalination; Renewable energy sources; Energy storage

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1. Introduction

Water desalination is an energy-intensive process that is used to produce fresh water, mainly from sea or brackish water, but also from deep water, including geothermal water. It is estimated that 30 kg of fossil fuel are needed to produce 1 m^3 of fresh water using desalination. However, the exploitation and refining of fossil fuels, as well as energy generation, not only increase water demand due to global warming, but also pollute water and air sources [1–4].

Desalination will also a process that is and will be used in the future, resulting directly from the demand for water as a rare resource necessary for human life [5]. This concerns use for consumption and food preparation, use for hygienic and sanitary purposes, industrial, agricultural, energy and recreational purposes. It can probably be summarised in one sentence that water is a fundamental element of life on Earth and plays an extremely important role in every area of human functioning. Unfortunately, water sources continue to be depleted and contaminated, among others, as a result of improper management, agricultural activities, and uncontrolled release of sewage from industrial plants to recipients [6,7]. Consequently, this determines the availability of water in particular areas of the world, which is presented in global terms in Fig. 1.

To optimise energy demand and reduce the costs of desalination processes, several techniques and technologies are currently being used, the main direction of which is the integration of desalination processes with renewable energy systems [9–11]. This integration is carried out to fully or partially meet the energy needs of desalination plants, and the use of renewable energy sources (RES)

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* Corresponding author.

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to power desalination processes can help reduce operating costs and reduce dependence on conventional energy sources [12,13]. Renewable energy sources play a fundamental role in the energy mix, which should be built in a balanced and diversified manner. At the same time, they constitute a basic response to the challenges related to reducing greenhouse gas emissions and ensuring sustainable development. The scientific literature increasingly emphasises the importance of renewable energy sources in the context of energy transformation and the search for alternative, more ecological energy sources. Their use not only in the power industry, but also in the field of water desalination indicates their versatility and potential to support ecological processes and sustainable development, which is an important research and practical topic [12,14–16].

According to Jones et al. [17] and Ahmed et al. [18], membrane water treatment systems currently dominate desalination processes. Their share is estimated at 69%–73%, and the most common solution is reverse osmosis (RO). The rest are thermal techniques (approx. 27%–31%). Although in theory renewable energy and desalination are actually different technologies, in practice they can work together in an energy-saving, economic and ecological way. The cooperation of these technologies with desalination processes is visible on an increasingly larger scale, with the use of solar energy and wind energy dominating [12,13]. This aspect was drawn up, among others, Ali et al. [19], adding, however, that it is possible that geothermal energy will also be used to a greater extent in the future than before, which is due to the stable nature of this energy source [16,20]. In this context, it is worth paying attention to hybrid installations, which are characterised by high complementarity and stability of energy generation, especially in combination with energy storage [21].

The article focusses on the aspect of the complementarity of energy supply generated using renewable energy sources for desalination installations. The literature on this issue was reviewed, strengths and weaknesses were indicated from the technological, ecological, and economic point of view, and energy storage possibilities were evaluated, as well as optimisation processes on the desalination plant side. The main determinant was adapting the production of fresh water to the demand of consumers, based on the possible maximum use of renewable energy technologies.

2. Complementarity of energy generation from RES

As is commonly known, renewable energy sources are characterised by the specific nature of their work, which in most cases involves a strong correlation with the prevailing meteorological conditions at a given time. These technologies include solar energy and wind energy, which are most commonly used as energy support for water desalination installations [12].

To address intermittency and complementarity issues, integrating different renewable energy sources into a well-designed energy system can help create a more stable and reliable energy supply [22]. This integration often includes advanced forecasting techniques, energy storage solutions and a smart grid system. These are methods that can effectively balance and distribute energy from various sources. Developing a strategy to manage this complementarity is crucial to creating a more reliable and stable grid based on renewable energy. This includes advanced planning, technology and infrastructure to maximize the overall efficiency and reliability of renewable energy generation.

As Jurasz et al. [23] noticed, global and regional trends had previously suggested that the increasing energy demand would soon be met by the widespread use of renewable energy sources, despite their notable spatial and temporal variations. Addressing the inconsistency between supply and demand in renewable energy, common proposals included hybrid power stations (such as wind-solar, solar-hydro, or combined sources) due to their mutually complementary aspects. Jurasz et al. [23] provided an extensive review of

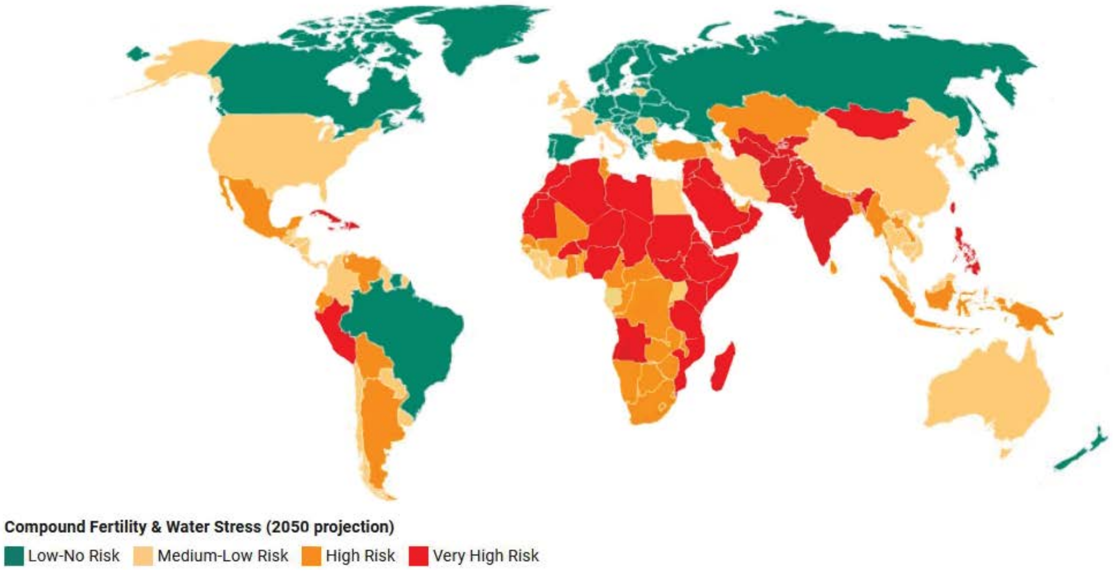

Fig. 1. Global per capita water availability and future population growth [8].

previous studies that explored, analysed, and applied the temporal, spatial, and spatiotemporal complementarity between different renewable energy sources. The review had highlighted the absence of standardised methodologies in assessing energetic complementarity in regions such as Africa and Asia, making direct comparisons challenging. It emphasised the necessity to expand complementarity metrics to consider factors beyond simple complementarity, such as the relationship between the capacity factor and the cost of energy. The study had urged for a broader understanding of complementarity's practical applications, integration into various models, comparative evaluations based on consistent criteria, inclusion of diverse renewable sources, consideration of future climate models, and a focus on distinguishing between measurement-based and model-based data to grasp complementarity dynamics.

The prevalent soft coupling of water and power system models had limitations in capturing the dynamic interdependencies between grid status and operational decisions at the water system level. To address this gap, Koh et al. [24] introduced a novel numerical modelling framework, hard-coupling a multi-reservoir system model and a power system model, enabling two-way feedback mechanisms and contingent operational decisions based on both water and energy system states. The framework was evaluated in the Cambodian grid under various configurations, demonstrating that hard coupling of the systems reduced operating costs and CO_2 emissions while improving renewable integration, with substantial savings in costs and emissions under favourable conditions. The spatiotemporal analysis highlighted the significance of monsoon timing and grid component interconnections in shaping system responses to this hard coupling, offering a valuable modelling tool for testing solutions to enhance water-energy system performance.

The review prepared by Pedruzzi et al. [25] aimed to explore various methodologies, data sources, and techniques for mapping solar and wind energy potential, as well as their complementarity, incorporating significant research and patent findings. Various mapping methodologies ranging from the global to microscale level, using observed data from various monitoring stations, satellite data, and meteorological modeling. A case study was presented to illustrate the methodology used to map solar and wind potential alongside their complementarity.

In pursuit of a diversified and sustainable energy mix, addressing the challenge of establishing effective cooperative mechanisms among various power sources was crucial for maximising economic benefits from multi-energy complementarity. Using cooperative game theory, Han et al. [26] investigated the joint offering and operation of complementary power sources such as wind, thermal, and pumped storage in the electricity spot market. The study demonstrated that these alliances effectively reduced imbalance power and increased renewable energy absorption, especially the wind-thermal-pumped storage alliance, which significantly reduced carbon emissions, offering valuable insights for stakeholders aiming to achieve effective multi-energy complementarity. As Sun et al. [27] stated, intermittent renewable sources played a pivotal role in the global push for carbon neutrality, compelling coastal nations to integrate offshore energy into on-shore sources due to land scarcity and environmental concerns. The lack of understanding of the synergy between on-shore and offshore energy hindered collaborative development. A study introduced a modelling framework examining the potential of solar and wind energy in China, highlighting high onshore potential and highlighting significant complementarity effects in specific regions. These findings stressed the importance of inter-regional resource cooperation, which helps in integrating renewable energy across the country.

Among the latest studies, the review of which is presented below, references to specific locations dominate. This is completely understandable from the point of view of achieving complementarity in energy production. Luz and Moura [28] focused on improving the integration of renewable energy by leveraging complementarity and flexibility options, such as demand management and batteries, to compensate for demand generation disparities. It presented a non-linear multi-objective problem aimed at maximising complementarity, minimizing total expansion costs, optimising battery integration, and managing various factors for a sustainable energy scenario. For the case of Brazil, the model proposed a scenario that ensured three consecutive years of extreme drought in 2050 through a strategic combination of 10% solar energy, 43% wind energy, 4.3% biomass, 41% hydropower, and 1.7% demand-side management without the need for new large reservoirs.

In the analysis of de Oliveira Costa Souza Rosa et al. [29], they indicated that the use of intermittent renewable energy sources (IRES) in traditional energy systems required careful planning due to their variability that affects both reliability and generation costs. The study assessed complementarity among multiple IRES and aimed to optimise their mix to counteract the variability from independent sources. Factor analysis was proposed to group similar data, presenting two reproducible optimisation models capable of accommodating various decision variables. Focused on the southern and central-western regions of Brazil, the research included global solar radiation, wind speed, and IRES of river inflow, revealing low correlation between these IRES, indicating potential complementarity. Despite distinct objectives, both optimisation models suggested a photovoltaic generation share of around 50% in the IRES mix, providing guidance for expanding renewable energy adoption in electricity generation within the region.

The annual and interannual complementarities of RES have been analysed by Henao et al. [30]. They examined the Colombian power sector's heavy reliance on hydroelectricity, which rendered it vulnerable to dry seasons and droughts caused by the El Niño-Southern Oscillation (ENSO). It investigated the complementarity between solar, wind, and hydropower resources in various geographic locations and different seasons and ENSO stages. The findings revealed that solar and wind resources, particularly in the Caribbean Coast and Central Andes regions, complemented the hydropower sector during dry seasons and both warm and cold phases of ENSO, highlighting the variability based on sources, locations, and seasonal and ENSO changes. This study provided insights into renewable behaviour and proposed an alternative approach to future power system expansions.

Gonzalez-Salazar and Poganietz [31] proposed a model that examined a combined approach of wind, solar and hydropower in Argentina, Brazil, Colombia, Mexico and Venezuela. The results revealed significant reductions in hydropower generation during the ENSO drought phases, especially impacting Colombia and Venezuela, while a combination of hydropower with variable renewable energy (VRE) helped mitigate power deficits, with Argentina showcasing the most effective resource combination, followed by Brazil and Mexico. These findings provided valuable information for the future planning of regional transmission grids in the region. The study by Huang et al. [32] emphasized the importance of hydropower regulation in managing fluctuations in wind and photovoltaic power to meet load demands. Addressing this, the research introduced a method of assessing the complementarity of hydropower systems tailored for hybrid energy systems, factoring in power grid load. This method proposed two assessment indicators, focussing on the probability that the power output of the hybrid energy system will be aligned with load demands. The evaluation, considering varied capacities of wind and photovoltaic plants, conducted at the Guandi wind-solar-hydro hybrid power plant in China's Yalong River, revealed the superiority of this approach over traditional methods and highlighted the importance of hydropower regulation, leading to a more accurate assessment of system complementarity and a reduction in power curtailment rates by approximately 20%. The findings contributed to a novel assessment method for hybrid renewable energy systems.

Delbeke et al. [33] recognised the combination of offshore wind and floating photovoltaics (PV) as a significant opportunity to expand renewable energy sources at sea. Optimising the grid connections for marine renewables was crucial due to their considerable impact on costs. The temporal complementarity of wind and solar resources was crucial to reducing grid costs per kWh, particularly on various timescales. When investigating the Belgian North Sea, this study used solar wind complementarity until 2100. It revealed substantial complementarity on monthly and weekly scales, extending to shorter timescales despite the effects of climate change. This research identified solar-wind hybridisation as a sustainable approach to lower offshore grid costs per kWh. Wind and solar resources have also been analyzed in Kenya by Muchiri et al. [34].

In a study conducted in Machakos, the investigation focused on the complementarity to enhance hybrid renewable energy systems in the region. The research, carried out in a rural-urban area, aimed to leverage the potential of wind and solar energy to create flexible and reliable energy systems. Wind distribution analysis revealed parameters that characterise the wind resource for energy generation, indicating a positively skewed profile and a wind power density of 17 W/m². Additionally, the study reported an annual solar insolation of 2130 kWh/m², providing valuable information for energy planning and the development of more reliable renewable energy systems for microgrids and utility applications under constantly changing conditions. Costoya et al. [35] emphasised the importance of understanding complementarity between wind and solar power amidst climate variations. Using a multi-model ensemble, the study examined wind and solar PV complementarity in North America from 2025 to 2054. It revealed reduced spatial variability in power and identified optimal regions for combining wind and solar energy, including coastal areas in the Gulf of Mexico, parts of the Caribbean Sea, the US-Canada border, northern regions such as Alaska, and lower complementarity in Mexico.

Finally Pennock et al. [36] investigated a very interesting topic of wave and tidal energy. They identified it as offering significant advantages to power systems heavily dependent on variable renewable sources, particularly when combined with wind and solar photovoltaics, thus enhancing the overall reliability of renewable energy. In this study, ten metrics were employed to evaluate the temporal complementarity and supply-demand balance within Great Britain's energy mix, utilising historical resource data and hydrodynamic models to generate wave and tidal energy profiles. The findings revealed that the integration of wave and tidal energy contributed to a more consistent and available renewable energy mix, especially during periods of peak demand and when wind and solar energy were not available. Regional case studies also demonstrated improved supply-demand matching, reduced energy shortages and excesses, and the potential to alleviate transmission congestion in specific areas within Great Britain. The implications were discussed in terms of the operation of the wholesale market operation, system and security.

Based on real data, the problem of complementarity of energy production using renewable energy sources is presented in Fig. 2 in relation to the production of electricity from wind and solar energy in January and July 2023, using the example of the Polish power grids, taking into account the freshwater demand during day [37,38].

The data presented in the graph clearly illustrate the situation facing operators of RES installations, regardless of meteorological conditions. This is due to the lack of stability of energy production, which, unfortunately, becomes visible in periods of increased demand for it. These are the morning and evening hours, marked with purple lines on the chart. Of course, these data can be presented more precisely, referring to a larger number of days, months or years. Changing meteorological conditions and variable water demand should be taken into account depending on the season or day of the week. It is true that such an analysis would be more complete. However, it does not change the fact that when the Sun sets, photovoltaic installations do not produce energy. It would also not change the general trend that wind speeds are higher at night than during the day. This dependence, even in the case of hybrid systems, in which the amount of energy generated in various technologies naturally compensates, makes it necessary to look for technological support outside the renewable energy industry. Energy storage systems and desalinated/treated water are a sure answer to this need.

The key aspects affecting the achievement of complementarity of energy production and, in the analysed case, supplying energy in a stable and continuous manner to the desalination installation are presented in Table 1.

When these methods together, the challenge of complementarity in renewable energy production can be addressed, creating a more reliable and sustainable energy system while reducing dependence on fossil fuels.

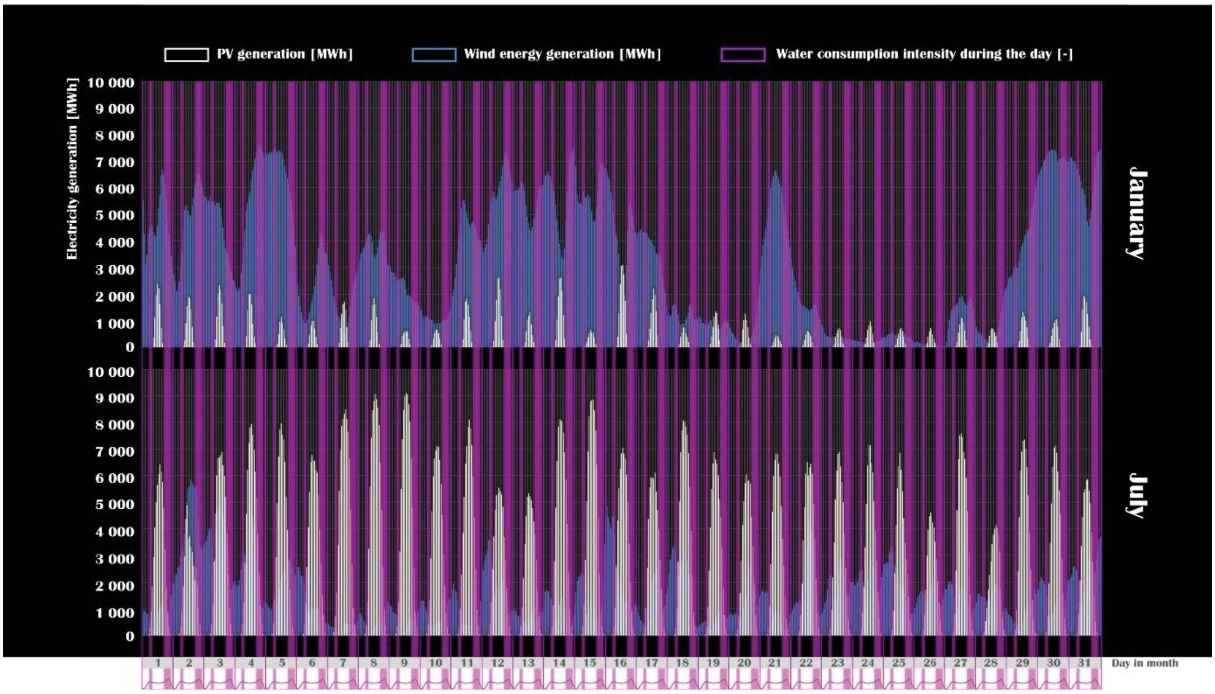

Fig. 2. Production of electricity from wind and solar energy in January and July 2023, on the example of Polish Power Grids, taking into account the daily water demand profile.

Table 1
Key aspects influencing the achievement of complementarity of energy production from renewable energy sources

Diversification and hybrid combination of renewable energy sources	Energy storage	Artificial intelligence	Coordinated policies and incentives
Mapping, resource assessment and geospatial data analysis	Chemical and electrochemical energy storage systems	Monitoring and data collection	Policy analysis and regulatory framework
Analysis of synergy and complementarity of resources	Thermal energy storage systems	Machine learning and predictive analytics	Economic modelling and cost-benefit analysis
System modeling and optimization	Mechanical energy storage technologies	Weather and climate modeling	Technological standards and certification
Estimating and forecasting energy yield	Grid-scale storage and distributed systems	Probabilistic forecasting and uncertainty analysis	Market mechanisms and auction design
Decentralized control and distributed energy resources	Control systems and intelligent energy management	Network automation and control systems	Socio-economic impact assessment
Network interconnection and planning	Economic viability and integration strategies	Load shifting and peak load management	Incentive structures and feed-in tariffs
Control and integration strategies	Life cycle analysis and sustainability	Demand-side response algorithms	Financing research and development
Testing, validation and continuous improvement		Behavioral economics and consumer behavior modeling	International cooperation and knowledge sharing
Life cycle analysis and sustainability			Dynamic pricing strategies and motivational mechanisms

The use of renewable energy sources is the topic of most discussion, but it is worth remembering about other possibilities of optimizing the desalination installation, which will also indirectly affect the operation of the renewable energy system. An example would be the use of energy recovery devices in the desalination process, such as pressure exchangers or isobaric chambers, which help recover energy from the brine stream to increase the pressure of the incoming feedwater. This process significantly reduces the overall energy requirement of the desalination process [39,40].

3. Role of the energy storage systems

In the case of supporting desalination processes, attention should be focused on large-scale energy storage, with a distinction between electricity storage and heat storage. In addition to storing the energy itself, an extremely important factor is the possibility of storing treated water, which allows for broader optimisation taking into account a larger number of variables.

The latest research in the field of energy storage and renewable energy sources was presented, among others, by Shar et al. [41]. As they stated, many arid and semi-arid regions around the world had been facing an increase in freshwater scarcity, necessitating an increased reliance on seawater desalination to supplement existing freshwater resources. Seawater reverse osmosis (RO) had been a predominant technology due to its efficiency and lower costs, but the challenge remained in the reliance on fossil fuels for the necessary energy. A study had introduced a mathematical model aimed at determining the most cost-effective energy mix and storage for large-scale seawater desalination plants, examining the feasibility of integrating renewable energy sources. Results had suggested that while renewable sources alone could not fully meet constant energy demands, intermittent operation and a strategic mix of energy sources had substantially reduced costs and emissions, providing a more adaptive approach to decarbonising desalination processes.

Ramirez-Ruiz et al. [42] developed a design approach for renewable-powered desalination in Colombia's Guajira Peninsula, demonstrating high reliability and lower costs compared to fossil fuels. It noted the variability in efficiency between PV-only and wind/hybrid systems, which reduced more than 150 tons of CO_2 emissions annually. Karaca et al. [43] introduced an integrated solar and wind energy system designed for a sustainable community, potentially in Antigua and Barbuda, replacing imported heavy fuel oil with renewable resources and utilising a compressed air energy storage (CAES) system for excess power. This system was engineered to produce 365 GWh of electrical energy annually, generate 376 tons of fresh water, and potentially fuel 168 pneumatic vehicles daily, with overall energetic and exergetic efficiencies evaluated at 62.8% and 48.5%, respectively.

Liu et al. [44] introduced a method to optimise a coastal hybrid renewable energy system (HRES) utilizing the characteristics of virtual energy storage (VES) in reverse osmosis desalination plants to accommodate renewable energy generation. This optimisation aimed to minimize the system's total cost, mitigate end-user satisfaction loss from demand side management (DSM), and stabilise tie-line power fluctuation, employing a modified nondominated sorting genetic algorithm-III (NSGA-III) variant called MINSGA-III. The method was validated through various case studies, which confirmed its effectiveness and the positive impact of both the DSM measures and the VES approach on the modelling of the system. Equally interesting research had been presented by Gevez and Dincer [45], who introduced an integrated system that provided five essential commodities, freshwater, space heating, hot water, power, and hydrogen for a community. It incorporated molten salt heat storage, a magnesium-chlorine (Mg-Cl) thermochemical cycle for hydrogen production, and a multieffect desalination plant to meet freshwater needs. Using a solar power tower and an organic Rankine cycle (ORC) for heat recovery, the system balanced energy demand and supply using molten salt storage during periods of absence of solar irradiation, targeting residential needs. Thermodynamic analyses assessed the system's efficiencies in various conditions, particularly in Vancouver, Canada, revealing energetic and exergetic efficiencies of 45.45% and 52.32%, respectively, with a total exergy destruction rate of 163.98 MW.

Outside the context of the desalination plant, lessons for future activities may come directly from research on the cooperation of renewable energy sources with energy storage systems. Wang et al. [46] extensively examined various energy storage technologies and their capacity to manage the uncertainty and fluctuations in renewable energy, analysing key techno-economic characteristics of systems such as superconducting magnetic energy storage, flywheel energy storage, redox flow batteries, compressed air energy storage, pump hydro storage, and lithium-ion batteries. Additionally, other options like supercapacitors, sodium-sulphur batteries, lead-acid batteries, and nickel-cadmium batteries were explored, enriching our understanding of their applications in handling renewable energy fluctuations.

As He et al. [47] think, the application of energy storage technologies was crucial in maximising off-grid renewable energy, mitigating intermittency, and managing supply-demand imbalances. While a hybrid energy storage system (HESS) proved more reliable and cost-effective, the choice of the optimal configuration remained uncertain. They examined ten HESS configurations, introduced a novel reliability index (LPSP-PoE) to handle long-term uncertainties, and established rule-based energy management strategies. Case studies showed that the thermal energy storage battery was the most cost-effective HESS, optimised strategies significantly reducing costs and enhancing reliability across various load profiles and probabilities of exceedance.

Gasanzade et al. [48] considered porous medium compressed air energy storage (PM-CAES) to address fluctuations in renewable energy-dominated supply systems. The interconnection between subsurface storage and surface power plants, reliant on compressed air pressure, required considerations regarding power supply variations, plant design, and storage processes. The study demonstrated the potential of PM-CAES, showcasing its ability to provide 115 MW of power and store between 12.1 and 49.9 GWh for up to 429 h, highlighting its grid-scale storage capacity. With efficiencies ranging from 0.54 to 0.67 and energy densities between 0.12 and 0.28 kWh per kg of stored air, the research suggested improving storage design by utilising horizontal wells and minimizing induced pressure increases. This comprehensive assessment evaluated PM-CAES based on future energy projections, geological settings, and engineering considerations, representing a significant step in the assessment of achievable storage rates and capacities.

Temiz and Dincer [49] explored an innovative solar and wind-driven energy system designed for self-sufficiency and sustainability in communities. It integrated a 340 MW wind farm and a 1500 MWp linear Fresnel concentrated solar system with thermal energy storage to meet electricity, heat, and cooling needs for a community of 65,000. Through steady-state and time-dependent analyses, the integrated system provided all the required energy, generating fresh water and hydrogen sustainably and achieving average energy and exergy efficiencies of 37.69% and 28.27%, respectively. This represented a unique solution that harnessed renewable energy in a combined and sustainable manner.

In microgrids, an effective energy storage system was essential to balance unpredictable supply and demand. Although distributed energy storage system (DESS) technology showed promise for future microgrids, determining the best capacity, placement, and allocation of storage devices (SDs) remained challenging. Tsao and Vu (2023) [50] introduced a two-stage approach to address SD decision-making, initially formulating problems related to SD location, capacity, and renewable energy investment with a long-term view, and subsequently optimising dispatch quantity to minimize operational costs.

The renewable energy community represented a new market paradigm, encouraging distributed renewable sources and customer flexibility with behind-the-metre storage systems. Diverse storage systems, from battery management in seconds to hydrogen handling in months, offered potential for aggregating various small-scale storage systems. Brusco et al. [51] proposed a day-ahead optimisation model for managing a local energy distributed storage community, aiming to improve self-consumption and provide ancillary services to the power system. It included a comprehensive analysis with simulation results based on a real-life test case. Whereas Kang et al. [52] developed a sophisticated deep-reinforcement learning methodology for real-time optimal energy storage planning amid uncertain curtailed renewable energy. It outperformed stochastic optimisation, maintained stability, and achieved over 90% profit accuracy.

The most important methods from the point of view of large-scale energy storage include the following: pumped hydro storage, compressed air energy storage (CAES), battery energy storage systems (BESS, flywheel energy storage, thermal energy storage (TES), hydrogen energy storage, molten salt thermal storage, flow batteries. These large-scale energy storage methods have various characteristics, including different storage capacities, response times, efficiencies, and suitability for different applications. Table 2 proposes a SWOT analysis for various energy storage technologies and their connection with renewable energy sources.

This SWOT analysis offers an overview of the strengths, weaknesses, opportunities, and threats of each energy storage technology. It highlights their key characteristics and aspects that affect their integration with renewable energy sources. This representation can aid in strategic decision making and understanding the landscape for energy storage technologies and their relationship with renewable energy sources.

An extension of SWOT analysis is the analysis of individual energy storage systems in the context of cooperation with renewable energy sources and desalination installations. Each renewable energy source, such as solar, wind and hydropower, has distinct characteristics in terms of intermittency, availability, and energy production potential. Accordingly, each energy storage technology should be selected based on its suitability for capturing, storing and releasing energy in accordance with the specific characteristics of these renewable sources. Table 3 links storage, renewable energy and desalination technologies and assesses the impact of energy storage on their efficiency.

When justifying the specific impacts of storage on renewable energy and desalination installations, it should be added that there is a scientific justification for combining renewable energy sources with specific storage technologies based on their operational characteristics. For example, technologies such as pumped hydro storage are well suited to intermittent renewable energy sources because of their ability to quickly store and release energy, while thermal storage methods are suitable for capturing and continuously delivering heat from concentrated solar power (CSP) to desalination. Selected energy storage technologies impact desalination plants in terms of providing a continuous and stable energy supply, supporting a high or variable energy demand, and meeting specific thermal or energy requirements. This impact is based on a scientific understanding of how each technology delivers or regulates power or heat to meet the demands of desalination processes.

The importance of desalination optimisation indicates the perceived importance of the impact of storage technology on optimising the operation of desalination plants. The classes are based on the stability, reliability and suitability of the energy storage method to meet the energy requirements of desalination processes. For example, thermal storage (TES) and liquid salt storage are assigned higher ratings because of their ability to provide continuous and stable heat, crucial for desalination. Hydrogen storage, although versatile, may require specific conversion technologies that impact the specific renewable energy method. In turn, the importance of complementarity in energy production means the importance of the storage method in complementing variable renewable energy sources. Higher ratings are awarded to technologies that effectively balance and support intermittent or variable energy supplies, helping to maintain grid stability and increasing the reliability of renewable energy sources. Thermal and molten salt storage methods stand out in this respect because of their ability to store and provide continuous energy regardless of weather conditions. Flywheel energy storage, while quick to respond, may have limitations in offering long-term support for renewable energy sources.

The medium, high, and very high categories reflect a subjective assessment of the impact of each energy storage technology on desalination plant optimisation and power generation complementarity based on their inherent characteristics and suitability for these applications.

4. Summary and conclusions

Renewable energy sources, such as solar, wind, and hydropower, are vital components in creating a stable and reliable energy supply. To address their intermittent nature and complementarity challenges, the integration of diverse renewable sources using advanced forecasting techniques, energy storage solutions, and smart grids is crucial. These integrative methods play an important role in balancing and distributing energy effectively. However, the current

Table 2
SWOT analysis of energy storage in relation to renewable energy technologies

Technology	Strengths	Weaknesses	Opportunities	Threats
Pumped hydro Storage (PHS)	• Established technology • High efficiency • Long lifespan	• Location-dependent • High initial costs	• Integration with variable renewables • Enhanced efficiency via technology upgrades	• Environmental impact • Land use issues
Compressed air energy storage (CAES)	• Scalability • Long lifespan • Low emissions	• Geologically limited locations for underground storage • Energy loss in compression	• Integration with renewable sources • Refined storage methods	• High installation costs • Technical challenges
Battery energy storage systems (BESS)	• Rapid response time • Modular and scalable • Versatility	• Limited lifecycle • Environmental impact of production	• Technological advancements for longer life and increased energy density • Integration with EVs	• Material supply constraints • Fire risks
Flywheel energy storage	• High power density • Long lifespan • Minimal degradation over cycles	• High initial costs • Limited energy storage duration	• Grid stabilization applications • Enhanced efficiency technologies	• Sensitive to external factors • Technological limitations
Thermal energy storage (TES)	• Long-duration storage capabilities • Reliability • Diverse applications	• Insulation requirements • High initial costs	• Enhanced efficiency in renewable integration • Integration with industrial processes	• Temperature fluctuations affecting performance • Thermal losses
Hydrogen energy storage	• Versatile energy carrier • Long-term storage • Zero emissions	• Efficiency in conversion • Infrastructure needs	• Advancements in electrolysis technology • Integration in fuel cell vehicles	• Safety concerns • Storage and transportation challenges
Molten salt thermal storage	• High-temperature storage • Long-duration capability • Efficiency	• Corrosion and material issues • High initial costs	• Enhanced solar power integration • Industrial heat applications	• Material degradation • Environmental impact
Flow batteries	• Long-duration and scalable • Modular design - Safety	• Limited energy density • Complex chemistry	• Improved energy density technologies • Integration with renewable grids	• Cost constraints • Market competition

literature indicates the absence of standardised methodologies for assessing energetic complementarity in various regions, emphasising the need for uniform metrics and a broader understanding of the integration of complementarity in different models. Novel numerical frameworks, like hard-coupling multireservoir and power system models, have shown improvements in grid performance, providing valuable tools for enhancing water-energy systems.

Real-world applications have showcased the strategic alliance of different power sources to minimise imbalance power, emphasizing the importance of interregional resource cooperation for optimising renewable energy-driven systems in communities. These practical scenarios demonstrate the importance of optimizing renewable-powered desalination, which offers high reliability and sustainability compared to traditional fossil fuel-driven systems.

In addition, analyses of various energy storage technologies, such as pumped hydro storage, thermal energy storage, and molten salt storage, have shown promising applications in managing renewable energy fluctuations. These findings contribute significantly to understanding the complementarity of energy and the integration of renewable sources into energy systems. Additionally, understanding the impact of storage technologies on renewable energy and desalination processes helps in the strategic selection of storage technologies that align with specific energy production needs, emphasising the importance of operational characteristics in this selection.

As can be seen, in the context of energy process management, an optimised installation operation schedule is also important to launch the desalination plant during periods of peak electricity demand. The demand response strategy takes advantage of fluctuating electricity prices by running the plant when electricity costs are lower. Additionally, intelligent controls and automation can adjust operating parameters in real time to meet changing energy

Table 3
Energy storage technologies and its impact on desalination optimization and complementarity of energy generation

Energy storage technologies	Renewable energy sources	Applications/ characteristics	Impact on desalination plant working characteristics	Influence on desalination optimization	Influence on complementarity of energy generation
Pumped hydro storage	Solar, wind, hydro	Large-scale, reliable, grid-balancing, long-duration storage	Stability for continuous operation supports high energy demand	High	High
Compressed air energy storage (CAES)	Solar, wind	Large-scale, adaptable, grid-balancing, medium-duration storage	Aids in managing energy fluctuations, supports intermittent energy supply	Medium	Medium
Battery energy storage systems (BESS)	Solar, wind	Versatile, scalable, rapid response, short to medium-duration storage	Enables on-demand energy supply, aids in load leveling	High	High
Flywheel energy storage	Solar, wind	Rapid response, short-duration storage, grid stabilization	Offers a quick power response, and supports energy stability	Medium	Medium
Thermal energy storage (TES)	Solar, concentrated solar power (CSP)	Long-duration, heat-based storage, continuous energy supply	Provides stable and continuous heat or cold for desalination processes	Very high	Very high
Hydrogen energy storage	Solar, wind, hydro	Long-term, versatile, energy carrier, fuel cell applications	Enables efficient energy conversion for desalination	High	High
Molten salt thermal storage	Solar (CSP)	High-temperature, long-duration, continuous energy supply	Provides consistent high-temperature heat for desalination	Very high	Very high
Flow batteries	Solar, wind	Scalable, long-duration, grid stability, multiple applications	Supports stable and continuous power supply for desalination	High	Medium

demands, contributing to more energy efficient operations. This includes statistical analysis and predictive algorithms that take into account historical data, market conditions, and network demand to predict favourable time frames for desalination operations. In this respect, access to information and integration with energy markets and network operators are necessary.

An interesting aspect is the use of hybrid systems and colocation with industry, which involves the implementation of hybrid systems that combine desalination with other industrial processes to use waste heat or are located near industries that can provide excess heat or energy, thus reducing overall energy demand.

Another issue that should be expected to develop in the future is the so-called predictive maintenance and process optimisation. Predictive maintenance strategies are used to optimise plant downtime. Engineers analyse historical operating data to plan maintenance during off-peak periods, minimising interruptions to desalination operations during periods of higher electricity costs. However, by implementing redundant systems and failure protection mechanisms, we will prevent energy from being wasted during a system failure. Automated fault-tolerant protocols ensure that in the event of a component failure, energy consumption remains optimised. This touches on the topic of life cycle cost analysis, which assesses the economic impact of different planning strategies. This includes considering not only the immediate savings but also the long-term benefits of an optimised schedule in terms of reduced overall operating costs. The future seems to be intelligent control and automation of energy-saving desalination using artificial intelligence. We are talking about sensor networks and real-time data acquisition, or predictive maintenance systems and adaptive control strategies using machine learning.

Taking this step further, expect the integration of IoT and cyberphysical systems (CPS) to create a connected and responsive desalination plant. Leveraging scientific advances in automation, control systems, machine learning, and predictive analytics, intelligent control, and automation can be expected to significantly contribute to the energy efficiency and operational optimisation of desalination plants, providing precise, real-time adjustments to match changing demand for energy and improving overall efficiency.

Taking into account all the presented aspects, it should be recognised that the integration of desalination, renewable energy, and energy storage is the key to the effective production and distribution of fresh water.

CRediT authorship contribution statement

Conceptualization: M. Kaczmarczyk, M. Bodzek, B. Tomaszewska; Writing-original draft preparation:

M. Kaczmarczyk, B. Tomaszewska; Writing-review and editing: M. Kaczmarczyk, M. Bodzek, B. Tomaszewska; Visualization: M. Kaczmarczyk; Supervision: B. Tomaszewska; Project administration: B. Tomaszewska.

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Conflicts of interest

The author declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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