Co-locating Desalination Plants and Reverse Electrodialysis

A Systematic Literature Review on
Economic and Technical Barriers

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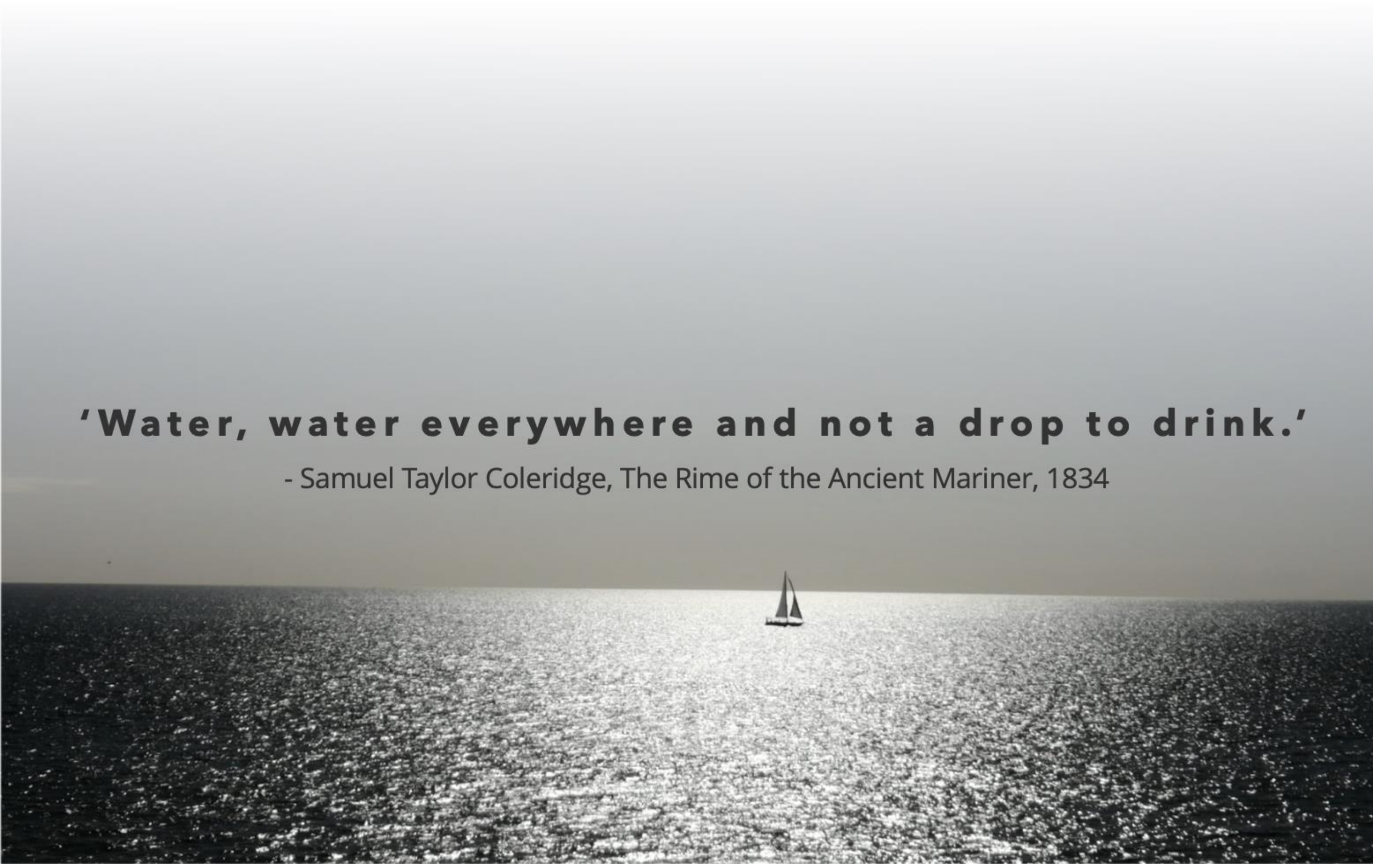

‘Water, water everywhere and not a drop to drink.’

- Samuel Taylor Coleridge, The Rime of the Ancient Mariner, 1834

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List of Abbreviations

AEM	Anion exchange membrane
CAPMIX	Capacitive mixing
CEM	Cation exchange membrane
GHG	Greenhouse gas
HSS	High salinity solution
IPCC	International Panel for Climate Change
LSS	Low salinity solution
PRO	Pressure retarded osmosis
RED	Reverse electrodialysis
SDG	Sustainable development goal
SGE	Salinity gradient energy
SWDU	Seawater desalination unit
SWDU-RED	Seawater desalination unit in co-location with reverse electrodialysis
SWDU-PRO	Seawater desalination unit in co-location with pressure retarded osmosis
TRL	Technological readiness level

Summary

Desalination is an increasingly common freshwater-provision strategy in arid regions with access to the ocean or another salt-water source. However, it is energy-intensive and is therefore responsible for substantial greenhouse gas (GHG) emissions. Further, toxic salt plumes are created in nearby bodies of water by waste desalination brine. Reverse electrodialysis (RED) in colocation with desalination plants is a promising method for reducing GHG emissions by creating renewable energy that can be used on-site. Additionally, through the process of RED, desalination waste brine is diluted which mitigates its toxicity to aquatic life.

However, despite its apparent benefits, RED is to date not commonly used in combination with desalination. This thesis is seeking to provide an overview of data about economic, as well as technological barriers in the way of upscaling and commercializing the approach by focusing on the following overarching research question:

> What are the main economic and technical barriers that impede the progress in technological readiness and subsequent upscaling and commercialization of integrated seawater desalination and reverse electrodialysis technology?

To elucidate this question, a systematic literature review including 75 publications was conducted. Quotations indicating economic and technical barriers were marked and categorized. Based on these quotations, four main barriers were identified. These barriers are (1) a low power density and energy efficiency, (2) high levelized cost of energy, (3) technological immaturity (4) a lack of competitiveness of SWDU-RED compared to technical solutions for the decarbonizing of the desalination industry and brine valorization.
It was further theorized that the technological immaturity of SWDU-RED is one of the prime reasons for the low power density and energy efficiency of SWDU-RED which are in turn in a causal relationship with the high costs associated with the technology. Additionally, the high costs may give rise to the lack of competitiveness.

It is concluded that these main barriers might cause SWDU-RED to fall victim to the so-called Valley of Death, a funding gap between the proof of concept within academia and the adoption of the technology by the industry on a commercial scale.

Further, it was concluded that pressure retarded osmosis (PRO) is likely a more suitable technology for the approach of co-locating desalination (SWDU-PRO) with salinity gradient energy because it delivers higher power densities. Therefore, it is recommended that in the context of decision-making about sustainable energy strategies in the desalination industry, funding is allocated for the development of SWDU-PRO instead of SWDU-RED. Moreover, additional research concerning legal barriers against salinity gradient energy applications, as well as research into the techno-economic feasibility of other novel RED technologies is advised.

1. Introduction

Challenges and Potential of Integrating Seawater Desalination with Reverse Electrodialysis

Desalination has become a prevalent strategy for freshwater provision in arid regions with access to seawater or other saltwater sources. According to Curto et al. (2021), there exist currently an estimated 16.000 desalination plants worldwide with a total daily desalination capacity of roughly 95.37 million cubic meters (ibid.). This is in the same order of magnitude as the volume of Lake Tahoe, one of the largest alpine lakes in North America.

However, changed precipitation trends originating from global warming may increase the frequencies of droughts and accordingly drive up the demand for seawater desalination in dry coastal regions even more (Tubi & Williams, 2021). At first glance, turning seawater into freshwater via desalination may seem like an excellent mitigation strategy for climate change induced dry periods. However, desalination has two major downsides:

(1) Desalination is highly energy intensive.
(2) The waste brine from desalination is commonly disposed of back into the ocean.

The energy-intensive nature of the desalination industry leads to substantial greenhouse gas emissions (Cornejo et al., 2014). Desalination is still predominantly powered by fossil fuels due to powerful technology lock-ins of the fossil fuel industry and enduringly low prices (ibid.). Therefore, in most cases, seawater desalination contributes to climate change. Consequentially, desalination exacerbates the underlying issue of freshwater scarcity while it is simultaneously attempting to solve it.

Further, the disposal of desalination brine creates toxic salt plumes in nearby bodies of water that are especially harmful to marine benthic communities (Portillo et al., 2014). The desalination brine has a higher density than sea- or freshwater and sinks therefore to the bottom of any natural body of water where it creates hypoxic conditions that numerous species are not adapted to tolerate (Lattemann & Höpner, 2008). This can change benthic communities by altering their species composition (ibid.).

To address both issues, the disposal of toxic brine in natural bodies of water, as well as the substantial GHG emissions of the desalination industry, the co-location of reverse electrodialysis (RED) with desalination plants emerges as a promising solution. RED generates renewable energy on-site, reducing GHG emissions (Tristán, Fallanza, et al., 2020b), and also dilutes the toxic waste brine, mitigating its impact on aquatic life (Pawlowski et al., 2020).

However, despite its potential benefits, the integration of RED with desalination is not common due to concerns regarding the novelty of the approach and associated technological and economic challenges. According to Olmos et al. (2012), technical and economic barriers in R&D, translate into underinvestment by private companies in the field of renewable energies. However, private capital is of crucial importance in the development of renewable energies because of the so-called “Valley of Death” which is the financing gap between the early stages of R&D that is commonly publicly funded and the stage of final commercialization

(Murphy et al., 2003). Therefore, SWDU-RED might be at risk of falling victim to a funding gap between the early stages of R&D and its commercialization.
As it is illustrated in Figure 1, the Valley of Death commonly occurs between the technological readiness levels (TRLs) 4 and 7 (Fasterholdt et al., 2018). The TRLs refer to a scale in which innovations are categorized while the progress from their basic principles being reported and their proof of concept (TRL 1 to 4), over testing in laboratory environments and pilot projects (TRL 4 to 7) to the proof of a functional system in a commercial environment (TRL 9) (ibid.).

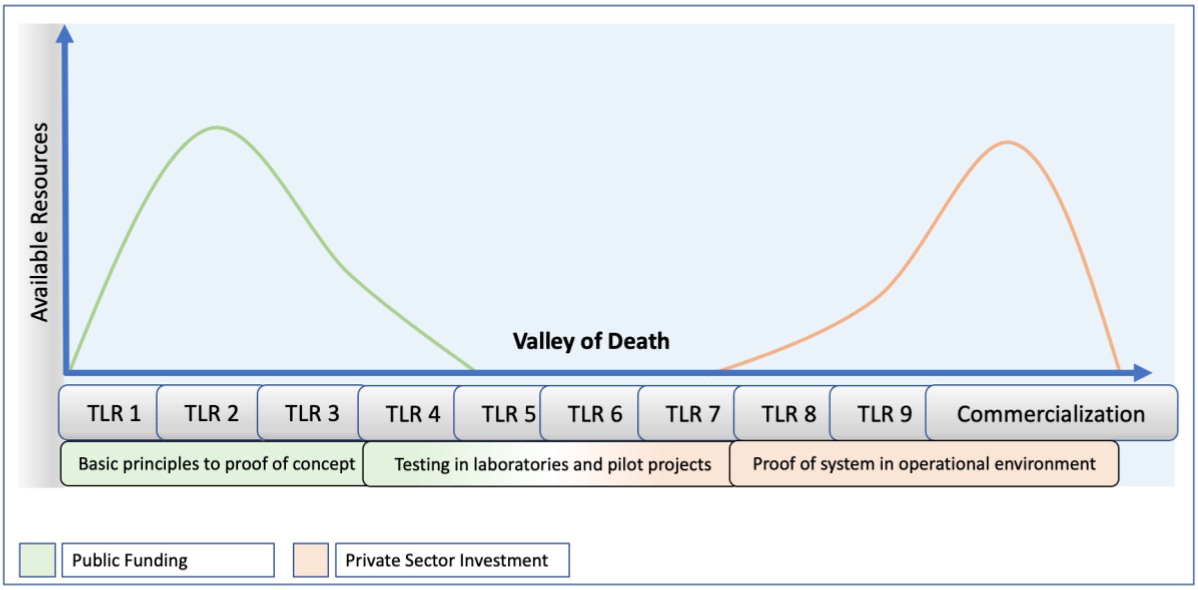


Figure 1: The funding gap between public capital for academic purposes and industry adoption coined the Valley of Death and corresponding technological readiness levels, own Illustration based on Gbadegeshin et al., (2022) and Hudson & Khazragui, (2013)

Jänicke (2008) states that systematic eco-innovation and diffusion ecological innovations “has by far the largest potential to achieve environmental improvements. (p. 557)“. Considering this perspective, SWDU-RED might have the potential to be regarded as such an eco-innovation, rendering it a possibly promising solution for addressing environmental challenges. The value this approach could add to society might be lost if the innovation cannot progress beyond the Valley of Death due to its current technical and economic shortcomings.

Therefore, this thesis aims to explore the economic and technical barriers hindering the commercialization and upscaling of integrated seawater desalination and reverse electrodialysis technology through a structured literature review. The main research question focuses on understanding the main obstacles that hamper the large-scale adoption of the SWDU-RED approach. By conducting a systematic literature review, the economic and technical barriers to co-locating desalination plants and RED are explored.

The overarching research question is:

> What are the main economic and technical barriers that impede the progress in technological readiness and subsequent upscaling and commercialization of integrated seawater desalination and reverse electrodialysis technology?

To elucidate the overarching research question the systematic literature review was conducted focusing on the following two sub-questions:

1. What are the economic barriers to co-locating desalination plants and reverse electrodialysis?

2. What are the technical barriers of co-locating desalination plants and reverse electrodialysis?

Research Gap and Academic Relevance

In recent years, the topic of combining desalination with renewable energies has attracted growing attention in the academic realm. Consequentially, the body of literature on SWDU-RED has grown substantially as can be seen in Figure 2a.

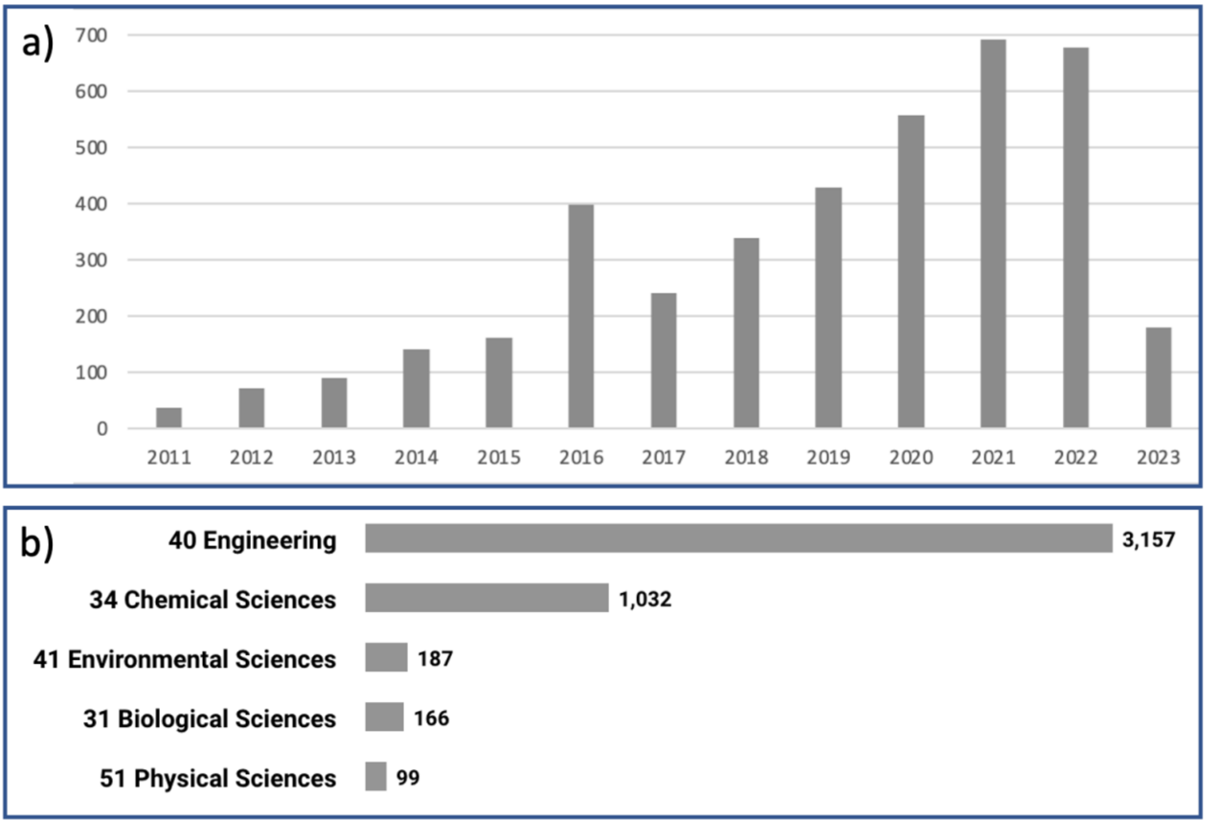


Figure 2: Increasing research interest in the combination of desalination and RED.
(a) Publications per year found with the search query ("Desalination" AND "Reverse Electrodialysis") on Dimensions.ai.
(b) The 5 fields of research after ANZSR 2020 classification with most papers published concerning ("Desalination" AND "Reverse Electrodialysis") on Dimensions.ai. The bars indicate the number of publications per research category.
Data for (a) and (b) were retrieved on the 16th of March 2023.

Generally, the literature on SWDU-RED is mainly focused on the fields of engineering and chemical science (Figure 2b), due to the technical challenges involved in applying and improving SWDU-RED and issues such as membrane fouling. Therefore, according to Daniilidis et al. (2014), technical challenges are at the forefront of academic discussion about RED. By extension, these barriers are also paramount in considerations about the upscaling and commercialization of SWDU-RED. However, there have been to date few publications addressing the economic challenges of SWDU-RED, and to my knowledge, there have been no publications addressing the topic from an innovation studies perspective. This thesis aims to make a valuable contribution to the academic field by addressing this research gap.

This systematic literature review focusing on the economic and technical obstacles in upscaling and commercializing reverse electrodialysis can have a substantial impact on spatial planning. By identifying challenges and evaluating the feasibility of widespread adoption, the review provides valuable insights for planners, enabling them to make well-informed decisions regarding the integration of RED into sustainable energy strategies and resource allocation in a spatial context, considering an innovation study perspective.

Societal Relevance of a Literature Review on the Economic and Technical Barriers against the Commercialization of SWDU-RED

The aim of the UN 2030 agenda is to achieve sustainable development by addressing social, economic, and environmental challenges. It is guided by 17 Sustainable Development Goals (SDGs) and aims to eradicate poverty, promote equality, protect the planet, and ensure prosperity for all (Pizzi et al., 2020). Therefore, the fulfillment of the 17 SDGs is of utmost societal relevance.

As will be described in Chapter 2, the desalination industry is gaining increasing importance in supplying freshwater to arid coastal nations. However, it has a substantial carbon footprint because it is mostly operated with fossil fuels. Therefore, desalination is effectively a tradeoff, in which water scarcity is alleviated, but at high energy costs which exacerbates global warming. This tradeoff scenario in which energy is swapped for clean water is commonly referred to as the water-energy-nexus (Fontananova et al., 2023). There is a high demand for technologies that make a positive impact on the water-energy-nexus, i.e. alleviating interconnected water- and energy provision issues (Rehman et al., 2020). Because desalinated water is being increasingly used for agricultural purposes, the tradeoff scenario can be expanded to the water-energy-food-nexus (C. Zhang et al., 2018).

As stated by T. Sun et al., (2022), RED technologies exhibit significant promise in tackling the complexities of the water-energy-food nexus. Utilizing SWDU-RED in the desalination industry could have a positive impact on the water-energy-food-nexus by increasing the energy efficiency of the desalination industry and partially decarbonizing it. Further, as highlighted by (Pawlowski et al., 2020), SWDU-RED aligns well with the Untitled Nations' SDG2030 agenda, as it could contribute to two sustainable development goals at once.

A widespread employment of SWDU-RED could make a positive impact on SDG 6 which targets the improved provision of clean water and sanitation. Further, it could have a positive impact on SDG 13 which is concerned with climate action. Jänicke (2008) states that systematic eco-innovation and diffusion of ecological innovations "has by far the largest potential to achieve environmental improvements. (p. 557)". SWDU-RED can be considered such an eco-innovation. In Warbroek et al.'s study (2022), recognizing cross-sectoral potentials and fostering synergies is emphasized for a successful energy transition. Combining desalination and RED appears as such a promising synergy. SWDU-RED has the potential to address both brine toxicity and GHG emissions from desalination plants. By utilizing the effluent brine from desalination as the high salinity feed solution in SWDU-RED, coupling the two technologies can mitigate GHG emissions by reducing overall energy needs through on-site electricity generation (Tristán, Fallanza, et al., 2020b)

Because of the importance of desalinated water for agriculture, wide-spread SWDU-RED employment could aid in reaching SDG 2 which is aiming to alleviate hunger globally. Additionally, the implementation of SWDU-RED potentially addresses SDG7 which seeks to provide affordable and clean energy. SWDU-RED utilizes a waste product to generate electricity, thereby reducing the strain on conventional energy sources (Sampedro et al., 2023). Finally, due to the valorization and subsequent dilution of the desalination brine in SWDU-RED as will be described in Chapter 2, an improvement concerning SDG 14, which concerns life below water, could be achieved. SWDU-RED makes the disposal of desalination brine more ecologically compatible with marine ecosystems. Through the dilution the salinity of the desalination brine is reduced, accordingly lowering the impact on marine ecological communities (Z. Wang, Li, Zhang, et al., 2022).

Due to the societal relevance of achieving the United Nations' SDGs, the possible contributions of SWDU-RED to several SDGs simultaneously are by extension also potentially of high societal relevance. However, there are significant barriers in the way of an upscaling and a commercialization of SWDU-RED (Chapter 4). Understanding what factors these barriers consist of and their connection among each other, is a crucial basis for making educated estimations on whether a commercialization is possible and advisable in light of current technical and economic barriers, as well as numerous renewable energy alternatives for powering desalination plants. This underlines the societal relevance of this thesis which seeks to provide an overview of the main technical and economic barriers in the way of a large-scale employment of SWDU-RED by the means of a systematic literature review.

2. Literature

Chapter 2.1 provides essential background information related to the topic of SWDU-RED. It begins with an exploration of desalination, encompassing its historical context, fundamental principles, and prevalent methods. Additionally, the drawbacks associated with desalination are presented. The discussion then transitions to salinity gradient energy (SGE) and subsequently delves into the principle of reverse electrodialysis, finally introducing the concept of SWDU-RED and its associated benefits. Following this, Chapter 2.2 introduces a theoretical framework for analyzing barriers SWDU-RED.

2.1 Background of and Developments in SWDU-RED Research

Desalination – A Brief History

The ocean is commonly stated to have played a key role in the development of life (Martin et al., 2008) and 78% of all animal biomass is found in marine environments (Ritchie, 2019). Generally, water is widely regarded as an essential building block for carbon-based life forms (Westall & Brack, 2018).

Even though the ocean has been crucial for the development of life and continues to be of major importance for all life on earth by being a carbon sink, for example (Landschützer et al., 2014), due to its high salt content, ocean water is only of limited use for land-based organisms, including humans. Clean freshwater is needed for cooking, washing, personal hygiene and most importantly drinking. Further, freshwater is essential for agriculture and by extension for food security, the global economy, and the socioeconomic stability of countries (Nesmith et al., 2021). However, about 97% of all water on earth is salt water and of the remaining three percent, the majority of freshwater is inaccessibly stored in glaciers and ice caps (Castelo, 2023). Only 0.4% of all water on earth is considered freshwater that is accessible to humans (ibid.).

Considering how little of the Earth's water is usable freshwater, the idea of converting ocean water into freshwater is close at hand. Indeed, the concept of simple technologies for desalinating sea water have already been known in the times of Aristotle (384-322 BC) (Angelakis et al., 2021). Further, there is evidence of desalination powered by solar energy being used as early as the 15th century by Arab alchemists by focusing sun rays onto glass vessels with concave mirrors (Kalogirou, 2005).

Similarly to these ancient Arabic desalination devices, the first large-scale desalination facility built in 1872 was solar powered, as well. It was built in Las Salinas, Chile to supply a mining town with potable water that was distilled from the high-salinity mining fluids of a saltpeter mine (Kalogirou, 2005). Reportedly, the desalination plant produced 22.70 m^3 of freshwater daily and was operational for 36 continuous years until the mining town gained access to freshwater from the nearby mountains through a pipe system (Garg, 1987).

Even though desalination had been known and practiced already in ancient times and the first large-scale desalination plant was constructed in the 19th century, it took until the 1960s until technological advances in membrane-desalination facilitated the upscaling of desalination to a worldwide industry branch (Judd, 2017).

To date, there are approximately 16.000 industrial desalination facilities distributed throughout the world with the majority being located in the Middle East and North America (Figure 3).

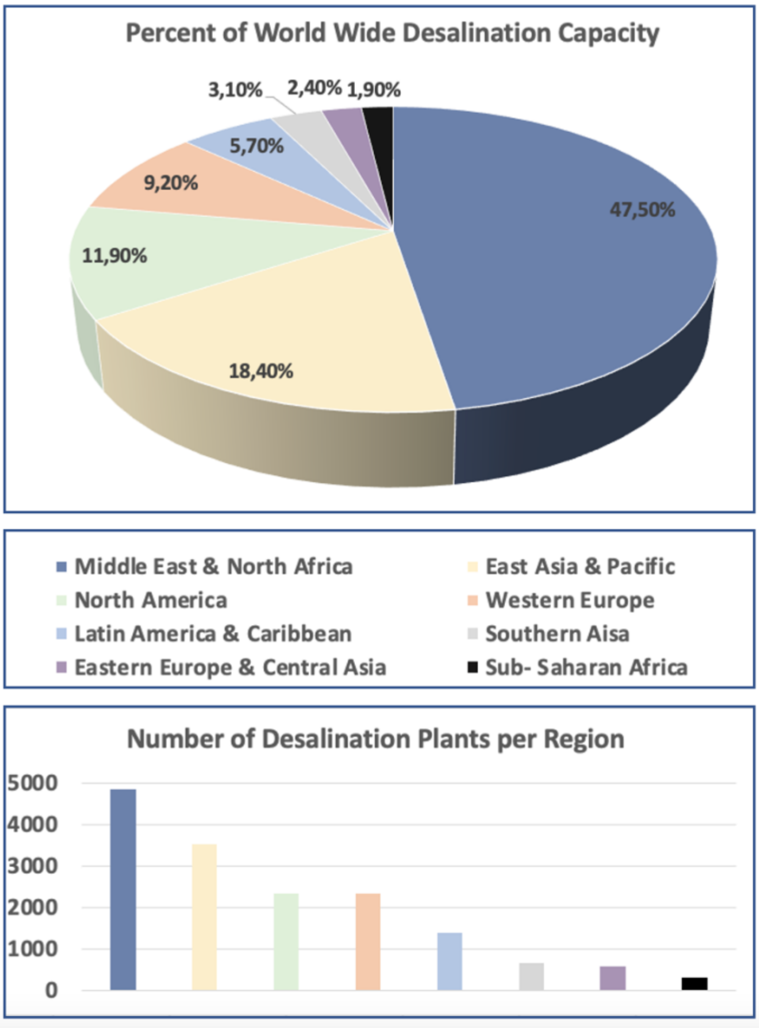


Figure 3: Distribution of desalination plants worldwide, own illustration, based on data from Jones et al. (2019).

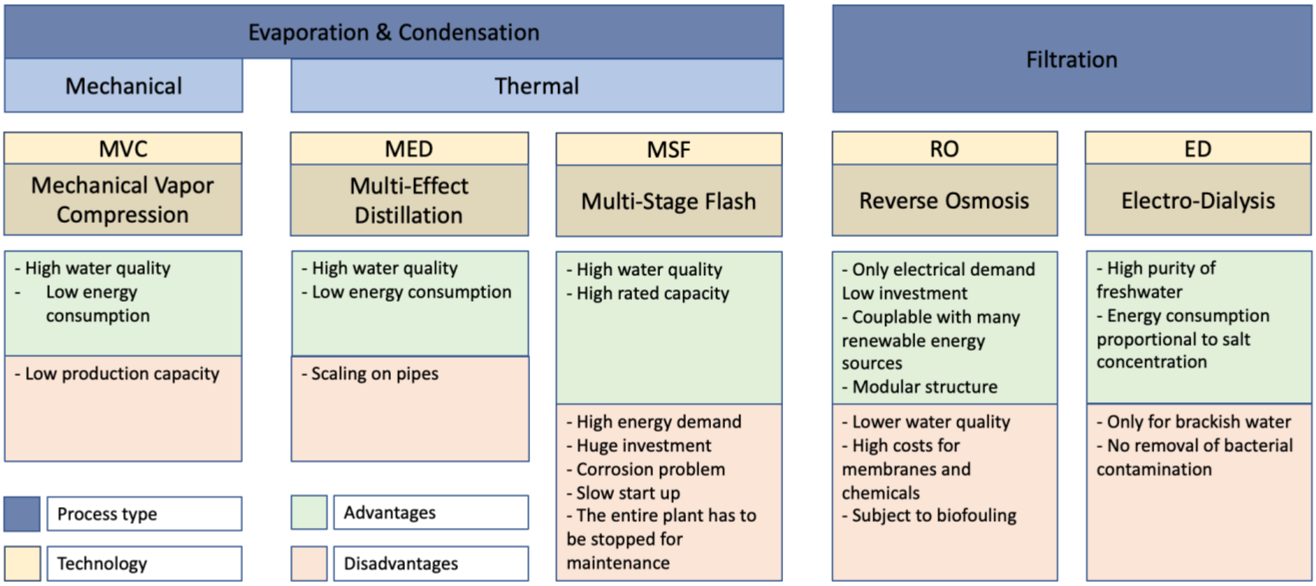
Basic Principles of Desalination

Generally, there are three basic working principles that underly all desalination methods: Evaporation with subsequent condensation, membrane filtration and crystallization (Curto et al., 2021).

During an evaporation/condensation desalination process, saltwater is evaporated using either mechanical or thermal energy to induce a phase change. Subsequently, the water vapor is let to condensate. Since salt does not evaporate, it is left behind in the process and the result is distilled freshwater (Curto et al., 2021). In desalination using filtration, saltwater passes through a semi-permeable membrane that retains the larger salt molecules but lets the water through (ibid.). Desalination via crystallization is a process of removing salts by cooling saltwater to a temperature below the freezing point of the dissolved salts. As the solution is cooled, the salts begin to crystallize out of the solution, leaving behind pure water. The crystals are then filtered out (El Kadi & Janajreh, 2017).

Concerning all three desalination principles, there is ongoing research on a wide variety of approaches within these principles, as well as hybrid processes between them (Park et al., 2018). While crystallization processes are not commercially used, there are commercial desalination plants that are based on evaporation and condensation processes and filtration (El Kadi & Janajreh, 2017). The most common commercial desalination methods with their advantages and disadvantages are listed in Figure 4.

In current times, membrane based desalination in the form of Reverse Osmosis is the most commonly applied working principle in large-scale desalination (Curto et al., 2021; Lee et al., 2011).



Evaporation & Condensation			Filtration	
Mechanical	Thermal			
MVC	MED	MSF	RO	ED
Mechanical Vapor Compression	Multi-Effect Distillation	Multi-Stage Flash	Reverse Osmosis	Electro-Dialysis
- High water quality - Low energy consumption	- High water quality - Low energy consumption	- High water quality - High rated capacity	- Only electrical demand Low investment - Couplable with many renewable energy sources - Modular structure	- High purity of freshwater - Energy consumption proportional to salt concentration
- Low production capacity	- Scaling on pipes	- High energy demand - Huge investment - Corrosion problem - Slow start up - The entire plant has to be stopped for maintenance	- Lower water quality - High costs for membranes and chemicals - Subject to biofouling	- Only for brackish water - No removal of bacterial contamination

🟦 Process type
🟨 Technology
🟩 Advantages
🟥 Disadvantages

Figure 4: Commercial desalination methods and their advantages and disadvantages, own illustration based on Curto et al. 2021.

Desalination Effluent and its Effects on Aquatic Ecosystems

While there are so called zero-liquid-discharge desalination processes with which it is possible to extract all water from the saltwater and leaving only salt behind, those approaches are still experimental and in commercial desalination there is usually a high salinity brine left behind as a waste product (Figure 5) (Q. Chen et al., 2021). To this day, it is a common industry practice to lead the brine effluent untreated back into the ocean (Omerspahic et al., 2022).

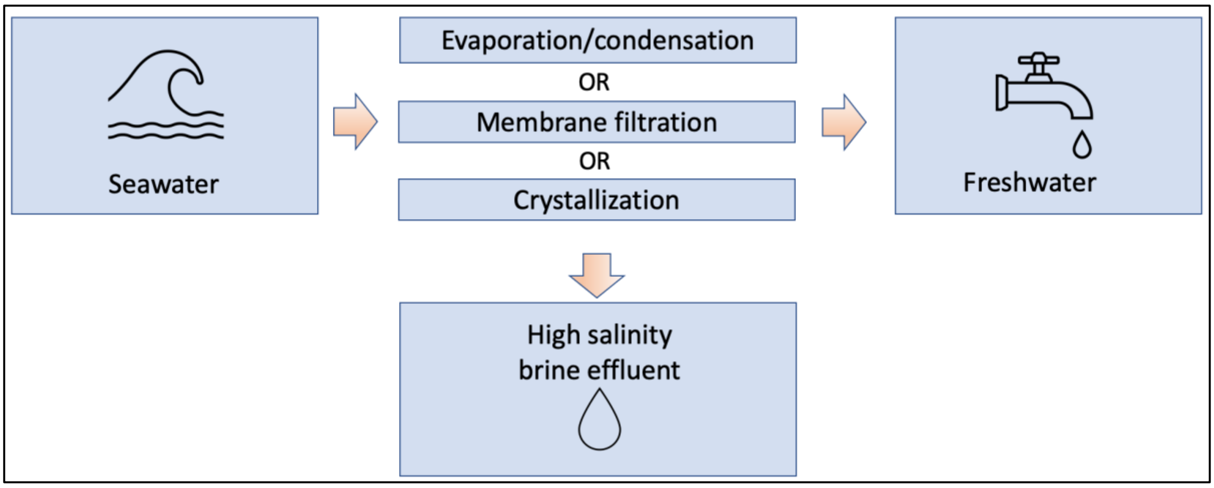


Figure 5: Basic principle of seawater desalination, own illustration based on Darre & Toor, (2018) and Curto et al., (2021)

This is problematic because marine organisms can adapt to minor deviations from optimal salinity and temperature conditions, and might even tolerate extreme conditions temporarily, but not continuously. Therefore, marine life can be killed by continuous discharge of reject streams with high salinity levels, and it can change the species composition and abundance in the discharge area (Mrozińska et al., 2021). Furthermore, very high concentrated salt-plumes from effluent desalination brine can result in hypoxic conditions which are detrimental to most higher organisms because they impact the uptake of oxygen (Shrivastava, 2018).

Due to the increased density of brine desalination discharge compared to ocean water, especially benthic communities such as seagrass meadows are negatively impacted by salt plumes creeping over the ocean floor (Portillo et al., 2014). Marine life in enclosed and shallow areas will generally be more sensitive to desalination plant discharges than in exposed, high-energy, open-sea areas that are better able to dilute and disperse discharges (Roberts et al., 2010).

The negative effects of desalination brine on marine organisms can be exacerbated by chemical residues from the desalination process such as chlorine against biofouling, coagulants, anti-foaming and anti-scaling chemicals, as well as heavy metals used in components of the desalination plant that enter the wastewater stream due to corrosion. Further, the effluents of thermal desalination plants commonly have a higher temperature than the ocean water which can add heat stress to the detrimental effects of desalination effluents on the marine environment (Lattemann & Höpner, 2008).

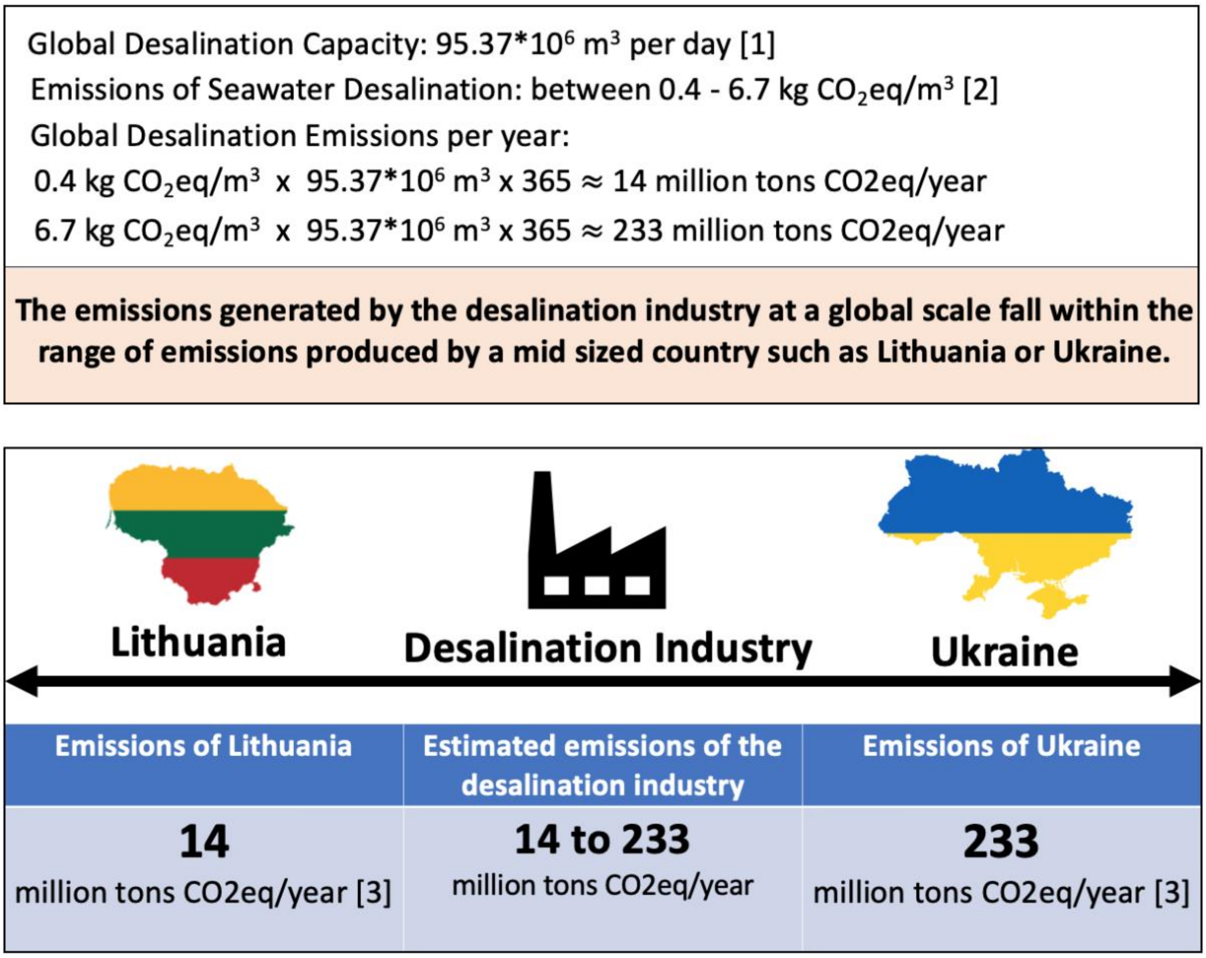
To avoid heat stress caused by desalination plant wastewater, cooling towers can be employed (Lattemann & Höpner, 2008). Further, concerning the toxic effects of brine on marine life, pre-dilution of brine with streams of low-salinity treated wastewater or cooling water from powerplants or diffusion of effluent brine are common mitigation strategies, however, these measures are tied to additional costs (Navarro et al., 2021).

The Need for Decarbonizing the Desalination Industry

Climate change is exacerbating water scarcities by changing precipitation patterns (Dai et al., 2018). This is particularly problematic as it induces land degradation and threatens food security (Hermans & McLeman, 2021). According to Smirnov et al. (2022), climate-related droughts are projected to increase human migration by 200 percent if the international community complies with the Paris Agreement from 2016 and up to 500 percent in a scenario in which GHG emissions follow current trends. According to Mekonnen & Hoekstra, (2016), around four billion people are globally threatened by severe water scarcity.

Desalination provides a mitigation strategy for local impacts of climate change induced droughts. Therefore, desalination is increasingly gaining importance as a method for freshwater provision on a global level as climate change is exacerbating arid conditions (Tubi & Williams, 2021). Further, the ongoing population growth and industrialization are expected to additionally increase global water demand (Sanchez et al., 2020). According to Sommariva (2017), the number of desalination plants worldwide has almost doubled between 2000 and 2017 and is expected to grow further.

Unfortunately, utilizing desalination as a method of freshwater provision in the face of climate-induced water shortages has a major downside: large-scale desalination is highly energy-intensive (Barone et al., 2021). Although the first large-scale desalination plant in the 19th century in Las Salinas, Chile, was based on solar distillation and therefore relied on a renewable energy source, the majority of modern-day desalination plants are powered by fossil fuels. An estimation concerning the scale of the emissions of the desalination industry is provided in Figure 6. according to calculations based on data by (Curto et al., 2021). Based on this estimate, the combined global emissions of the desalination industry are comparable with the emissions of a mid-sized country. Therefore, while temporarily mitigating the effects of longer and more severe droughts caused by the climate crisis, the currently prevalent method of desalination is exacerbating the root cause of the problem (Roth & Tal, 2022).



Global Desalination Capacity: $95.37*10^6$ m^3 per day [1]

Emissions of Seawater Desalination: between 0.4 - 6.7 kg CO_2eq/m^3 [2]

Global Desalination Emissions per year:

0.4 kg CO_2eq/m^3 x $95.37*10^6$ m^3 x 365 ≈ 14 million tons CO2eq/year

6.7 kg CO_2eq/m^3 x $95.37*10^6$ m^3 x 365 ≈ 233 million tons CO2eq/year

The emissions generated by the desalination industry at a global scale fall within the range of emissions produced by a mid sized country such as Lithuania or Ukraine.

Emissions of Lithuania	Estimated emissions of the desalination industry	Emissions of Ukraine
14 million tons CO2eq/year [3]	**14 to 233** million tons CO2eq/year	**233** million tons CO2eq/year [3]

Figure 6: Estimation of the scale of the emissions of the global desalination industry
own illustration based on data by [1] Curto et al., (2021), [2] (Cornejo et al., 2014) [3] (Worldometer, n.d.)

Considering the scenarios by the Intergovernmental Panel on Climate Change (IPCC), an energy transition is imperative. According to the IPCC, climate change impacts and risks are becoming progressively complicated and harder to manage. After 2040, considering the level of global warming, several risks to natural and human systems are to be expected. Adverse impacts of climate change on a global scale include a loss in biodiversity, threats to water and food security due to droughts, heatwaves, storms and other extreme weather events and rising sea levels (IPCC, 2022). Because of these risks that climate change is posing on a global scale, a transition in energy provision away from fossil fuels is imperative. Therefore, worldwide decarbonization in all industry branches, including desalination is desirable in light of the substantial challenges that climate change is posing for the global population.

According to Ghazi et al. (2022, p. 114), "the correct combination of renewable energy and desalination technologies is the key to meeting water demand in a cost-effective, efficient, and environmentally responsible manner." Although the energy needed for desalination is currently most commonly provided via fossil fuels, there are many approaches to provide energy for desalination through renewable energy sources such as wind, photovoltaic, solar, geothermal or wave energy and the body of research on how to fuel desalination with renewable energy is growing (ibid.).

In addition, there is ongoing research on methods for generating energy by utilizing the high-salinity effluent brine from the desalination process. Several promising approaches for doing so are based on utilizing the salt gradient between ocean water and desalination brine for the generation of electrical power that can be used directly on-site, used to power other facilities or for hydrogen production (Yip et al., 2016).

History of Development of Salinity Gradient Power

Although this principle has been known since 1954, it took several more decades until experimentation on this possibility for electricity generation graduated beyond small-scale laboratory experiments. For about 20 years after Pattle insight on the possibility of electricity generation from salt gradients, there were no further publications on the matter until Sydney Loeb introduced the concept of PRO in 1975 (Achilli & Childress, 2010). Further, there was a theoretical paper by Weinstein and Leitz in 1976 that concluded based on a mathematical model that electricity generation with RED could be possible with technological advances (Weinstein & Leitz, 1976).

According to Lacey (1980), the main limiting factors in the 1980s that inhibited the further development of RED from an idea into an economically feasible approach were of technical nature with economic implications. Lacey (1980) stated the main inhibiting factors were the high internal resistance of the cells, a low power output and the lack of an appropriate manufacturing method for membranes. Finally, in 1988, Bernard Ramsey Bligh patented RED in 1988 (Bligh, 1988). Later drivers for the development of salt gradient energy were the call for renewable energies at the first Kyoto meeting in 1997, the blue energy program by the Wetsus center for sustainable water technologies in the Netherlands in 2005 and subsequently the oil price increase in 2008 (Achilli & Childress, 2010; Post et al., 2010).

Finally, in 2014, the first pilot plant for RED was opened which is situated on the Afsluitdijk. The Afsluitdijk is a major closure dyke in the Netherlands between the province of Friesland and North Holland that separates the Ijsselmeer and the Wadden Sea. The plant operates by generating electricity through the salt gradient between the freshwater from the IJsselmeer and seawater from the Wadden Sea. (NWP, 2014)

Additionally, RED with different concentrations of salty and hypersaline water has been tested for the first time at a larger scale in the REApower project in corporation with a salt mining company in Sicily, Italy. Tamburini et al., (2019) describe that the project was successful in operating a pilot power plant that performed well under real environmental conditions. On page 410 of the report, desalination brine is mentioned as an example of a possible source of brine for RED.

Moreover, Tristán et al., (2020) stated that using RED to generate energy from desalination brine on-site could potentially lower the overall energy needs of desalination plants and could therefore be an important contribution to the energy transition. An approach related to this concept has been tested in the most recent pilot testing plant for RED which is located in Okinawa, Japan. In this RED plant, power generation using RED with treated wastewater streams and waste brine from a desalination plant as feed solutions have been tested with the encouraging result that the power yield was significantly higher compared to RED using river and sea water as feed solutions (Yasukawa et al., 2020). It can be inferred that the colocation of desalination with reverse electrodialysis is a promising approach for the renewable generation of electricity.

Salinity Gradient Power (SGP) General Working Principle

There are several approaches for using salinity gradients between fluids for power generation. Among the two most promising are pressure retarded osmosis (PRO) and reverse electrodialysis (RED) (Yip et al., 2016). Both approaches are based on utilizing the ion gradient between two solutions of different salinity for power generation (ibid.).

When two solutions have differing ion concentrations and are connected via a semipermeable membrane that lets water pass, but retains salt ions, the solution with the higher concentration of salt ions will attract water from the solution with the lower ion concentration in order to equalize ion concentrations. This results in a water flow that is based on passive transport and therefore requires no additional energy input. (Lopez & Hall, 2023)

PRO harnesses the osmotic pressure that differs between two solutions with different salt concentrations to drive a turbine which in turn generates electricity (Achilli & Childress, 2010). RED on the other hand is an electrochemical approach that utilizes the ion flow to generate electricity via ion exchange membranes, separating positive and negative charges which results in an electrochemical potential that is converted into (Mei & Tang, 2018).

That the tendency of fluids with different ion concentrations to equalize themselves could be used for the production of electric power has been described first by Pattle (1954, p. 660):
“When a volume V of a pure solvent mixes irreversibly with a much larger volume of a solution the osmotic pressure of which is P, the free energy lost is equal to P V. The osmotic pressure of sea-water is about 20 atmospheres so that when a river mixes with the sea, free energy equal to that obtainable from a waterfall 680 ft. high is lost. There thus exists an untapped source of power which has (so far as I know) been unmentioned in the literature.“

RED Basic Working Principle

RED utilizes an ion flow to generate electricity via ion exchange membranes. There are two types of membranes: one type only lets positively charged ions pass, also known as a Cation Exchange Membrane (CEM). The other membrane type only lets negatively charged ions through and is known as an Anion Exchange Membrane (AEM). Between the CEM and AEM membranes, there is alternatingly a High Salinity Solution (HSS) and a Low Salinity solution (LSS). Further, the membranes are also stacked in an alternating pattern which forces the ions to move in specific directions which, in turn, generates an electrochemical potential that can is converted into electricity via a redox reaction by electrodes that are connected to an external circuit (Tufa et al., 2018). Further, so-called spacers create separation between ion-exchange membranes, allowing for the smooth flow of concentrated and diluted saltwater solutions. They optimize ion movement and maximize electrical energy generation during the ion exchange process (Długołęcki et al., 2010). Ion exchange membranes, electrodes and spacers constitute together a so-called “stack” (ibid.). The basic working principle of a RED-stack is illustrated in Figure 7.

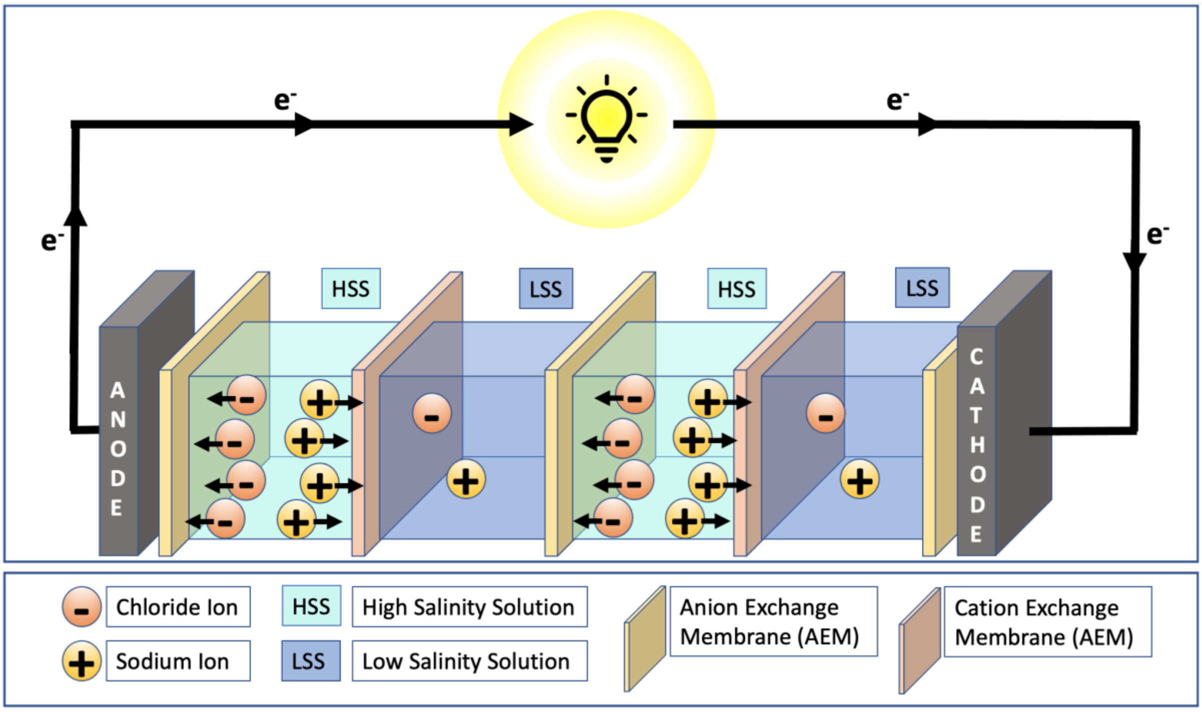


Figure 7: *Basic working principle of RED, own illustration adapted from Tufa et al. (2018).*

RED in Colocation with a Sea Water Desalination Unit (SWDU-RED)

RED is most commonly referred to as a method for energy generation using salt- and fresh water, but it is also possible to utilize it in a scenario where salt water and highly saline water such as desalination brine are available (Tamburini et al., 2019; Tristán, Fallanza, et al., 2020b). Co-locating a seawater desalination unit (SWDU) with reverse electrodialysis has the potential to produce renewable electricity that can be utilized directly on-site in the desalination (Tian et al., 2020).

In the approach of co-location of RED with a seawater desalination plant (SWDU-RED), initially seawater is being desalinated via a SWDU (Figure 8). Subsequently, the highly concentrated brine which is a waste-product of the desalination process, is being utilized as the high salinity solution in RED to generate electricity. The low salinity solution consists of a solution that has a lower ion concentration than the brine such as seawater, brackish water, treated waste-water or a combination of those. The products of this process are freshwater, electricity and diluted effluent water. (Tian et al., 2020; Yasukawa et al., 2020)

Generally, the SWDU-RED process underlies many contextual influences such as the type of seawater desalination plant that is being utilized. For an overview of the most common commercial desalination processes, see Figure 4. Therefore, there are actually several different SWDU-RED processes, depending on the type of the SWDU-plant and the availability of low-salinity solutions (Tian et al., 2020).

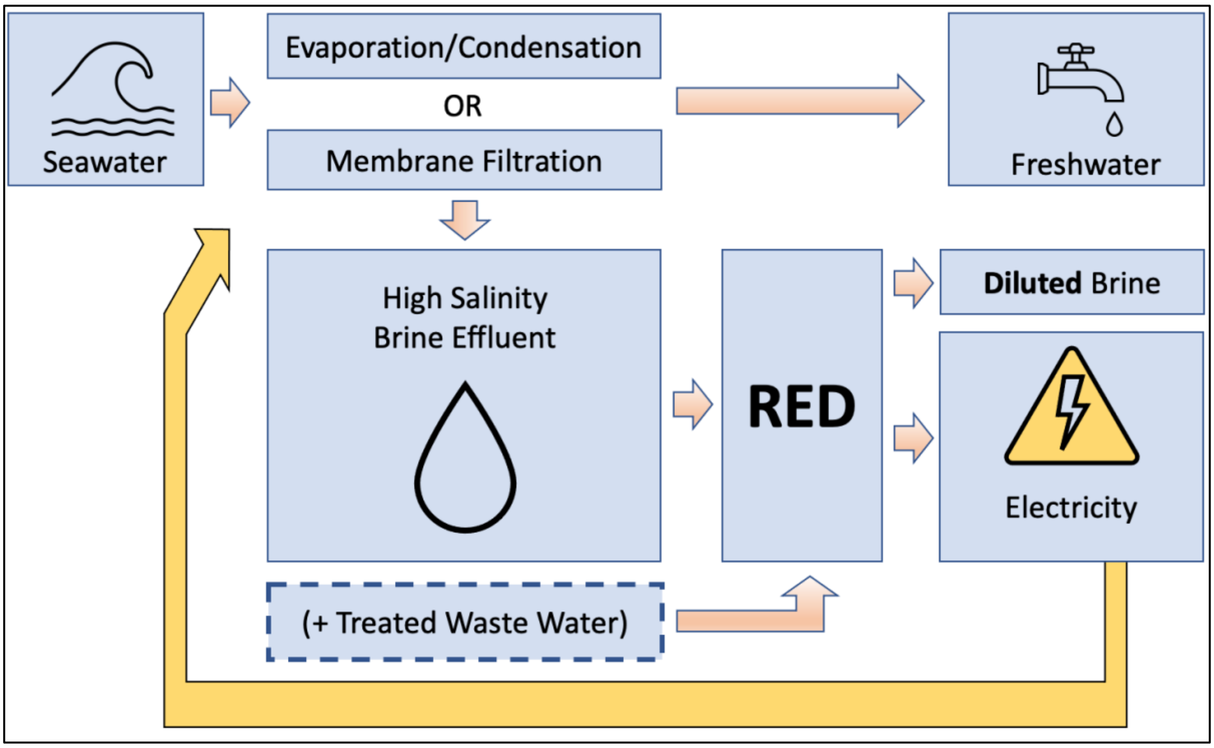


Figure 8: Basic working principle of SWDU-RED,
own illustration based on information by Tian et al., (2020) and Yasukawa et al., (2020)

Benefits and Potential of RED and SWDU-RED

As discussed previously, desalination has two major downsides: brine is created as a waste product that is often lead back into the ocean which can have detrimental effects for marine organisms and entire ecosystems such as sea-grass meadows. Further, desalination is highly energy intensive. Because desalination is most commonly supplied with energy generated via fossil fuels, it is connected to major GHG emissions. In light of the global climate crisis, there is an urgent need for decarbonizing the desalination industry.

According to Warbroek et al., (2022), it is paramount for the energy transition that cross-sectoral potentials for integrative solutions are recognized and synergies are built. Combining desalination and RED could be such a promising synergy. SWDU-RED has the potential to tackle both problems (brine toxicity and GHG emissions of desalination plants) simultaneously. The effluent brine from desalination plants can be used as the HSS feed solution in SWDU-RED. Thus, coupling RED with desalination could mitigate the GHG emissions of desalination by reducing the overall energy needs of the process by utilizing the generated electricity from SWDU-RED directly on-site (Tristán, Fallanza, et al., 2020b).

Additionally, when using desalination brine in SWDU-RED as the high salinity solution, the brine is diluted with the low salinity solution, for example, sea-water or treated waste-water (Alkaisi et al., 2017; Yasukawa et al., 2020). Consequentially, the effluent of the desalination plant after undergoing SWDU-RED, is significantly less salty than without the process and by extension less likely to create environmental issues such as hypoxic conditions (W. Li et al., 2013; Navarro et al., 2021). Dilution and diffusion of desalination brine before leading the effluent back into the environment is a well-known recommended step for mitigating the negative environmental impacts of desalination brine in marine environments this is commonly avoided due to the additional costs of the measure (Navarro et al., 2021). However, if SWDU-RED is implemented, dilution takes place without creating additional costs. In fact, due to the electricity that is generated, the process has the potential to be economically beneficial by winning back energy that can be used directly on-site to power nearby facilities or for hydrogen production (Nazemi et al., 2016; Tristán, Fallanza, et al., 2020b).

Further, granted there are continuous streams of high- and low salinity feed solutions, SWDU-RED can deliver electricity at all times of the day, every day of the year. Therefore, it has the crucial benefit of being independent of seasonal or daily variations of environmental conditions and stands out from other renewable energies due to its reliability (Guler & Nijmeijer, 2018; Tufa et al., 2018). For example, solar energy cannot be exploited at night and underlies further seasonal and daily variations in solar radiation for its electricity production. Wind energy depends on wind speeds which are challenging to predict accurately long term, especially in regard to climate change induced variations, but can have a significant impact on the profitability of a wind farm (Watson, 2019). Further, climate change appears to be lowering average near-surface wind-speeds on a global scale in a phenomenon termed “global stilling” (Azorin-Molina et al., 2017) which could reduce the energy output of wind energy in the long run. According to (F. Liu et al., 2023), global stilling caused an approximated 5.5% decline in global surface wind speed average per decade between 1971 and 2015. This trend might constrain the development of the wind industry (ibid.).

However, Tristán et al. (2020) estimate based on computer modeling that theoretically, RED could supply only 40% of the energy demand of desalination plants under nearly all contextual configurations of the 20 desalination plants that were examined in their work. If accounting efficiency losses inherent to the SWDU-RED process such as pumping and untapped SGE, the energy saving is closer to about 10%. Because of this, a total decarbonization of the desalination industry through SWDU-RED is not possible. Hence, SWDU-RED would need to be co-located with another renewable energy source in order to reduce carbon emissions of desalination to zero. Thus, a combination of SWDU-RED with solar or wind energy is a likely future scenario in case SWDU-RED reaches full technological maturity and commercialization (Brauns, 2010).

Why not supply the energy for desalination by solar or wind energy in its entirety?
Solar and wind energy have significantly higher spatial requirements than RED. According to a design by Post (2009), a RED module producing 200 kW continuously could fit into a 40 feet sea container. This type of container has a 30 square meter surface area. For comparison, using data from (SunWatts, n.d.), a solar-power plant producing the same 200 kW would need an area of approximately 1300 square meters. Further, this solar power plant would not produce any electricity at night. Wind energy has an even larger spatial requirement than solar energy (Delichatsios, 2022). According to Delichatsios (2022), the land footprint of wind farms is around seven times as much as the land requirement for solar energy. For a visual comparison of the theoretical spatial requirements of RED, solar and wind energy see Figure 9.

The spatial requirements for RED are so low because different to e.g. solar energy where every panel needs to be reachable by sunlight, RED membranes can be stacked tightly on top or beside each other. Therefore, the same overall surface area of solar panels compared to RED ion exchange membranes has a much lower spatial requirement. (Pawlowski et al., 2014)

Since seawater desalination plants are typically located in urban or semi-urban coastal settings where real estate is costly, RED could save space compared to an application in which desalination is purely fueled by solar or wind energy which could translate into a tangible cost benefit.

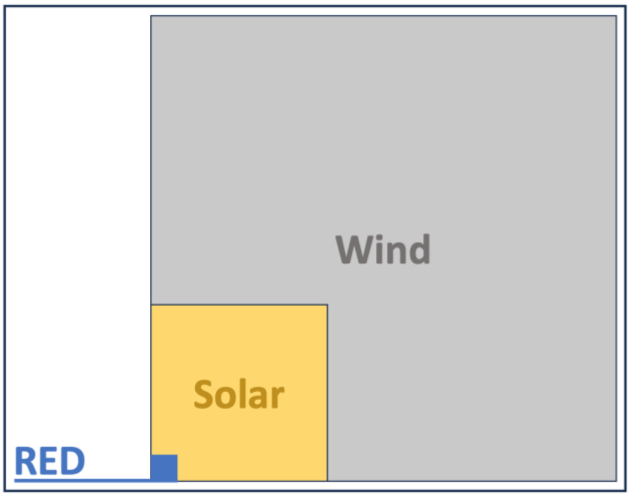


Figure 9: Comparison of the estimated relations of spatial requirements of wind and solar energy and RED, own illustration

2.2 A Theoretical Framework for Analyzing Barriers to SWDU-RED

The technical barriers of a technology lower its Technological Readiness Level (TRL) (Figure 10). The TRL is a measure used to assess the maturity and readiness of a technology or innovation for practical application. It ranges from TRL 1 (basic concept) to TRL 9 (fully implemented and proven in real-world conditions). The TRL scale helps researchers, engineers, and decision-makers gauge the development stage and potential risks of adopting a particular technology (Britt et al., 2008). However, between TRL 4 and TRL 7, many promising technologies are impeded in their progress due to a phenomenon known as the Valley of Death (Figure 11).

This phenomenon stands between academic research and successful commercialization (Hudson & Khazragui, 2013). The Valley of Death refers to the challenging phase where a promising technology faces significant difficulties in securing sufficient funding for transitioning from the laboratory or early development stages to commercial implementation (ibid.). Initially, the research on a promising innovation is funded publicly for academic research purposes. As research progresses in the early stages of invention, funding also increases because the evidence that the concept is feasible accumulates over time. However, academic interest typically peaks with the full proof of concept, usually with the creation of a prototype. Since knowledge creation is inherent to the self-perception of science, academic interest declines after a technical concept has been fully proven. Therefore, public funding for further development declines accordingly. However, there are still many costly steps necessary to develop a proven concept into a product that is ready for adoption by the private sector such as the construction of commercial manufacturing sites or the creation of a recycling scheme for spent parts. If a technology is in this stage between translation and adoption by the private sector, it is at risk of falling into a competency gap between academics and the private sector. Academic funding is hard to allocate for further development because the underlying concept has been proven exhaustively, but private sector funding is also challenging to allocate because the technology in question has not been proven at a commercial scale and there are possibly open questions concerning the feasibility of production and recycling chains, as well as maintenance.

Many innovations fail to progress beyond this stage due to a lack of financial support and market uncertainties, making it a critical and risky phase in the innovation process (Gbadegeshin et al., 2022).

Technical barriers in energy systems can translate into economic barriers and vice versa (Rae et al., 2020). Technical barriers directly impact the price of adopting the technology and hence the willingness of early adopters to consider SWDU-RED (Mankins, 2009). For example, technical limitations of a renewable energy technology can translate into lower energy efficiency and consequentially a higher cost of the electricity that is being produced. In turn, the higher electricity price might make the technology a less attractive option for investors and there might be a lack of funding for further research and development which leads to the persistence of technological barriers (Pérez Odeh et al., 2018). Further, more established technologies profit from a cost-benefit due to economies of scale that less developed technologies cannot benefit from (Weber, 2012).

This reciprocal relationship of technical and economic barriers can lead to a vicious cycle in which the existence of technical barriers leads to economic challenges that in turn lead to the continued existence of technical barriers (Sara et al., 2015). This cycle can cause promising technologies to come to an indefinite halt in their development. This can delay, or in the worst case, impede the adoption of a technology that would have had great potential for solving or mitigating pressing societal challenges such as global warming (ibid.).

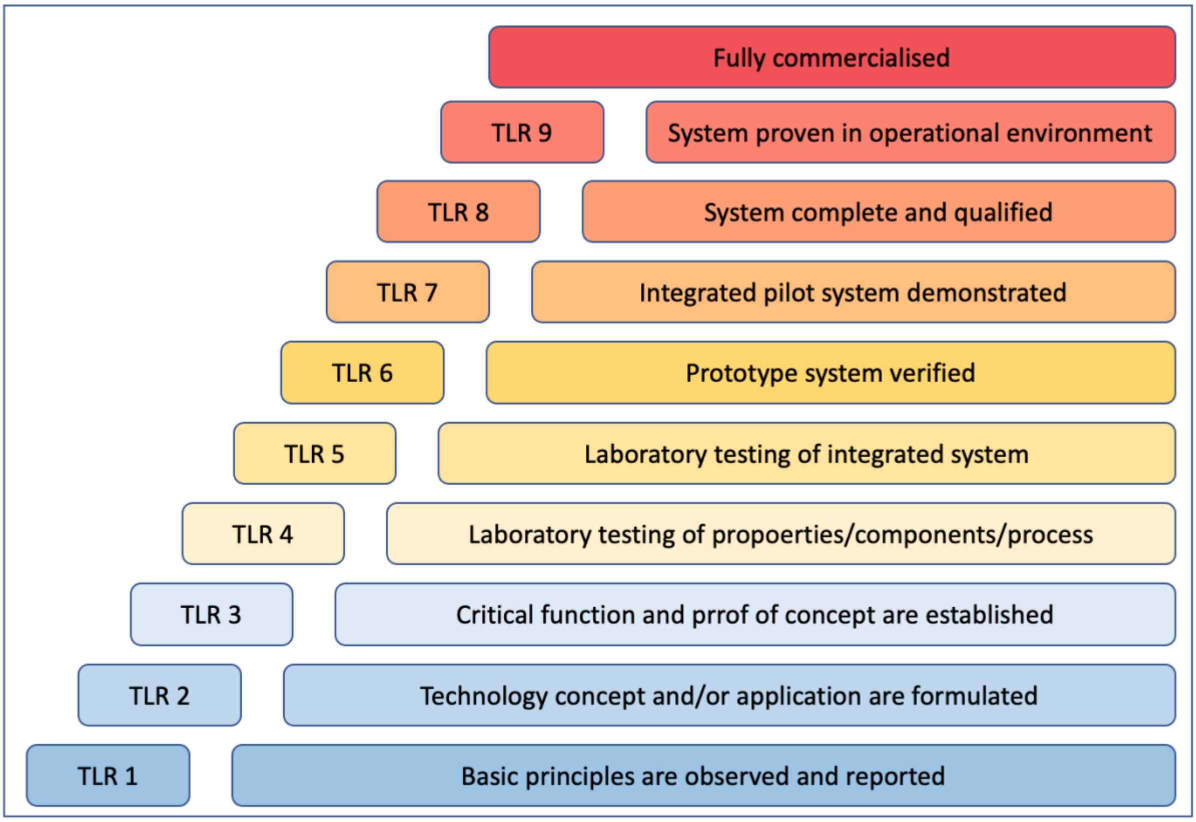


Figure 10: The scale of technological readiness levels (TRLs), own illustration based on (Fasterholdt et al., 2018)

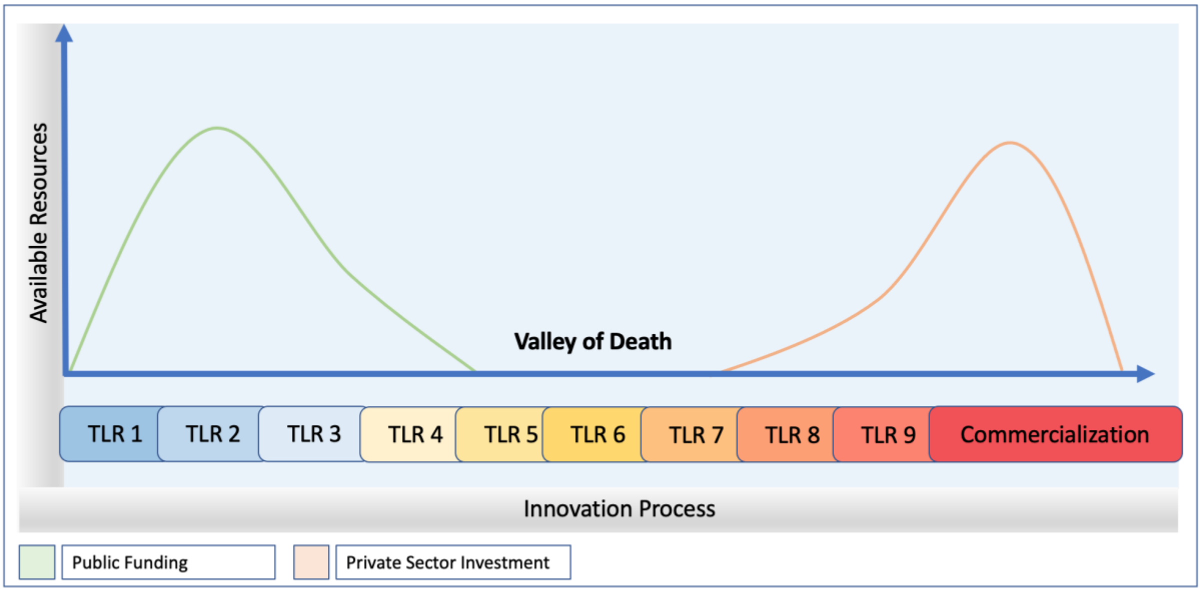


Figure 11: The funding gap between public capital for academic purposes and industry adoption coined the Valley of Death, own Illustration based on Gbadegeshin et al., (2022) and Hudson & Khazragui, (2013)

The Valley of Death arises due to several reasons. One primary cause is the uncertainty surrounding how a technology will perform on a larger scale, as well as uncertainty if this technology will be perceived as compliant with current regulatory frameworks. This can create a vicious cycle where the technology requires testing on a larger scale, but to do so, it needs funding and resources. However, securing funding becomes challenging as its viability on a larger scale remains unproven (Nemet et al., 2018). Additionally, established technologies pose stiff competition due to path dependencies and technology lock-ins (Breetz et al., 2018). Further, innovations in the sector of renewable energy have to overcome lock-ins and path dependencies in the energy sector which are classified as technological barriers by Polzin (2017) because of the insufficient technological maturity compared to fossil fuels.

Moreover, investors often exhibit risk aversion, being hesitant to invest in unproven technologies because of market uncertainties, adding to the challenges of crossing the Valley of Death and bringing innovations to fruition (Nemet et al., 2018). This market uncertainty and uncertain return on investment are also stated by Karakaya (2014) as major barriers to the technology diffusion of renewable energies. The capital intensity of radical innovation in renewable energy coupled with the high investment risk connected to them create an economic barrier in their development and make them especially vulnerable to not progressing beyond the funding gap of the Valley of Death.

This is especially the case for technologies that need substantial long-term investments to facilitate their commercialization. For example, if a technology needs large infrastructure or dedicated production facilities, the financial risk for investors is especially great, causing additional reluctance from potential investors (Weber, 2012). This makes renewable energy technologies especially vulnerable to falling victim to the Valley of Death because their upscaling commonly requires additional infrastructure, as well as production facilities for their parts (Goodfellow-Smith et al., 2020). Further, development times for renewable energies are very slow and can take up to 15 years from TRL1 to TRL9 (Weber, 2012). Other expenses may become necessary for example for recycling schemes of decommissioned parts or for training skilled labor in the maintenance and operation of the technology in question. Therefore, according to Olmos et al. (2012), technical and economic barriers, translate into underinvestment by private companies in the field of renewable energies, in particular.

Another issue specific to the energy sector is that provided energy is not a product in itself, but it is being used to deliver another product such as light, transportation or heat. Therefore, from a consumer perspective, using renewable energy over fossil fuels does not add any value to another product and often even goes unnoticed. Because of this, the competition of different sources of energy is largely based on price and, although this has been starting to change in recent years, fossil fuel has been - and largely still is - cheaper than renewable energy (Polzin, 2017; Trace, 2016). However, private capital is of crucial importance in the development of renewable energies (Murphy et al., 2003) and in the transition to renewable energies as a whole (J. Lee & Yang, 2019).

To summarize, technological and economic barriers are threatening radical innovations in the renewable energy sector because they contribute to the funding gap between the R&D stage and commercialization of a technology which is also known as the Valley of Death (Gbadegeshin et al., 2022). The valley of death can be bridged by private or public investment (Murphy et al., 2003). However, investing in radical innovations in the renewable energy sector is unattractive for investors because of the high necessary capital (Jenkins and Mansur, 2011), the insecurity of investment returns (Karakaya, 2014), fierce market competition from the fossil fuel industry (Polzin, 2017) and the general uncertainty from a project management point of view that is connected to radical innovations (Filippov & Mooi, 2010) (Figure 12). Nevertheless, investments in renewable energy are of crucial importance for the energy transition and by extension, the mitigation of the climate crisis (Olabi & Abdelkareem, 2022). Therefore, it is desirable to reduce hindrances to funding for promising renewable energy technologies such as SWDU-RED.

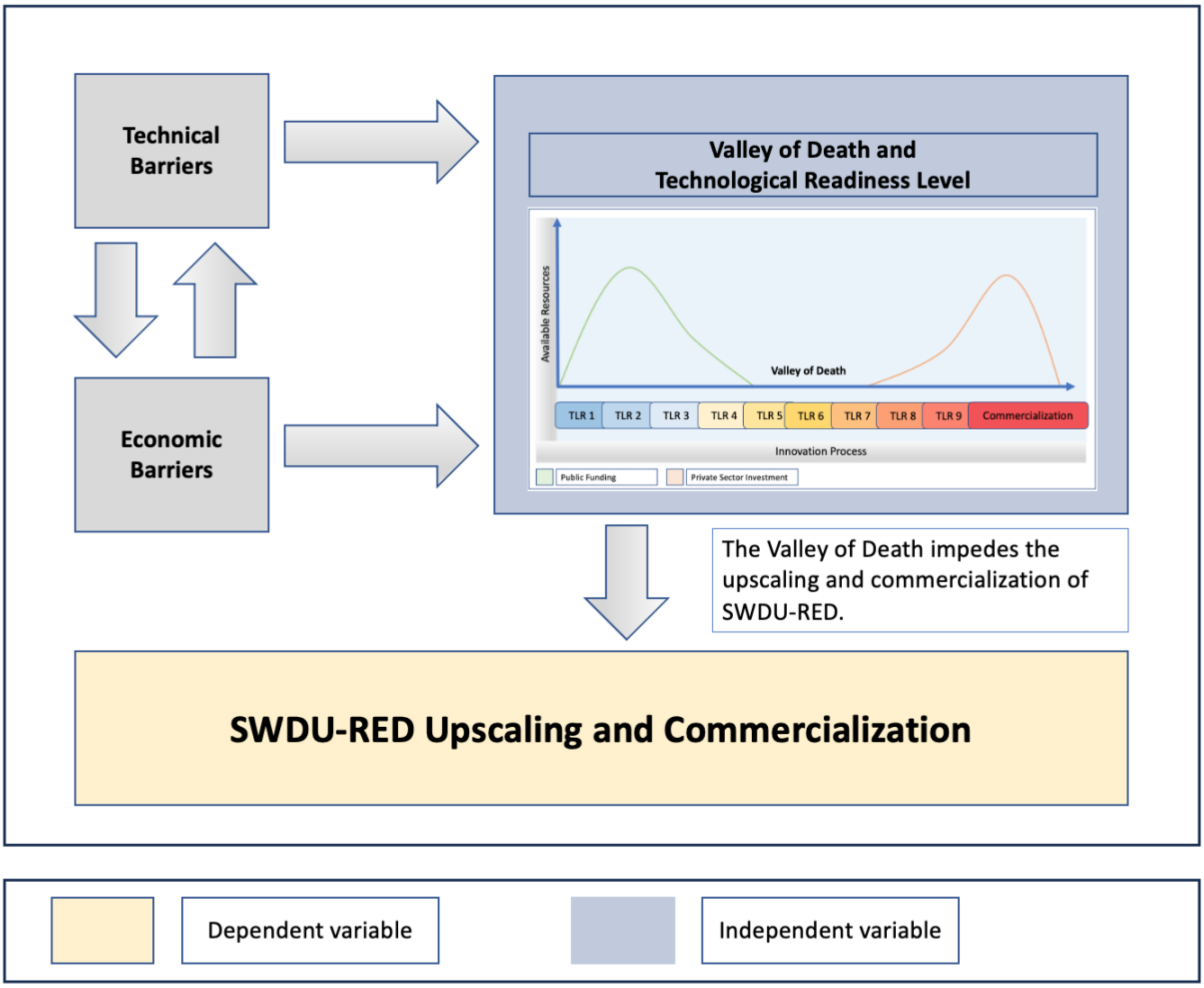


Figure 12: Graphical abstract of the conceptual model, own illustration.

3. Methodology

A Systematic Literature Review as a Tool for Elucidating Technical and Economic Barriers of SWDU-RED

As mentioned in Chapter 2, the body of literature concerning RED and SWDU-RED is growing rapidly and technical challenges are currently the main focus of the academic discussion. These technical barriers are closely connected to economic barriers that are in the way of the upscaling and commercialization of the approach of co-locating desalination plants with reverse electrodialysis. To synthesize existing knowledge from these numerous publications, a systematic literature review is an appropriate tool because it could aid in alleviating uncertainties on the side of private and public investors by providing unbiased, information regarding the current technological readiness of SWDU-RED, and technical as well as economic barriers.

Systematic literature reviews offer significant advantages in research and decision-making processes. By conducting a thorough analysis of existing studies on a specific topic, these reviews provide a comprehensive and unbiased assessment of the available evidence (Xiao & Watson, 2019). Researchers and policymakers rely on the evidence-based insights derived from systematic reviews to make informed decisions and develop effective strategies (Haddaway & Pullin, 2014). The rigorous methodologies employed in these reviews minimize bias, ensuring the reliability and credibility of the findings (ibid.). Furthermore, they help identify gaps in current research, guiding future studies and directing resources where needed (ibid.). Overall, systematic literature reviews play a crucial role in streamlining research efforts, saving time and resources, and enhancing the trustworthiness and generalizability of research outcomes. Their impact extends to influencing policy decisions, shaping professional practices, and contributing to broader knowledge advancement (ibid.).

An overview of the subsequent steps that were employed to conduct the systematic literature for this thesis can be gained in Figure 13.

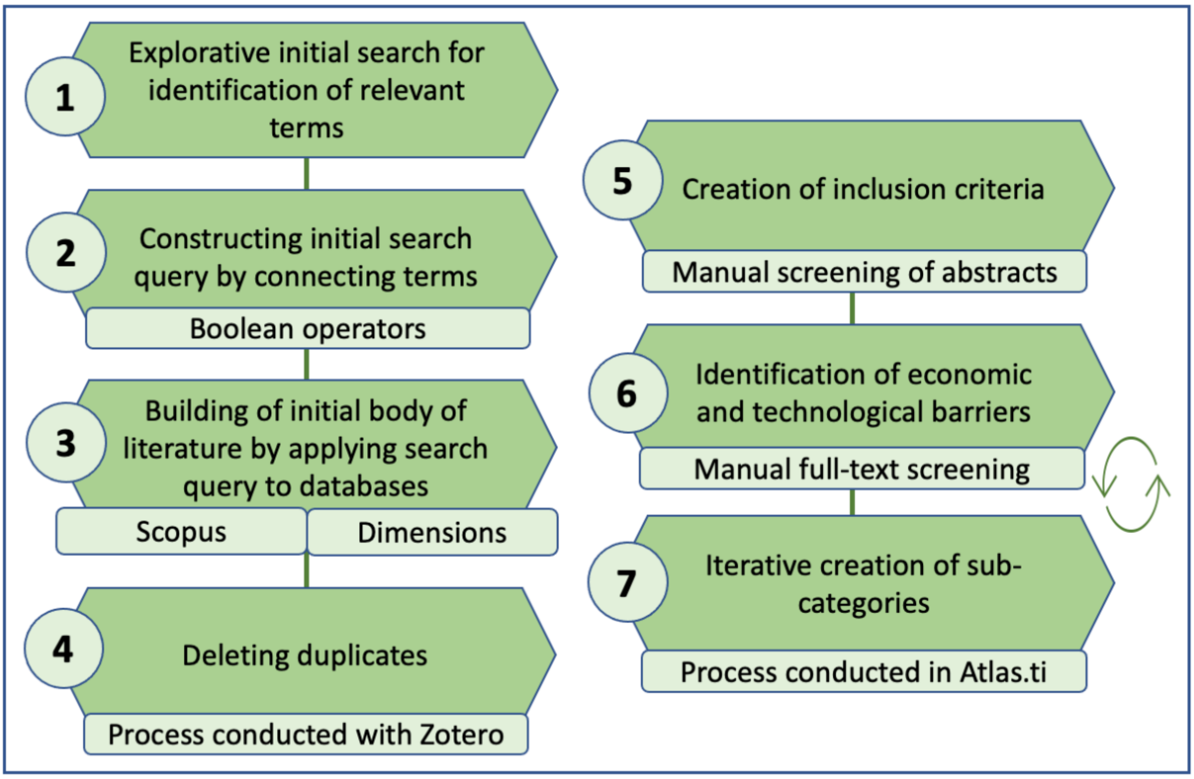


Figure 13: The subsequent steps of the systematic literature on economic and technical barriers against the upscaling and commercialization of SWDU-RED, own illustration.

Building of a Search Query with Boolean Operators

The approach for the literature review conducted in this work is adapted from the PALETTE method by Zwakman et al., (2018). PALETTE is geared towards conducting literature reviews in a rapidly evolving research field that lacks standardized terminology. It has been created to perform well even with explorative review questions that make term-based inquiries challenging. Good performance is achieved through an iterative process that allows for adjustments whenever a new search term or new literature is identified. Further, PALETTE consists of a combination of several literature retrieval methods and a validation process for testing whether all publications relevant to the research question are included in the review.

To shed light on political and economic barriers with the potential to hamper the upscaling and diffusion of SDWU-RED, a systematic literature based on Boolean operators was conducted (Table 1). Boolean operators are utilized to establish logical connections between search terms. For instance, the operator "AND" is employed to locate articles that encompass all the specified search terms, "OR" is employed to find articles that include any of the search terms, and "NOT" is used to eliminate articles that contain particular terms (Ryan, 2022). This provides a possibility to construct precise and focused search queries by connecting terms and specifying relationships between them, allowing for retrieving the most relevant articles. Boolean operators are key features of literature reviews because they assure reproducibility and transparency (Hollier, 2020). The search terms that build the basis for the search query were sourced based on synonyms of the key terms related to the main research question and the associated sub-questions.

Table 1: Search terms and resulting search query for explorative initial explorative search on economic and technical barriers against the upscaling and commercialization of SWDU-RED

RED and related	**Desalination plant**	**Desalination**	**Brine**
- Blue energy - Reverse-electrodialysis - reversed electrodialysis - Salt gradient energy - salinity gradient power - osmotic power	- desalination plant	- desalination	- Brine - saltwater

Search query with Boolean Operators for initial explorative search
(“Blue energy” OR “Reverse-electrodialysis” OR “Salt gradient energy” OR “salinity gradient power” OR “osmotic power”) AND (“desalination” OR “brine” OR “saltwater”)

Application of the Search Query to the Databases Dimensions and Scopus

The search query was applied to the databases Dimensions and Scopus. Dimensions was chosen for its exhaustive journal coverage. Dimensions has been launched in 2018 (Williams, 2018) and is therefore relatively new compared to other more established databases such as Scopus which exists since 2004 (Sullo, 2007) and Web of Science which originates from the 1960s as the Science Citation Index (Birkle et al., 2020). However, Dimensions has the most comprehensive journal coverage, containing 82.22% more journals than Web of Science and 48.17% more than Scopus (Singh et al., 2021). Scopus was selected for this literature review because its usage for scientific literature inquiries is well established in the academic community (Harzing & Alakangas, 2016).

An explorative literature search with terms based on the research questions was conducted. In the process of this, 337 papers from Scopus and 243 from Dimensions.ai between the years 2017 and 2023 have been downloaded manually. The initial combined body of literature was therefore comprised of 580 academic publications. Almost all publications could be accessed through either the online portal of the University of Groningen or the Carl von Ossietzky University of Oldenburg. However, four articles remained inaccessible. These articles were requested from the corresponding authors of the publications via the online platform Research Gate. However, at the time of writing this document, there has not been any reaction to these requests. Consequentially, these four inaccessible articles were omitted from the analysis for the systematic literature review.

Further, all articles older than 2019 have been omitted from the analysis, because of the large number of encountered publications in the initially set time frame for sourced publication dates ranging from 2017 to 2023. The large number of these articles highlights how rapidly the research field around RED and SWDU-RED is evolving. Therefore, because the field of RED is constantly advancing, older articles may not reflect the latest developments, technologies, or findings, leading to outdated and potentially inaccurate information. Further, methodologies used in older studies might not meet current standards or lack the robustness of more recent research, impacting the reliability and validity of their findings. Additionally, newer publications may have addressed gaps or limitations identified in older studies, providing more comprehensive and up-to-date insights. Consequentially, focusing on more recent articles ensures that the review incorporates the most relevant and reliable research, leading to more accurate and up-to-date conclusions. After all publications older than 2019 had been excluded from the literature review, the remaining body of literature counted 213 articles.

Further, all duplicates of the remaining articles that were published between 2019 and 2023 that have been found with the above mentioned search query (Table 1) in Dimensions.ai, as well as in the Scopus database have been deleted. For this purpose, a register in the citation management software Zotero has been created and all downloaded articles have been imported into a dedicated Zotero folder. Since the Zotero citation manager lists all articles alphabetically, all duplicate articles were listed next to each other and via comparing article titles, all duplicates could be manually deleted. After the manual deletion of duplicate articles, 213 articles were remaining.

Subsequently, screening criteria based on PRISMA guidelines (Page et al., 2021) were developed (Table 2) and applied to the body of literature to classify eligible publications. After performing the search in Scopus and Dimensions.ai databases, the eligibility criteria were applied to all sourced articles to remove unsuitable publications.

Table 2: Inclusion criteria for publications to be included in the systematic literature review.

Inclusion Criteria
Not older than 2019
Must be a scientific article
Main article in English
Must be concerned with SWDU-RED
Must mention economic or technical barriers

RED must be employed as an open system to exclude RED literature that is focused on RED heat engines
The literature needs to concern RED applications in which the utilized brine must stem from a desalination plant or if the brine is artificially produced for experimental studies, it needs to be manufactured to be similar to desalination brine. Further, the brine needs to be used as the high salinity solution in RED to exclude RED literature that concerns brines from other sources than desalination such as brine from oilfields or geothermal brine.

Initially, the screening criteria were applied only to the abstracts of the remaining 213 articles in order to advance the screening process faster. After the abstract screening, 115 articles remained for closer inspection with manual full-text screening.

In the manual full-text screening, abstract, discussion and conclusion were screened for technical and economic barriers against the upscaling and commercialization of SWDU-RED. However, there were some isolated cases in which publications did not follow the traditional structure that includes abstract, introduction, methodology, results, discussion and conclusion. Instead, individual titles were chosen for the sections of these publications by their authors. Therefore, a screening of the full text including all sections was conducted for these instances.

For the manual full-text screening of the articles, all 115 publications were imported into Atlas.ti. However, during the full-text screening process, further articles that did not match the inclusion criteria and had not been discovered during the abstract screening were excluded. Although these articles were mostly closely related to the topic of economic and technical barriers in the commercialization of SWDU-RED, most of them had their main focus on pressure retarded osmosis which is another form of salinity gradient energy. Further, some publications were excluded that focused on other RED applications, such as RED as a heat engine for the energy recuperation from industrial residual heat. During the process of screening the articles more in detail, 40 more articles were excluded in this way. Consequentially, 75 articles remained included in the systematic literature review after the application of the inclusion criteria during full text screening of all articles.

Collection of Economic and Technical Barriers in the Literature Screening Process

After the eligibility criteria were employed to reduce the number of articles that would be screened for the literature review, the remaining publications were screened for economic and technical barriers to the diffusion and upscaling of SWDU-RED using Atlas.ti.

Initially, the eligible publications were uploaded into Atlas.ti for further analysis. The screening process involved identifying economic and technical barriers by marking relevant quotations within the software. The literature screening encompassed the abstract, results, discussion, and conclusions of the publications. Throughout the identification of barriers, the creation of sub-categories (Tables 4 to 7) was undertaken concurrently, employing an iterative approach. This iterative process allowed for the refinement and development of sub-categories as new information and insights emerged from the analysis. During the screening and categorization, a total number of 894 quotations were marked, reflecting the breadth and depth of the identified barriers. Further, a total of 142 codes were created for the categorization of these barriers.

Subsequently, the marked barriers were sorted into appropriate sub-categories based on their thematic relevance, enabling a more organized representation of the diverse challenges. To enhance the categorization process, the establishment of sub-sub-categories was carried out simultaneously with the sub-categories.

Lastly, a final screening of all quotations was conducted to ensure that no barriers had been overlooked or inadvertently omitted. This step aimed to maintain the integrity and completeness of the identified barriers, allowing for a robust analysis and synthesis of the findings.

4. Results

The Four Main Barriers Against the Upscaling and Commercialization of SWDU-RED

The structured literature revealed four main barriers that are potentially constricting the commercialization and upscaling of SWDU-RED (Table 3). These four main barriers consist of a major technical barrier, one main economic barrier and two techno-economic barriers. The four main barriers are:

(1) Low power density/energy efficiency of SWDU-RED (technical)
(2) High cost of SWDU-RED and subsequently high cost of energy (economic)
(3) Immaturity of the technology (techno-economic)
(4) Lack of competitiveness against other technologies that could be used instead of SWDU-RED (techno-economic)

These four main barriers each consist of several sub-barriers that will be presented in the following sections.

Table 3: The main four barriers against the upscaling and commercialization of SWDU-RED according to literature.

	Barriers	Sources
1	Low power density and energy efficiency	(Ahmed et al., 2020; Avci, Messana, et al., 2020; Avci et al., 2021; Bazinet & Geoffroy, 2020; M. Chen et al., 2019; Fan & Yip, 2019; Gurreri et al., 2020; J.-H. Han, 2022; X.-W. Han et al., 2021; Herrero-Gonzalez & Ibañez, 2021; Hossen et al., 2020; Hulme et al., 2021; Jeanmairet et al., 2022; Ju et al., 2021, 2022; Kang et al., 2022; S. Lee et al., 2019; J. Li et al., 2022; Mavukkandy et al., 2019; Mehdizadeh et al., 2021; Mishchuk, 2023; Nazif et al., 2022; Panagopoulos & Giannika, 2022; Pawlowski et al., 2020; Ranade et al., 2022; Sampedro et al., 2023; Santoro et al., 2021; Sedighi et al., 2023; Shadravan et al., 2022; T. Sun et al., 2022; Tian et al., 2020; Tristán, Fallanza, et al., 2020a; Tufa et al., 2019; J. Wang, Wang, et al.,

		2023; J. Wang, Zhou, et al., 2023; Xin et al., 2019, 2021; Yasukawa et al., 2020; Zoungrana & Çakmakci, 2021a)
2	High costs	(Ahmed et al., 2020; Avci, Rijnaarts, et al., 2020; Avci et al., 2021; Bazinet & Geoffroy, 2020; M. Chen et al., 2019; Choi, Oh, et al., 2019; Gurreri et al., 2022; X.-W. Han et al., 2021; Herrero-Gonzalez & Ibañez, 2021; Hulme et al., 2021; Mavukkandy et al., 2019; Mei et al., 2020; Nazif et al., 2022; Panagopoulos & Giannika, 2022; Pawlowski et al., 2020; Ranade et al., 2022; Sedighi et al., 2023; Tian et al., 2020; Tristán, Fallanza, et al., 2020a; Tufa et al., 2019; X. Zhang et al., 2021; Zhou et al., 2022; Zoungrana & Çakmakci, 2021a)
3	Technological immaturity	(Ahmed et al., 2020; Avci, Messana, et al., 2020; Avci, Rijnaarts, et al., 2020; Avci et al., 2021; Bazinet & Geoffroy, 2020; M. Chen et al., 2019; Choi, Oh, et al., 2019; Culcasi et al., 2020; Faghihi & Jalali, 2022; Fan et al., 2020; Fan & Yip, 2019; Gómez-Coma et al., 2019; Gurreri et al., 2022; J.-H. Han, 2022; Herrero-Gonzalez & Ibañez, 2021; Hossen et al., 2020; Jianbo et al., 2021; Ju et al., 2022; S. Lee et al., 2019; J. Li et al., 2022; Mavukkandy et al., 2019; Mei et al., 2020; Mishchuk, 2023; Nazif et al., 2022; Panagopoulos & Giannika, 2022; Pawlowski et al., 2020; Ranade et al., 2022; Rehman et al., 2020; Sampedro et al., 2023; Santoro et al., 2021; Sedighi et al., 2023; Seyfried et al., 2019; Tian et al., 2020; Tristán, Fallanza, et al., 2020a; Tristán, Rumayor, et al., 2020; Tufa et al., 2019; Wagholikar et al., 2020; J. Wang, Zhou, et al., 2023; Z. Wang, Li, Wang, et al., 2022; Xin et al., 2021; Yasukawa et al., 2020; Zoungrana & Çakmakci, 2021a)
4	Lack of competitiveness	(Ahmed et al., 2020; X.-W. Han et al., 2021; Herrero-Gonzalez & Ibañez, 2021; Ju et al., 2021; S. Lee et al., 2019; Marbach & Bocquet, 2019; Mavukkandy et al., 2019; Mei et al., 2020; Panagopoulos, 2022; Panagopoulos & Giannika, 2022; Ranade et al., 2022; Shadravan et al., 2022; Tristán, Rumayor, et al., 2020; X. Zhang et al., 2021; Zoungrana & Çakmakci, 2021a)

The Low Power Density and Energy Efficiency of SWDU-RED

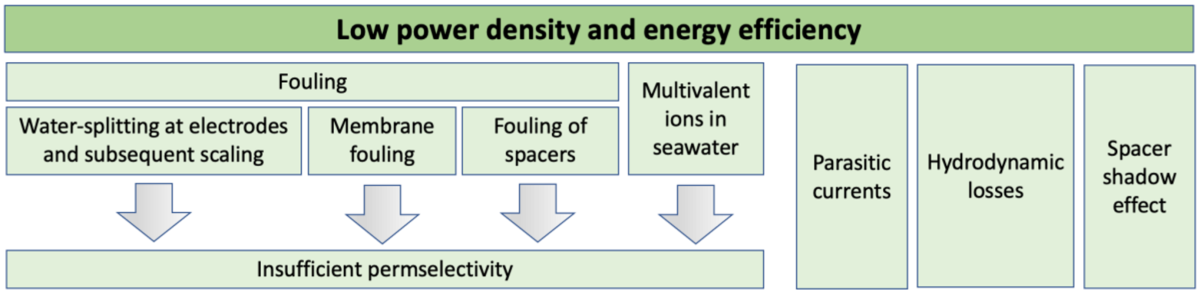


Figure 14: Connection of the sub-barriers of the major barrier of low power density and energy efficiency, own illustration.

The main technical barrier in the way of the commercialization of SWDU-RED that is widely acknowledged in literature consists of low power densities and low energy efficiencies (Table 3, Row 1) (Figure 14). The cause of this is poor energy conversion irreversibility of SWDU-RED

(Table 4, Row 1). Energy conversion irreversibility refers to the energy losses that occur during the process of converting one form of energy into another, resulting in a decrease in the overall available energy. While some energy losses are inevitable in any energy technology, losses should be minimized in order to harness as much usable energy as possible to improve overall system efficiency.

Generally, salinity gradient technologies currently dissipate a significant portion of the extractable energy, as noted by (Jeanmairet et al., 2022). In the case of SWDU-RED, if all the salinity gradient energy could be harnessed, SGE-RED could meet approximately 40% of the total energy demand for desalination plants worldwide, but due to the poor energy conversion irreversibility of SWDU-RED, there is a large untapped potential (Tristán, Fallanza, et al., 2020b, 2020a). Therefore, the actual contribution to the energy needed for desalination that could be supplied by SWDU-RED would be closer to 10%, accounting for the poor current energy efficiency of SWDU-RED.

The in literature most widely acknowledged factor that reduces the energy efficiency of RED and SWDU-RED is the insufficient permselectivity of ion exchange membranes (Table 4, Row 3). Permselectivity refers to the membrane's ability to selectively allow the passage of certain ions while blocking others. The membrane discriminates between different ions based on their size, charge, and other chemical properties (Fan et al., 2020; Fan & Yip, 2019). An inhibition of permselectivity consequentially diminishes the ion flux that is converted into electricity at the electrodes and therefore diminishes the overall power density (Pintossi et al., 2021). This can be caused by several phenomena, but the most notable among them is membrane fouling (Table 4, Row 2).

Fouling refers to the accumulation of unwanted substances on the surface of ion exchange membranes or other stack components, hindering their performance. It occurs when particles, organic matter, or inorganic mineral deposits adhere to the stack components (Nazif et al., 2022). If fouling is caused by inorganic substances it is commonly referred to as scaling (Gurreri et al., 2022). According to Han et al., (2021, p. 4), fouling is a major hurdle against RED-development because it can reduce power density by up to 60%. Membrane fouling leads to these large losses in power density because it reduces ion transport (Nazif et al., 2022) due to the clogging of membrane channels (Ma et al., 2021) which ultimately results in a reduced membrane permselectivity (Kang et al., 2022). Further, membrane channel clogging leads to a heightened resistance of the whole system which in turn has an additional negative impact on the energy efficiency (Santoro et al., 2021). Moreover, fouling decreases membrane lifetimes which leads to the necessity to replace membranes with a higher frequency (Zoungrana & Çakmakci, 2021b).

However, not only membranes are susceptible to fouling. Less frequently mentioned, but prevalent nonetheless are the fouling propensity of other stack components such as spacers and electrodes. It is worth noting that spacers are even more susceptible to fouling compared to membranes themselves, as emphasized by Bazinet and Geoffroy (2020) which increases the overall stack resistance.

Further, unwanted water splitting at the electrodes can induce inorganic fouling, also known as scaling. Water splitting refers to the process of electrochemically splitting water into H+

and OH- ions (Mavukkandy et al., 2019). In RED this can be utilized for hydrogen production (Ranade et al., 2022), but happens also unwanted in applications where this is not intended (Gurreri et al., 2022; Mavukkandy et al., 2019). Unwanted water splitting increases the pH level of the feed solutions which causes minerals to solidify in the feed solutions and deposit on stack components (J.-H. Han, 2022). As described previously, scaling causes significant energy efficiency losses. In the case of involuntary water splitting, especially ohmic losses at the electrode are to be considered (Yasukawa et al., 2020).

Another cause of reduced permselectivity in ion exchange membranes of RED and SWDU-RED is caused by multivalent ions. Multivalent ions, such as Mg2+, Ca2+, and SO42−, occur naturally in seawater and have a detrimental impact on the performance of reverse electrodialysis (RED) systems. Choi et al. (2019) explain that these ions cause a decrease in power density and permselectivity while increasing stack resistance. This phenomenon occurs due to the uphill transport of multivalent ions against the concentration gradient, as described by Nazif et al. (2022). Uphill ionic transport refers to the movement of multivalent ions against the concentration gradient during the ion exchange process. Among these ions, Mg2+ has the most significant reduction in the output power of the stack, as noted by Z. Wang et al. (2022). Vermaas et al. (cited in Zoungrana & Çakmakci, 2021a) reported a decrease in power density ranging from 29% to 50% due to Mg2+ and SO42−, raising concerns about the practical feasibility of RED in real-world environments.

Additional losses in energy efficiency that are considered in literature (Table 4, Row 4) are caused by so-called parasitic currents (Culcasi et al., 2020; Gurreri et al., 2022; Tufa et al., 2018). Parasitic currents are unintended electrical pathways that occur in ion exchange membranes. These currents bypass the desired ion transport pathways and create alternative routes for the flow of electrical charge which reduces the efficiency of ion transport and compromises the overall performance of ion exchange membranes (Culcasi et al., 2020).

Further, as emphasized by Nazif et al. (2022) and other publications (Table 4, Row 5) there is a need to minimize resistance by optimizing the hydrodynamic design of the stack and reducing residence time of feed solutions.

Additional energy efficiency losses are caused by spacers. Spacers serve two primary purposes in the RED system: providing mechanical support to ion exchange membranes and creating flow channels to separate the feed solutions within the module. However, the non-conducting nature of spacer materials, typically meshes, introduces additional resistance known as the "spacer shadow effect," as stated by Zoungrana and Çakmakci (2021a).

Table 4: Sub- barriers of barrier (1) Low power density and energy efficiency.

	Barriers	**Sources**
1	Energy efficiency losses due to energy conversion irreversibility	(Avci, Messana, et al., 2020; Avci et al., 2021; Choi, Oh, et al., 2019; Gurreri et al., 2022; X.-W. Han et al., 2021; Herrero-Gonzalez & Ibañez, 2021; Jeanmairet et al., 2022; Kang et al., 2022; S. Lee et al., 2019; Mehdizadeh et al., 2021; Mishchuk, 2023; Nazif et al., 2022; Sampedro et al., 2023; Tristán, Fallanza, et al., 2020a, 2020b; Tristán, Rumayor, et al., 2020; J. Wang, Zhou, et al., 2023; Xin et al., 2019, 2021; Zoungrana & Çakmakci, 2021a)

2	Fouling	(Bazinet & Geoffroy, 2020; Choi, Oh, et al., 2019; Faghihi & Jalali, 2022; Gurreri et al., 2022; J.-H. Han, 2022; X.-W. Han et al., 2021; Ju et al., 2022; Kang et al., 2022; L. Ma et al., 2021; Mavukkandy et al., 2019; Mishchuk, 2023; Nazif et al., 2022; Pawlowski et al., 2020; Roman et al., 2019; Santoro et al., 2021; Sedighi et al., 2023; Seyfried et al., 2019; Tian et al., 2020; Tristán, Rumayor, et al., 2020; J. Wang, Zhou, et al., 2023; Xin et al., 2021; Yasukawa et al., 2020; Y. Zhang et al., 2019; Zoungrana & Çakmakci, 2021a)
3	Insufficient permselectivity	(Avci, Messana, et al., 2020; Avci, Rijnaarts, et al., 2020; Bazinet & Geoffroy, 2020; M. Chen et al., 2019; Choi, Oh, et al., 2019; Fan et al., 2020; Fan & Yip, 2019; Gómez-Coma et al., 2019; Gurreri et al., 2022; Herrero-Gonzalez & Ibañez, 2021; Hossen et al., 2020; Hulme et al., 2021; Jianbo et al., 2021; Ju et al., 2022; Kang et al., 2022; J. Li et al., 2022; L. Ma et al., 2021; Mavukkandy et al., 2019; Mehdizadeh et al., 2021; Mei et al., 2020; Mishchuk, 2023; Nazif et al., 2022; Ortiz-Imedio et al., 2019; Panagopoulos & Giannika, 2022; Pawlowski et al., 2020; Ranade et al., 2022; Santoro et al., 2021; Sedighi et al., 2023; Shadravan et al., 2022; X. Sun et al., 2022; Tristán, Fallanza, et al., 2020b; Tufa et al., 2019; J. Wang, Wang, et al., 2023; J. Wang, Zhou, et al., 2023; Z. Wang, Li, Wang, et al., 2022; Xin et al., 2021; Yasukawa et al., 2020; Zoungrana & Çakmakci, 2021a)
4	Parasitic currents	(Culcasi et al., 2020; Gurreri et al., 2020; J.-H. Han, 2022; Tufa et al., 2019)
5	Hydrodynamic losses	(Ahmed et al., 2020; Bazinet & Geoffroy, 2020; Choi, Oh, et al., 2019; Jianbo et al., 2021; Kang et al., 2022; J. Li et al., 2022; W. Liu et al., 2022; Nazif et al., 2022)
6	Spacer shadow effect	(Wagholikar et al., 2020; Zoungrana & Çakmakci, 2021b)

The High Cost of SWDU-RED and Subsequently High Cost of Produced Energy

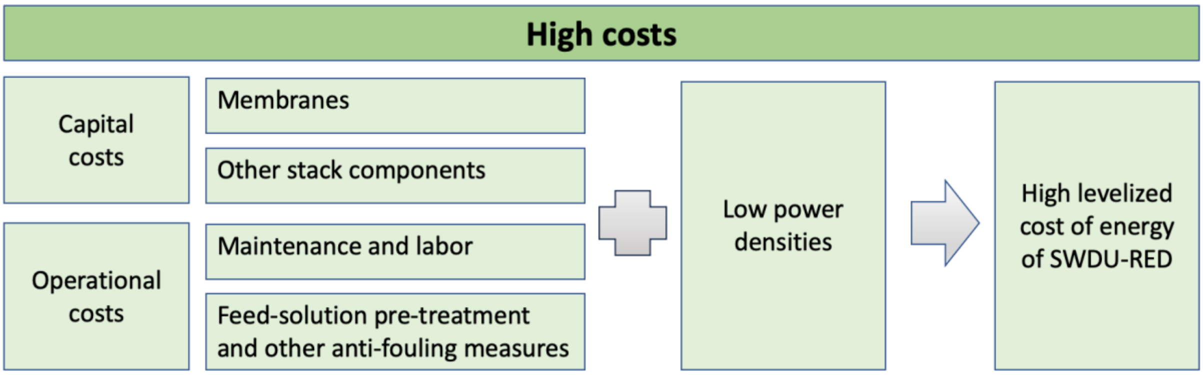


Figure 15: Connection of the sub-barriers of the major barrier of high costs of SWDU-RED, own illustration.

Currently, RED is generally associated with high costs according to Panagopoulos & Giannika (2022) and numerous other publications (Table 3, Row 2) (Figure 15). These high capital and operational costs for RED constitute a major economic barrier for SWDU-RED because they make it challenging for RED to compete with established energy sources in desalination that have benefited from economies of scale and widespread deployment.

The high capital costs of RED are mainly caused by high prices for the components of RED stacks. The most notable costs are caused by high prices for ion exchange membranes (Bazinet & Geoffroy, 2020; Herrero-Gonzalez & Ibañez, 2021). This is also emphasized by numerous other publications (Table 5, Row 2). Avci et al., (2020, p. 9) regard membrane prices as “one of the most challenging limitations” for RED and Zhang et al., (2021 p. 21) conclude that membranes make up approximately 50 to 80% of the overall capital costs for RED. Currently, the prices for membranes range from 10 to 30€ per square meter and would need to be lessened to 2 to 5€ per square meter of ion exchange membrane (ibid.). Additional capital costs are caused by other stack components such as spacers and electrodes (M. Chen et al., 2019; Zoungrana & Çakmakci, 2021b).

Further, in addition to the capital expenditures necessary to build a RED plant in the first place, there are substantial operational costs (Table 5, Row 3). According to Ranade et al., (2022), the operational costs of RED are primarily caused by pre-treatment of feed solutions, as well as cleaning and maintenance of membranes. A smooth operation of SWDU-RED depends on regular membrane cleaning and anti-fouling treatments of feed solutions because they prevent the premature deterioration of ion exchange membranes (Gurreri et al., 2020). These fouling prevention measures are especially costly because they require skilled labor (Ranade et al., 2022).

The elevated prices associated with ion exchange membranes, spacers, electrodes, and labor costs during the operation of SWDU-RED in combination with low power densities (Chapter 4) consequentially cause a substantial levelized cost of the produced energy (Table 5, Row 4). The consequence of these high levelized costs of energy is that RED may be perceived as a less favorable choice for co-locating with desalination plants when compared to alternative renewable energy sources. In comparison to other renewable energy technologies, the elevated levelized cost of energy could potentially hinder the widespread adoption of SWDU-RED. The perceived disparity in costs may incline decision-makers to favor alternative renewable energy options that demonstrate more favorable economic viability and cost-effectiveness.

Table 5: Sub- barriers of barrier (2) High cost of SWDU-RED and subsequently high cost of energy.

	Barriers	**Sources**
1	Generally high costs for RED and SWDU-RED	(Choi, Dorji, et al., 2019; Gurreri et al., 2020; Herrero-Gonzalez & Ibañez, 2021; Hulme et al., 2021; Mavukkandy et al., 2019; Nazif et al., 2022; Panagopoulos & Giannika, 2022; Ranade et al., 2022; Santoro et al., 2021; Seyfried et al., 2019; Tristán, Fallanza, et al., 2020a; Zhou et al., 2022; Zoungrana & Çakmakci, 2021a)
2	Capital costs	
	Membrane cost	(Ahmed et al., 2020; Avci et al., 2021; Avci, Rijnaarts, et al., 2020; Bazinet & Geoffroy, 2020; M. Chen et al., 2019; X.-W. Han et al., 2021; Herrero-Gonzalez & Ibañez, 2021; Hulme et al., 2021; Mei et al., 2020; Mueller et al., 2021; Nazif et al., 2022; Pawlowski et al.,

		2020; Ranade et al., 2022; Sedighi et al., 2023; Tian et al., 2020; Tufa et al., 2019; X. Zhang et al., 2021; Zoungrana & Çakmakci, 2021a)
	Other components such as spacers and electrodes	(M. Chen et al., 2019; Sedighi et al., 2023; Zoungrana & Çakmakci, 2021b)
3	Operational costs	(Bazinet & Geoffroy, 2020; Gurreri et al., 2020; X.-W. Han et al., 2021; Mavukkandy et al., 2019; Mueller et al., 2021; Nazif et al., 2022; Pawlowski et al., 2020; Ranade et al., 2022; Santoro et al., 2021; Sedighi et al., 2023; Seyfried et al., 2019; Xin et al., 2021; Zoungrana & Çakmakci, 2021a)
4	High levelized cost of energy	(X. Zhang et al., 2021; Zoungrana & Çakmakci, 2021b)

Technological Immaturity

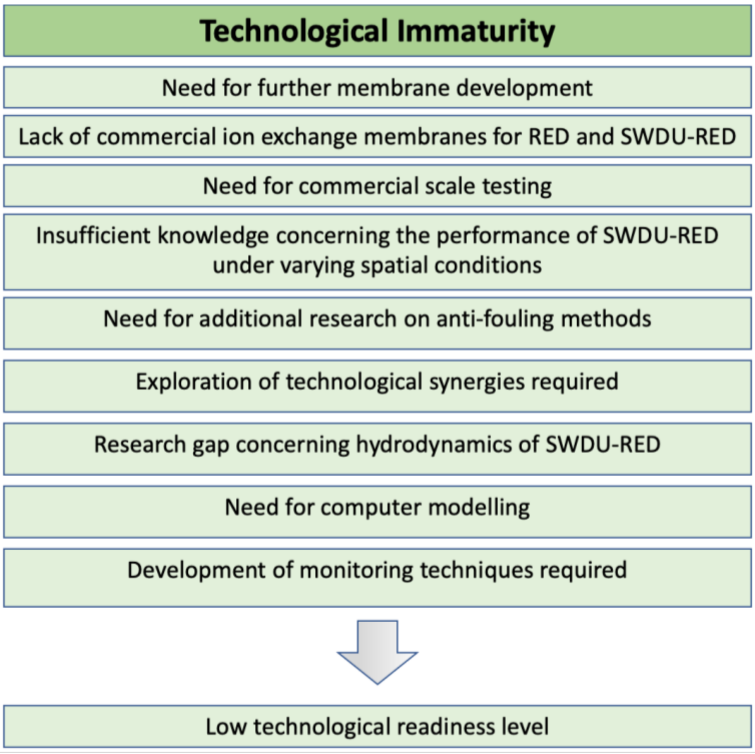


Figure 16: Connection of the sub-barriers of the technological immaturity of SWDU-RED, own illustration.

As emphasized by the academic community in numerous publications (Table 3, Row 3), there is still a substantial need for further research concerning RED and SWDU-RED despite the rapidly growing body of literature in this field (Figure 16). This demand for further research is mainly focused on advancing ion exchange membranes (Table 6, Rows 2 and 3).

As mentioned by Herrero-Gonzalez & Ibañez, (2021), further research on membranes is crucial for the economic viability of SWDU-RED because for a commercialization of the approach, it is necessary to decrease membrane prices and increase the energy efficiency of ion exchange membranes for SWDU-RED.

However, there are to date no membranes commercially available that have been specifically designed for the purpose of RED (Avci, Rijnaarts, et al., 2020; Nazif et al., 2022) which is regarded as a major issue in several publications (Table 6, row 3). Commonly, electrodialysis (ED) membranes are being utilized for RED (Zoungrana & Çakmakci, 2021b). ED is an established desalination method and therefore, ED membranes are commercially available at reasonable prices. Because RED is the reversed process of ED, ED membranes are to a degree functional for RED applications (ibid.). However, the energy yield is not ideal because ED membranes do not fit the technical requirements for energy efficient RED fully (ibid.).

Additionally, SWDU-RED requires membranes that perform well with very high salinity solutions because of the high salt content of the concentrated brine from desalination plants. However, currently commercially available ion exchange membranes underperform when the ion content of the feed solutions is too high (Fan & Yip, 2019). This renders the lack of commercial membranes an even larger barrier for SWDU-RED than for RED which is commonly performed with lower salinity feed solutions.

Because of the lack of commercially available membranes, the energy efficiency of SWDU-RED with ED membranes is low which increases the overall levelized cost of energy of SWDU-RED (Zoungrana & Çakmakci, 2021a). Other membranes that are better suitable for SWDU-RED are currently being developed and there are promising results (Avci, Rijnaarts, et al., 2020; Bazinet & Geoffroy, 2020; Culcasi et al., 2020). However, they are not yet commercially available which means that supplying SWDU-RED with novel membrane technologies would make SWDU-RED more energy efficient on one hand, but organizationally difficult and expensive because the experimental membrane technologies do not yet benefit from the economics of scale due to being produced in limited numbers in experimental processes.

Further, there are calls from the academic community that more large-scale testing for RED, as well as SWDU-RED, is necessary to alleviate uncertainties. While there are pre-existing pilot plants testing RED, as well as SWDU-RED, they are not yet at the scale of an actual commercial application (Zoungrana & Çakmakci, 2021b).

For example, Ahmed et al., (2020, p. 19) stated that the acceleration and evaluation of pilot plant implementation would enhance the viability of their transition, making them more commercially feasible for large-scale industrial operation alongside alternative desalination methods. Further, in addition to larger scale testing, Ma et al., (2021) consider longer time frames essential. Moreover, Panagopoulos & Giannika, (2022) note that the large-scale operation of PRO has been investigated more in depth compared to scaled-up RED operations which constitutes a disadvantage for RED concerning the commercialization of both technologies. Wagholikar et al., (2020) consider scaled up experiments with SWDU-RED important for determining how to achieve the greatest possible efficiency concerning the parameters such as stack size and flow path length. Further, Zoungrana & Çakmakci, (2021a) criticize that due to the lack of full-scale SWDU-RED implementations, there is no reliable data available on the energy return on investment of potential commercial applications. Further, Tristán et al. (2020) concluded that full scale operation is a necessity in order to conduct a comprehensive environmental load assessment for SWDU-RED. Other publications that also recommend the scaled-up application of RED as a crucial step for its commercialization include Seyfried et al., (2019) and Wagholikar et al. (2020).

Further, most experimental research concerning RED and SWDU-RED has been conducted with artificial laboratory made feed solutions (Choi, Oh, et al., 2019; Gurreri et al., 2020). This is regarded as problematic in the research community (Table 6, Row 5). Real feed solutions for SWDU-RED, namely desalination brine and sea water, contain organic, as well as inorganic compounds that can cause membrane fouling and scaling which can drastically influence the energy efficiency of SWDU-RED (Bazinet & Geoffroy, 2020; Faghihi & Jalali, 2022).

Additionally, there are concerns from the research community regarding the lack of studies on the influence of spatial conditions such as sea water temperature and other water parameters on the performance of SWDU-RED (Table 6, Row 6). For example, Hossen et al., (2020) criticize that the prevailing assumption underlying current global estimates of electricity generation from coastal salinity gradient energy resources is that these gradients remain stable in both spatial and temporal dimensions. However, they tested the power density in lab-scale RED delivered by water samples from the coast of Carolina and found that the power density varied widely between values of 94.4 and 247.5 mW·m−2 (ibid.). Especially during a storm event the power density was negatively impacted due to increased freshwater influxes (ibid.). Fluctuations like this are not accounted for in lab-scale experiments with artificial feed solutions which may lead to discrepancies between theoretical power density estimations of SWDU-RED and commercial applications with non-artificial feed solutions.

As mentioned in section 4.2, fouling is a major problem in the operation of SWDU-RED that negatively impacts the energy efficiency of the approach. Therefore, research on how to prevent or mitigate fouling in SWDU-RED is regarded as an area that requires further research (Table 6, Row 7). Further, the exploration of synergistic combinations of SWDU-RED with other technologies is regarded as an area that requires further research efforts (Table 6, Row 8).

Additionally, there is insufficient knowledge concerning the hydrodynamics of SWDU-RED (Table 6, Row 9) and a need for improved computer modeling in this field (Culcasi et al., 2020). This area needs to be explored more in depth in order to make estimates about the energy efficiency of potential full-scale commercial applications of SWDU-RED. Further, computer modelling in other areas is also lacking (Table 6, Row 10). Gómez-Coma et al., (2019) point to a lack of computational models regarding power density and membrane performance under various circumstances.

All these above mentioned factors lead to a low technological readiness level (TRL) of SWDU-RED (Table 6, Row 9). However, a sufficient TRL is crucial for industry engagement (Clausing & Holmes, 2010). Industry involvement for the commercialization of SWDU-RED is crucial because the scaling up and practical implementation of the technology surpasses academic expertise, emphasizing the essential requirement for collaboration with the industry (Nijmeijer & Metz, 2010, p. 5).

Table 6: Sub- barriers of barrier (3) technological immaturity.

	Barriers	Sources
1	General research need concerning RED and SWDU-RED	(Gurreri et al., 2020; Herrero-Gonzalez & Ibañez, 2021; Mavukkandy et al., 2019; Mishchuk, 2023; Mueller et al., 2021; Panagopoulos & Giannika, 2022; Rehman et al., 2020; Tian et al., 2020; Tristán, Rumayor, et al., 2020; J. Wang, Zhou, et al., 2023; Zoungrana & Çakmakci, 2021a)
2	Need for further membrane development	(Ahmed et al., 2020; Avci et al., 2021; Faghihi & Jalali, 2022; Fan et al., 2020; Fan & Yip, 2019; J.-H. Han, 2022; Herrero-Gonzalez & Ibañez, 2021; Ju et al., 2022; S. Lee et al., 2019; W. Liu et al., 2022; Mishchuk, 2023; Mueller et al., 2021; Nazif et al., 2022; Pawlowski et al., 2020; Ranade et al., 2022; Santoro et al., 2021; Sedighi et al., 2023; Tristán, Fallanza, et al., 2020b; Tufa et al., 2019; J. Wang, Zhou, et al., 2023; Xin et al., 2021; Zoungrana & Çakmakci, 2021a)
3	Lack of commercial ion exchange membranes for RED and SWDU-RED	(Avci, Rijnaarts, et al., 2020; Fan & Yip, 2019; Mishchuk, 2023; Nazif et al., 2022; Santoro et al., 2021; Shadravan et al., 2022; Zoungrana & Çakmakci, 2021a)
4	Need for commercial scale testing	(Ahmed et al., 2020; Gurreri et al., 2020; S. Lee et al., 2019; L. Ma et al., 2021; Mavukkandy et al., 2019; Panagopoulos & Giannika, 2022; Rehman et al., 2020; Seyfried et al., 2019; Tristán, Fallanza, et al., 2020a; Tristán, Rumayor, et al., 2020; Wagholikar et al., 2020; Yasukawa et al., 2020; Zoungrana & Çakmakci, 2021a)
5	Lack of research with non-artificial feed solutions	(Choi, Dorji, et al., 2019; Gurreri et al., 2020; L. Ma et al., 2021; Wagholikar et al., 2020; Yasukawa et al., 2020; Zoungrana & Çakmakci, 2021a)
6	Insufficient knowledge concerning the performance of SWDU-RED under varying spatial conditions	(Choi, Oh, et al., 2019; Hossen et al., 2020; Pawlowski et al., 2020; Sedighi et al., 2023; Tufa et al., 2019; Wagholikar et al., 2020; Zoungrana & Çakmakci, 2021a)
7	Need for additional research on anti-fouling methods	(Gurreri et al., 2020; Ju et al., 2022; S. Lee et al., 2019; L. Ma et al., 2021; Nazif et al., 2022; Pawlowski et al., 2020; Santoro et al., 2021)
8	Exploration of technological synergies	(Ahmed et al., 2020; Jianbo et al., 2021; S. Lee et al., 2019; W. Liu et al., 2022; Mei et al., 2020; Nazif et al., 2022; Ranade et al., 2022; Tian et al., 2020; Tristán, Fallanza, et al., 2020a; Tufa et al., 2019)
9	Hydrodynamics research gap	(Culcasi et al., 2020; J. Li et al., 2022; Pawlowski et al., 2020; Rehman et al., 2020; Zoungrana & Çakmakci, 2021a)
10	Need for computer modelling	(Culcasi et al., 2020; Gómez-Coma et al., 2019; Mueller et al., 2021; Sampedro et al., 2023; J. Wang, Zhou, et al., 2023)
11	Need for monitoring techniques	(Pawlowski et al., 2020; Zoungrana & Çakmakci, 2021b)
12	Low TRL	(Herrero-Gonzalez & Ibañez, 2021)

The Lack of Competitiveness Against Other Technologies

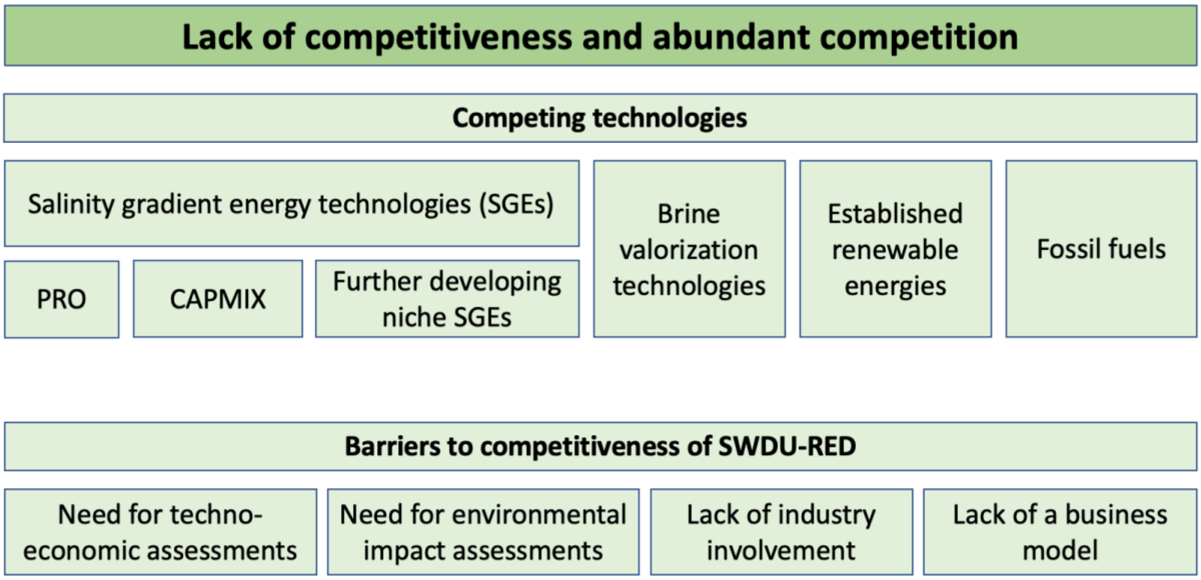


Figure 17: Connection of the sub-barriers of lack of competitiveness of SWDU-RED and the abundant competition, own illustration.

A fourth major barrier against the upscaling and commercialization of SWDU-RED are competing technologies such as other salinity gradient energies (Figure 17). The in literature most prominently mentioned alternative to SWDU-RED is the co-location of desalination plants with pressure retarded osmosis (Table 3, row 4). While RED utilizes the ion flow between the low-salinity and the high salinity solution to generate electricity via ion exchange membranes, pressure retarded osmosis (PRO) harnesses the osmotic pressure difference between the solutions to drive a turbine (Post et al., 2007). PRO is the strongest competitor to RED among the salinity gradient energies because it delivers higher power densities than RED when operated with a high salt gradient between the feed solutions (Ahmed et al., 2020; Ju et al., 2021).

Less frequently mentioned as competition to RED, but still highly represented in literature, is capacitive mixing (CAPMIX) (Table 7, Row 3). CAPMIX leverages the voltage increase that occurs between two electrodes immersed in a saline solution when the salt concentration is altered (Brogioli et al., 2013). CAPMIX is generally seen as less promising than RED because achieves lower power densities (Mavukkandy et al., 2019). Nevertheless, CAPMIX is still an active area of research, and can therefore be seen as direct competition to RED in the market for salinity gradient energies. However, Ramasamy et al., (2021) proposed that CAPMIX electrodes could be integrated into RED to increase the power density of RED. This indicates that rather than competing with each other, the development of RED and CAPMIX might support each other through synergistic combinations of both technologies.

Further, there are several developing niche technologies among the salinity gradient energies that are promising but currently have a lower technological readiness level than RED (Table 6, Row 4). While they do not pose any serious competition, yet, because of their low technological readiness level, they might prove to be more viable than RED once they are further developed.

Additionally, RED can be viewed as a tool to valorize brine which is a waste product of desalination. In SWDU-RED, brine is being utilized as the high salinity feed solution (Tristán, Fallanza, et al., 2020b). Therefore, RED is also competing with other brine valorization technologies (Table 7, Row 5). Competing brine valorization technologies are mentioned in a review on resource recovery from desalination brine by Mavukkandy et al., (2019). They describe for example solar ponds and other solar distillation facilities in which desalination brine is evaporated until only its solid compounds remain which can be utilized in other industry processes.

In addition, Reverse Electrodialysis (RED) is in competition with other renewable energy sources like solar and wind to reduce emissions in desalination plants (Table 7, Row 6). Solar and wind technologies have the advantage of being more established and widely recognized compared to RED.

Despite being scarcely mentioned in the literature that has been analyzed for the purpose of this work, the strongest competition against RED, however, are likely the fossil fuel technologies (Table 7, Row 7) that are currently being utilized predominantly to power desalination plants. While there is overwhelming consensus in the academic community that there needs to be a shift away from fossil energy sources to renewables, there are powerful lock-in mechanisms that are holding renewables in place (Meerganz Von Medeazza, 2005).

In addition to the mentioned competing technologies, there are several factors that lower the overall competitiveness of SWDU-RED such as a lack of techno-economic impact assessments (Table 7, Row 8) and environmental impact studies (Table 7, Row 9), as well as insufficient industry involvement in the R&D of RED applications (Table 7, Row 11) and the lack of a business model (Table 7, Row 12).

According to publications such as Gurreri et al. (2022), Santoro et al., (2021) and Wagholikar et al., (2020), there is a need for additional techno-economic assessments to evaluate the performance of RED (Table 7, Row 8). Techno-economic assessments are crucial to the marketability of novel renewable energies because they provide a comprehensive evaluation of both the technological and economic aspects of a new energy technology. Conducting a techno-economic analysis of hybrid renewable energy systems such as SWDU-RED is crucial in showcasing its advantages and determining the appropriate system and associated considerations for specific situations (W. Ma et al., 2018). By assessing factors such as cost-effectiveness, scalability, performance, and market potential, these assessments enable stakeholders to make informed decisions about investing in and promoting the adoption of new renewable energy solutions (ibid.).
Further, (Lee et al., 2019) state that a business model for SWDU-RED has yet to be developed. Without a clear business model, the marketing of any product is challenging.

Further, there are to-date few studies concerning possible environmental impact studies of SWDU-RED that are based on studying existing pilot plants (Mavukkandy et al., 2019; Seyfried et al., 2019). This can cause uncertainties regarding environmental impacts and benefits of full-scale SWDU-RED.

Table 7: Sub- barriers of barrier (4) lack of competitiveness and abundant competition.

	Barriers	**Sources**
1	General Existence of competing technologies	(Ahmed et al., 2020; X.-W. Han et al., 2021; Herrero-Gonzalez & Ibañez, 2021; Ju et al., 2021; S. Lee et al., 2019; Marbach & Bocquet, 2019; Mavukkandy et al., 2019; Mei et al., 2020; Mueller et al., 2021; Panagopoulos, 2022; Panagopoulos & Giannika, 2022; Ranade et al., 2022; Rehman et al., 2020; Shadravan et al., 2022; X. Zhang et al., 2021; Zoungrana & Çakmakci, 2021a)
2	PRO	(Ahmed et al., 2020; X.-W. Han et al., 2021; Ju et al., 2021; S. Lee et al., 2019; Mavukkandy et al., 2019; Mei et al., 2020; Panagopoulos, 2022; Panagopoulos & Giannika, 2022; Rehman et al., 2020; Shadravan et al., 2022; X. Zhang et al., 2021; Zoungrana & Çakmakci, 2021a)
3	CAPMIX	(X.-W. Han et al., 2021; Marbach & Bocquet, 2019; Mavukkandy et al., 2019; Panagopoulos, 2022; Panagopoulos & Giannika, 2022)
4	Salinity gradient niche technologies	(X.-W. Han et al., 2021; Herrero-Gonzalez & Ibañez, 2021; Mavukkandy et al., 2019; Rehman et al., 2020)
5	Brine valorization technologies	(Mavukkandy et al., 2019; Panagopoulos & Giannika, 2022)
6	Other more established renewable energies	(Herrero-Gonzalez & Ibañez, 2021; Mueller et al., 2021; Ranade et al., 2022; X. Zhang et al., 2021)
7	Fossil fuels	(Zoungrana & Çakmakci, 2021a)
8	Need for techno-economic assessments	(Gurreri et al., 2020; Mavukkandy et al., 2019; Nazif et al., 2022; Pawlowski et al., 2020; Santoro et al., 2021; Tristán, Rumayor, et al., 2020; Tufa et al., 2019; Wagholikar et al., 2020; Zoungrana & Çakmakci, 2021a)
9	Need for environmental impact assessments	(Seyfried et al., 2019; Tristán, Rumayor, et al., 2020; Wagholikar et al., 2020)
10	Lack of marketability in general	(Herrero-Gonzalez & Ibañez, 2021; Ranade et al., 2022; Tristán, Rumayor, et al., 2020; Zoungrana & Çakmakci, 2021a)
11	Lack of industry involvement in R&D	(Herrero-Gonzalez & Ibañez, 2021; Tristán, Rumayor, et al., 2020; J. Wang, Zhou, et al., 2023; Zoungrana & Çakmakci, 2021a)
12	Lack of a business model	(S. Lee et al., 2019; Tristán, Rumayor, et al., 2020)

5. Discussion

In this section, Chapter 5.1 delves into a comprehensive discussion of the primary technical and economic barriers that have emerged from the results section. Additionally, the interrelations between these four key barriers are explored, shedding light on their interconnected nature. Continuing to Chapter 5.2, the focus shifts towards assessing the technological readiness level (TRL) of SWDU-RED. The discussion centres on whether SWDU-RED might be vulnerable to the Valley of Death phenomenon, a critical consideration for its successful implementation and commercialization.

5.1 Technical and Economic Barriers to SWDU-RED and their Interrelations

In the course of the conducted systematic literature review, four main barriers against the upscaling and commercialization of SWDU-RED were identified which consist of several sub-barriers:

(1) Low power density and energy efficiency,
(2) High levelized cost of energy,
(3) Technological immaturity
(4) Lack of competitiveness of SWDU-RED and strong competition

Among the four barriers that have been discerned in the systematic literature review, it is evident that (1) constitutes a purely technical impediment, while (2) is the principal economic obstacle. Furthermore, (3) and (4) encompass two distinctive techno-economic barriers.

Main Barrier (1): Low Power Density and Energy Efficiency

Noteworthy about barrier (1) is the discouraging prevalence of statements in literature that express concern regarding the low power densities and energy efficiencies of RED and SWDU-RED. Among the 75 analyzed publications, 39 criticized low power densities and energy efficiencies (Table 3, Row 1). Therefore, it can be assumed that this is a major obstacle against the upscaling and commercialization of SWDU-RED. The main underlying causes of this barrier are fouling phenomena and insufficient permselectivity of currently available ion exchange membranes.

While the literature analysis made it evident that low power densities are a major hurdle, there are differing estimates among publications concerning the power density that RED applications would need to reach in order to be commercially viable. The estimates from the analyzed literature vary in a range from 2 W/m2 (Bazinet & Geoffroy, 2020) to 5 W/m2 (S. Wang, Wang, et al., 2023).

Multiple experimental studies have investigated RED operations with desalination brine as the high salinity feed solution. While some of these studies report power densities that fall into the upper range of these estimates such as (Hulme et al., 2021) who reported power densities up to 4.78 W/m2, these relatively high power densities were reached with artificial laboratory made feed solutions.

However, real feed solutions such as waste brine from desalination plants and seawater have impurities that lead to lower power densities for several reasons (L. Ma et al., 2021). Of the studies included in the literature review, there were six studies that conducted experiments with non-artificial feed solutions (Figure 18). Among these studies utilizing non-artificial solutions, only one, namely Faghihi & Jalali, (2022) reached power densities up to 2.4 W/m2 which is only slightly higher than the lowest estimate of a commercial benchmark concerning minimum power densities for commercial viability of RED-applications by Bazinet & Geoffroy, (2020).

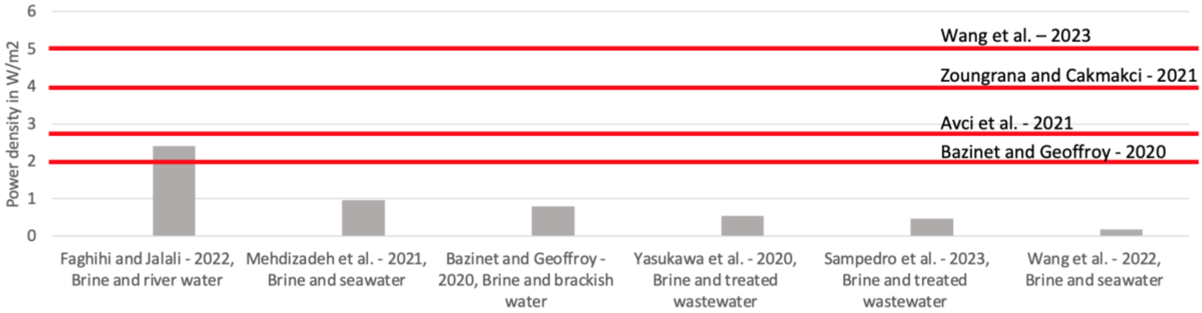


Figure 18: Estimated commercial thresholds for power densities necessary for a commercialization of SWDU-RED compared to values currently achieved in applications with non-artificial feed solutions, own illustration.

The large difference between the estimated thresholds for commercial RED applications and the actual reached power densities in SWDU-RED in combination with barrier (1) being frequently mentioned in literature showcase the severity of this technical barrier.

Main Barrier (2): High Costs

A further discouraging result of the systematic literature review concerns main barrier (2) the high levelized cost of energy. As shown in the results section, this is on one hand a result of the low power densities and energy efficiencies, resulting in less harvestable electricity at the end of the SWDU-RED process. On the other hand, the in literature frequently mentioned high capital and operational costs for SWDU-RED are responsible. It is noteworthy that capital costs are a more prominent hurdle than operational costs.

Further, it is remarkable that the largest costs among the capital costs are due to ion exchange members, as stated by (X. Zhang et al., 2021). Membranes are currently priced between 10 and 30 euros per square meter, but to be on par with other renewable energy sources, their price needs to decrease significantly to around 2 to 5 euros per square meter (ibid.).

As stated earlier, main barrier (1) is to a large extent caused by insufficiencies of current commercially available ion exchange membranes due to membrane fouling and permselectivity issues. Since major barrier (2) is also largely caused by ion exchange membranes due to their high price compared to the estimated commercial threshold by Zhang et al., (2021), it can be assumed that improvements in ion exchange membrane design that allow for higher power densities, as well as cheaper production are crucial for the upscaling and commercialization of SWDU-RED.

Main barrier (3): Technological Immaturity

However, for the development of improved ion exchange membranes with low costs that deliver high power densities, it is crucial that the major barrier (3) which consists of the technological immaturity of SWDU-RED, is tackled. This ties well into the fact that a need for further membrane development is the in literature most mentioned sub-barrier of technological immaturity (Table 6, Row 2). However, it is noteworthy, that as it has been previously described in Chapter 2, the academic interest in RED and SWDU-RED is substantial and growing, as indicated by a fast growing body of literature surrounding the topic. Further, according to Mavukkandy et al., (2019, p. 15), a general substantial interest in brine valorization methods has developed in the academic community over the last ten years. The research resulting from this heightened academic interest may increase power densities of RED ion exchange membranes, as well as open up opportunities for decreasing membrane cost.

Thus, as will be showcased in the following paragraphs, ongoing research based on the previously stated substantial academic interest may alleviate main barrier (3) and therefore have a positive influence in reducing the major barriers (1) and (2):

A main problem stemming from barrier (3) and influencing main barriers (1) and (2) is the fact that the currently commercially available membranes for RED and SWDU-RED are not specifically designed for these applications (Table 6, Row 3), but rather designed for electrodialysis (Hulme et al., 2021). Electrodialysis is a desalination method to which the process of RED is closely related because it has been derived from it (Tedesco, Hamelers, et al., 2017). Therefore, electrodialysis membranes are functional in RED applications, but they are far from delivering optimal power densities (ibid.). However, there is currently ongoing research that is focused on developing specialized membranes tailored for RED applications (Abidin et al., 2022; S. Wang, Wang, et al., 2023; Xin et al., 2019).

Recent advances in this field include the development of several new approaches to increase the power density of ion exchange membranes for RED (Ahmed et al., 2020; Bazinet & Geoffroy, 2020). For example, Hulme et al., (2021) reported that RED power density could be doubled by using alternative membranes better suited to RED due to lower water permeability and higher permselectivity as opposed to commercial electrodialysis membranes.

In current research, novel materials are being explored for the production of more efficient ion exchange membranes for RED-applications. Conventionally, ion exchange membranes are manufactured from polymers or resins. However, Xin et al., (2019) developed a membrane based on natural silk and aluminum oxide that delivers comparatively good power densities under a broad spectrum of different conditions and would likely be cheaper in production than current options because of the wide availability of silkworms. Further, (J. Wang, Wang, et al., 2023) state to have developed novel ion exchange membranes based on titanium carbide that are capable of delivering power densities up to 16 W/m2, which would exceed all estimations of commercialization thresholds by far. Further, ion exchange membranes based on the polymer Nafion have been tested for RED-applications with promising results (Avci, Messana, et al., 2020). However, although Nafion membranes are promising because of their outstanding permselecivity, conductivity and high durability (ibid.), their usage is constricted by high prices due to their challenging manufacturing process (Yee et al., 2012).

Moreover, there are research efforts to modify membrane surfaces with sulfonating agents or nanomaterials to mitigate membrane fouling issues that can lead to decreased power densities (Nazif et al., 2022). This is encouraging regarding the in literature stated need for research on anti-fouling methods (Table 6, Row 7) which is a in literature mentioned sub-barrier of main barrier (3).

Additional power density and energy efficiency increases could furthermore be achieved through alternative arrangements of stack components. For example, Kang et al. (2022) reported that by connecting several RED stacks in series into so-called multi-stage RED stacks, the energy conversion efficiency for salinity gradient power in desalination plants can be enhanced.

The existence of these ongoing promising investigations suggests that main barrier (3) might be alleviated by current and future research advances which consequentially creates possibilities for increased power densities and lowered costs of RED-applications such as SWDU-RED.

Nevertheless, prevailing research primarily centers on RED membranes, and it is crucial to acknowledge that SWDU-RED membranes present distinct requirements owing to their elevated ion contents in the feed solutions, particularly the desalination brine as the high salinity feed solution. This underlines the necessity for upscaled testing with non-artificial feed solutions (Table 6, Rows 5 and 6) in order to also evaluate these research advances in the context of SWDU-RED under realistic conditions.

Main Barrier (4): Lack of Competitiveness of SWDU-RED and Strong Competition

Despite ongoing research and improvements in SWDU-RED which can make one hopeful for its potential as an approach to aid in decarbonizing the desalination industry, large-scale investments in SWDU-RED upscaling might lose their justification if there are other more promising alternatives that could receive investments instead. Therefore, it is paramount to evaluate carefully how differing technical approaches compare. The competition against SWDU-RED consists of other salinity gradient technologies, further brine-valorization technologies, as well as more established renewable energies such as solar energy (Table 7).

As can be seen in Table 7, Row 2, the strongest competitor against SWDU-RED as per the results of the systematic literature review is pressure retarded osmosis (PRO). PRO is another salinity gradient energy with a differing working principle from RED. RED is an electrochemical methodology that harnesses ion movement to produce electricity by means of ion exchange membranes, segregating positive and negative charges, thereby generating an electrochemical potential that is subsequently converted (Mei & Tang, 2018). PRO on the other hand utilizes the osmotic pressure between the high salinity solution and the low salinity solution to drive a turbine in order to generate electricity (Achilli & Childress, 2010).

It is noteworthy that PRO poses fierce competition to RED because the maximum power densities that can be reached with PRO are currently larger than with RED (S. Lee et al., 2019). Especially under non-fouling conditions, this difference is highly noticeable according to experiments by Ju et al., (2021) in which PRO exhibited power densities of up to 3.24W/m2. RED on the other hand reached a maximum power density of only 1.66 W/m2. This illustrates the interrelation of main barrier (1), low power densities and energy efficiencies, and main barrier (4), the lack of competitiveness of SWDU-RED.

The difference in reachable power densities between RED and PRO is even starker with a higher salinity-gradient between the low salinity feed solution and the high salinity feed solution (Ju et al., 2021). This is a considerable disadvantage for RED because the higher the salinity gradient between the feed solutions is, the higher is also the theoretically extractable Gibbs free energy of mixing (Lin et al., 2014) and accordingly the electricity that could theoretically be produced (ibid.).

According to Shadravan et al. (2022), current commercially available RED-membranes are constricted in their ability to utilize salt-gradients that are too high because of the Donnan exclusion effect. The Donnan exclusion effect is a phenomenon that occurs when ions are unequally distributed across a semi-permeable membrane that separates two solutions containing different concentrations of electrolytes (Ogawara et al., 2016). In this scenario, the membrane allows only certain ions to pass through, while others are excluded due to their charge and size. When a charged semi-permeable membrane is placed between two solutions with different concentrations of ions, the ions with the same charge as the membrane are repelled and prevented from passing through (ibid.). As a result, these excluded ions accumulate near the membrane, creating an electric potential difference across it (ibid.).

Due to this effect, PRO has a clear advantage over RED concerning potential extractable power densities. This is especially a disadvantage for RED in an application that involves the co-location of RED with a desalination plant in order to utilize the desalination brine as the high salinity feed solution because due to the extremely high salinities of desalination brine, very high power densities would theoretically be possible with feed solutions that have a much lower salinity such as treated waste-water or river water. However, because of the Donnan exclusion effect, SWDU-RED is restricted to lower salinity gradients to conserve its permselectivity (Shadravan et al., 2022). Therefore, PRO is able to produce higher power densities in co-location with desalination plants than RED with the current commercially available ion exchange membranes.

Additionally, PRO demonstrates greater potential for commercialization due to its extensive investigation in pilot-scale operations compared to RED (Panagopoulos & Giannika, 2022). This indicates that in addition to being more advanced regarding extractable power densities, PRO also has an advantage over RED considering main barrier (3).

The discouraging notion of PRO outcompeting RED for the application of co-location with desalination facilities is further strengthened by the fact that according to Panagopoulos (2022), there has been a system proposed that co-locates PRO with reverse-osmosis desalination plants. This system is expected to be economically and technically feasible, showing a levelized cost of energy amounting to US$1.11/kW and an annualized system cost of US$110,456 (ibid.).

However, PRO has also some disadvantages compared to RED. PRO is significantly more susceptible to fouling phenomena than RED (Panagopoulos & Giannika, 2022). This has been showcased by Ju et al. (2021). They compared the performances of RED and PRO under fouling conditions and found that RED did not lose any power density over time while PRO on the other hand lost 58% of its original power density (ibid.). This notion is also supported by literature review findings of Mei et al., (2020) that additionally found that PRO suffers from mechanically more unstable membranes than RED. Moreover, in contrast to the mechanical energy output in PRO, which involves pressure exchangers and hydroturbines in a relatively intricate setup, the direct electricity output from RED offers a simpler process design and increased flexibility in adjusting the output (ibid.). A further disadvantage of PRO compared to RED has been noted by Seyfried et al. (2019) who concluded that a PRO plant of equivalent capacity would probably generate more noise compared to a RED facility since it necessitates a running generator and more powerful pumps to maintain stable water pressure.

Nevertheless, despite the disadvantage that PRO may have compared to RED, in a technology application that seeks to co-locate a form of salinity gradient energy with a desalination plant, PRO might outcompete RED due to higher possible power densities, which translates into a lower levelized cost of energy and consequentially a better cost-benefit ratio for private sector investors.

To conclude this section, RED will likely be outcompeted by PRO because it is better suited for applications with higher salinity gradients such as the co-location of salinity gradient energy with desalination plants. Accordingly, overall higher power densities can be reached with PRO compared to RED. Further, PRO has a higher technological maturity. Other more established renewable energies such as solar or wind energy have advantages compared to RED because of economies of scale, as well as a longer learning curve.

Summary on the Interrelations of the Four Main Barriers

As becomes apparent in the previous sections the main four barriers against the upscaling and commercialization of SWDU-RED are highly interrelated. The main technical barrier (1) that is being described repeatedly in current literature consists of low energy efficiencies and power densities. This is caused by main barrier (3), the current technological immaturity of the SWDU-RED approach. In combination with high capital and operational costs, the low power density and energy efficiency result in a high levelized cost of energy, main barrier (2). This high levelized cost of energy in turn contributes to the currently poor competitiveness of SWDU-RED against other approaches to decarbonize the desalination industry and valorize waste brine which is main barrier (4). Consequentially, as it is illustrated in Figure 19, the four main barriers described in the results section are closely interlinked in a cause-and-effect relationship.

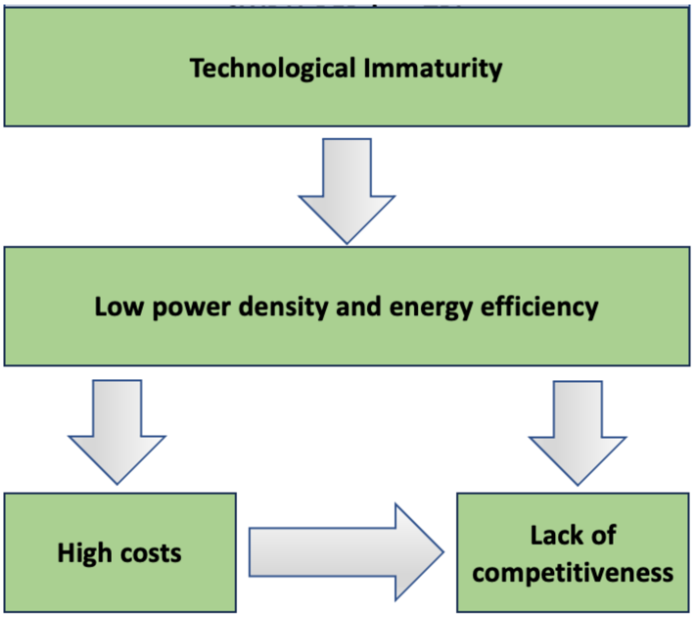


Figure 19: Interlinkages of the four major barriers against the upscaling and commercialization of SWDU-RED, own illustration.

5.2 Is SWDU-RED Susceptible to Falling Victim to the Valley of Death?

The Technological Readiness Level of SWDU-RED

In this section, the technological readiness level (TRL) of SWDU-RED will be estimated by comparing the current stage of research as evidenced by pilot projects to the TRL-scale that has been established in the theoretical framework.

Originally developed by NASA, the concept of the Technological Readiness Level (TRL) is a systematic method used to assess the maturity and development stage of a technology (Mankins, 2009). The TRL framework has been widely adopted across various industries, including aerospace, defense, engineering, and emerging technologies (ibid.) and provides a standardized scale for researchers, engineers, and decision-makers to communicate the status of a technology's development. It assists in understanding the progress of a technology, estimating the remaining development efforts, and assessing the risks associated with its implementation. The TRL scale ranges from TRL 1 to TRL 9 (Figure 20). As a technology progresses through the TRL levels, it becomes more feasible for practical application and commercialization.

Among the existing RED pilot facilities are a South Korean pilot plant with power densities of up to 0.38 W/m2 using seawater and wastewater (Bazinet & Geoffroy, 2020) and the Blue Energy Project on the Afsluitdijk in the Netherlands, generating electricity between the ion gradient of the North Sea and the Ijsselmeer (van Kann et al., 2023).

Further, there has been a pilot project by Tedesco, Cipollina, et al., (2017) that has experimented with higher salinity solutions based on salt-mining brine in the project REAPower. The pilot plant reached a power density of about 0.8 W/m2 over 5 months with non-artificial feed solutions. Moreover, in Okinawa Island in Japan, the first pilot project with desalination brine from reverse osmosis as the high salinity feed solution has been successfully conducted with power densities up to 0.96W/m2 with non-artificial feed solutions (Mehdizadeh et al., 2021).

While early research and development in novel renewable energy forms is commonly funded publicly under academic institutions, the upscaling and commercialization of renewable energy forms is related to enormous investment challenges that cannot be conquered by the academic sector, alone (Nijmeijer & Metz, 2010). While the concept of SWDU-RED has been proven to be theoretically feasible at bench-scale, as well as pilot-scale research endeavors, an actual commercialization of SWDU-RED requires investments that make the large scale production of essential components such as ion exchange membranes that are specialized on SWDU-RED possible. Current commercial ion exchange membranes that are being used for RED are not delivering ideal power densities and specialized membranes with better power densities are not commercially available (Hulme et al., 2021).

Due to the existence of small-scale pilot plants in combination with the current technical and economic barriers it can be estimated that SWDU-RED is at TRL 7 (Figure 20). When a technology can be classified as TRL 7, it has reached the stage in which integrated pilot systems are demonstrated. For SWDU-RED to reach TRL 8, the level on which the system is complete and qualified, further advances are necessary to increase power densities and energy efficiencies. Subsequent to that, to reach TRL 9, it would be crucial to operate SWDU-RED with non-artificial feed solutions on a scale that is comparable to anticipated future commercial scales in order to prove the system in an operational environment. Finally, for SWDU-RED to reach full commercialization, a reduction in RED membrane cost is of high importance (Abidin et al., 2022).

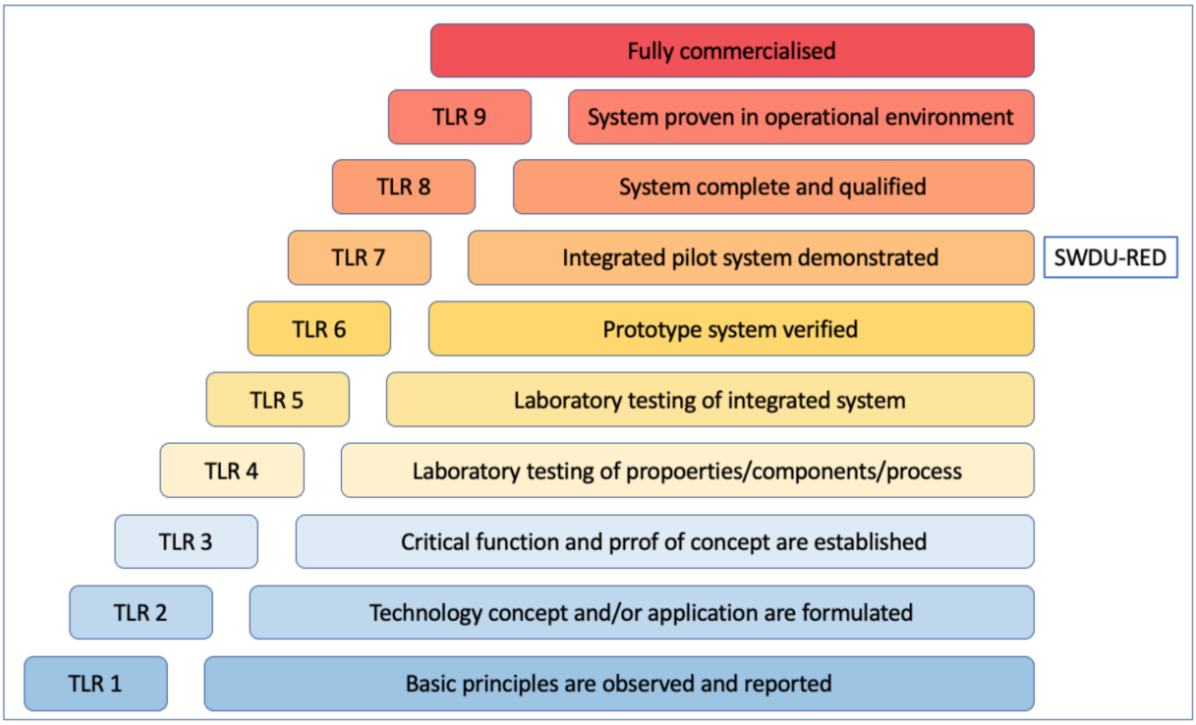


Figure 20: The scale of technological readiness levels (TRLs) and the position of SWDU-RED within this framework. TRL framework based on (Fasterholdt et al., 2018) own illustration.

Connection of the Technological Readiness Level of SWDU-RED and Valley of Death

As it has been established in the previous section, SWDU-RED is likely on TRL 7 within its development. However, TRL7, the stage in which the concept of SWDU-RED is fully proven, but still lacks the previously described important factors for full industry adoption, is within the TRL-range in which upcoming technologies are most at risk of falling victim to the Valley of Death (Figure 22). According to Mcintyre, (2014), technologies are typically threatened by the valley of death from TRL 4 to TRL 7.

The Valley of Death refers to a critical stage in the development process where promising innovations often encounter significant challenges and face a high risk of failure before they can successfully transition from the research or prototype stage to practical implementation or market adoption (Bonnin Roca & O’Sullivan, 2022). The Valley of Death represents the funding gap or between early-stage development, often funded by universities or government grants, and the later-stage commercialization and market adoption where private investors, venture capitalists, or industry players typically provide funding (ibid.). In the Valley of Death, innovations may struggle to attract sufficient funding because they still face technical hurdles and subsequently fail to meet industry requirements (Gbadegeshin et al., 2022). This period can be highly challenging as it requires a significant infusion of financial resources (ibid.). Many potentially game-changing innovations have been lost in this valley due to the lack of funding or support required to progress through this critical stage (ibid.).

As evidenced in earlier sections, the SWDU-RED technology faces significant challenges, namely its low power density that results from its technological immaturity and an accordingly high levelized cost of energy.
Although there have been successful RED and SWDU-RED pilot plants, they have been smaller than commercial scale applications and the power densities are below commercial thresholds. The main technical barrier of SWDU-RED, namely the low power densities and high costs of SWDU-RED raise the question of whether a commercialization of the approach is feasible in the first place.

However, in the past, renewable energies that are well established nowadays like solar energy were too expensive for commercial applications, as well (Avenston, 2023). Early solar panels, much like SWDU-RED today, were criticized for being too inefficient, converting less than 1% of light energy into electricity (Matasci, 2022). Nevertheless, solar energy has become one of the most affordable sources of electricity (Puiu, 2022). The increase in efficiency and the price drop of solar panels was possible due to substantial investments over several decades that were kicked off by the space race between the US and the Soviet Union (Potter, 2022). Additionally, oil companies invested in solar energy (Hsu, 2019) and the 1970s energy crisis further accelerated solar energy development with large-scale governmental investments (Tsur & Zemel, 2000). As costs for solar power fell due to technical advances, the potential applications expanded, driving increased output and further price reductions, creating a virtuous cycle of innovation, policy support, and market growth (Potter, 2022).

The success story of solar energy can make one hopeful for the commercialization of other renewable energy approaches such as RED and SWDU-RED. However, making solar energy competitive with grid-scale electricity required decades of extensive public and private investments. Similarly, the further development of SWDU-RED towards commercial scales likely requires substantial investments, as well. Currently, SWDU-RED power densities and costs associated with the approach are far from reaching the thresholds that have been estimated in the associated literature. Therefore, additional cost intense research and development efforts over an extended time-frame would likely be necessary for a commercialization of SWDU-RED.

However, for SWDU-RED to receive funding, there needs to be an incentive for investors in the first place to provide it. Especially if there is strong competition, such as PRO, it can be challenging to reason for investments into SWDU-RED. Consequently, the high capital and operational costs associated with SWDU-RED are likely to discourage potential industrial investors from providing financing for the implementation of SWDU-RED plants. As a result, other alternatives that offer more attractive economic prospects may be preferred by investors and stakeholders.

Based on the previously established linkages between the technical and economic main barriers against SWDU-RED, SWDU-RED might get caught in a vicious cycle caused by the reciprocal relationship of technical and economic barriers that prevents the technology from progressing into a higher technological readiness level and subsequently to commercialization. The main technical barrier (1), namely low power densities and energy efficiencies causes main barrier (2), high levelized cost of energy (Table 3, Row 1). This constitutes a major hurdle for industry investments in SWDU-RED. A lack of funding could be the consequence. Further, this lack of funding might impede upscaled SWDU-RED applications. However, as evidenced by the literature in Table 6, Row 4, larger scale SWDU-RED applications are a central element in the research that is necessary for establishing a complete and qualified SWDU-RED system that is operational in real environments. The development of such a system would be necessary in order for SWDU-RED to graduate to TRL 8 and 9 (Figure 20) and subsequently for commercialization. Accordingly, without significant funding might be caught in a vicious cycle as illustrated in Figure 21 (a).

Additionally, with only small scale applications, essential parts for improving the power density of SWDU-RED such as ion exchange membranes that have been specifically designed for SWDU-RED cannot benefit from economies of scale because they would be seldomly requested and therefore not produced on larger scales. This would mean an additional barrier to the cost-effectiveness of SWDU-RED. This could mean another cycle that could potentially prevent the upscaling and commercialization of SWDU-RED as illustrated in Figure 21 (b).

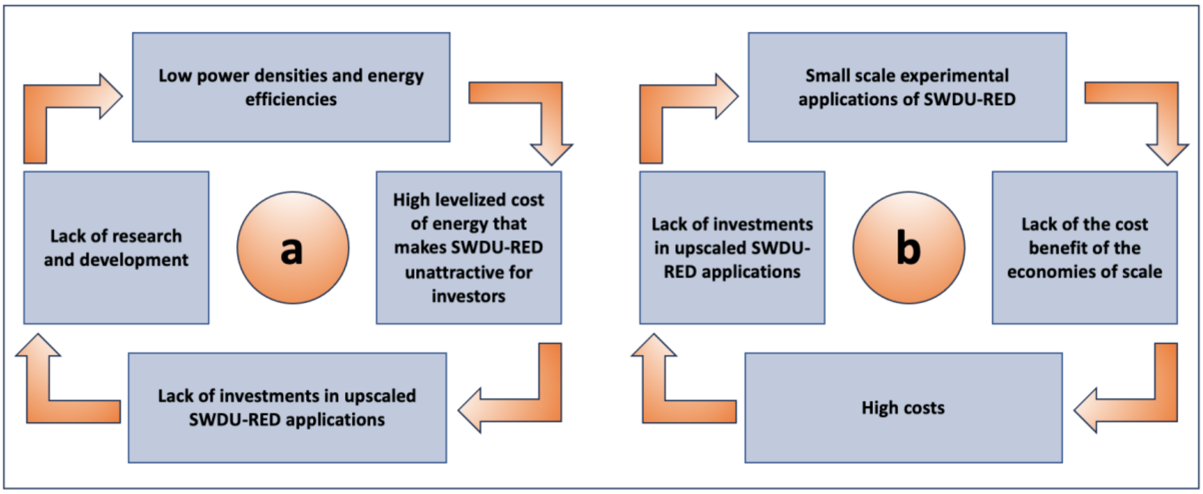


Figure 21: Theorized cycles that might cause SWDU-RED to be hampered in its way to upscaling and commercialization, own illustration.

Therefore, due to the four main barriers that SWDU-RED is currently restricted by, SWDU-RED might be prevented from progressing further toward its commercialization stage. Additionally, the in this document exhaustively described interlinkages of these four main barriers and their sub-components may lead to SWDU-RED in fact falling victim to the valley of death as illustrated in Figure 22. The current TRL of SWDU-RED is too low for commercialization. Associated with this is the technological immaturity of the technology. This negatively influences the power densities and energy efficiencies that can be obtained with SWDU-RED. In turn, the produced electricity is costly. This high levelized cost of energy together with the low power densities and energy efficiencies has an adverse effect on the competitiveness of SWDU-RED. This lack of competitiveness together with the high costs may cause SWDU-RED to not progress further in its development and consequentially fall victim to the Valley of Death. Especially the fierce competition of PRO is likely to hamper the commercial application of SWDU-RED as described in Chapter 5.

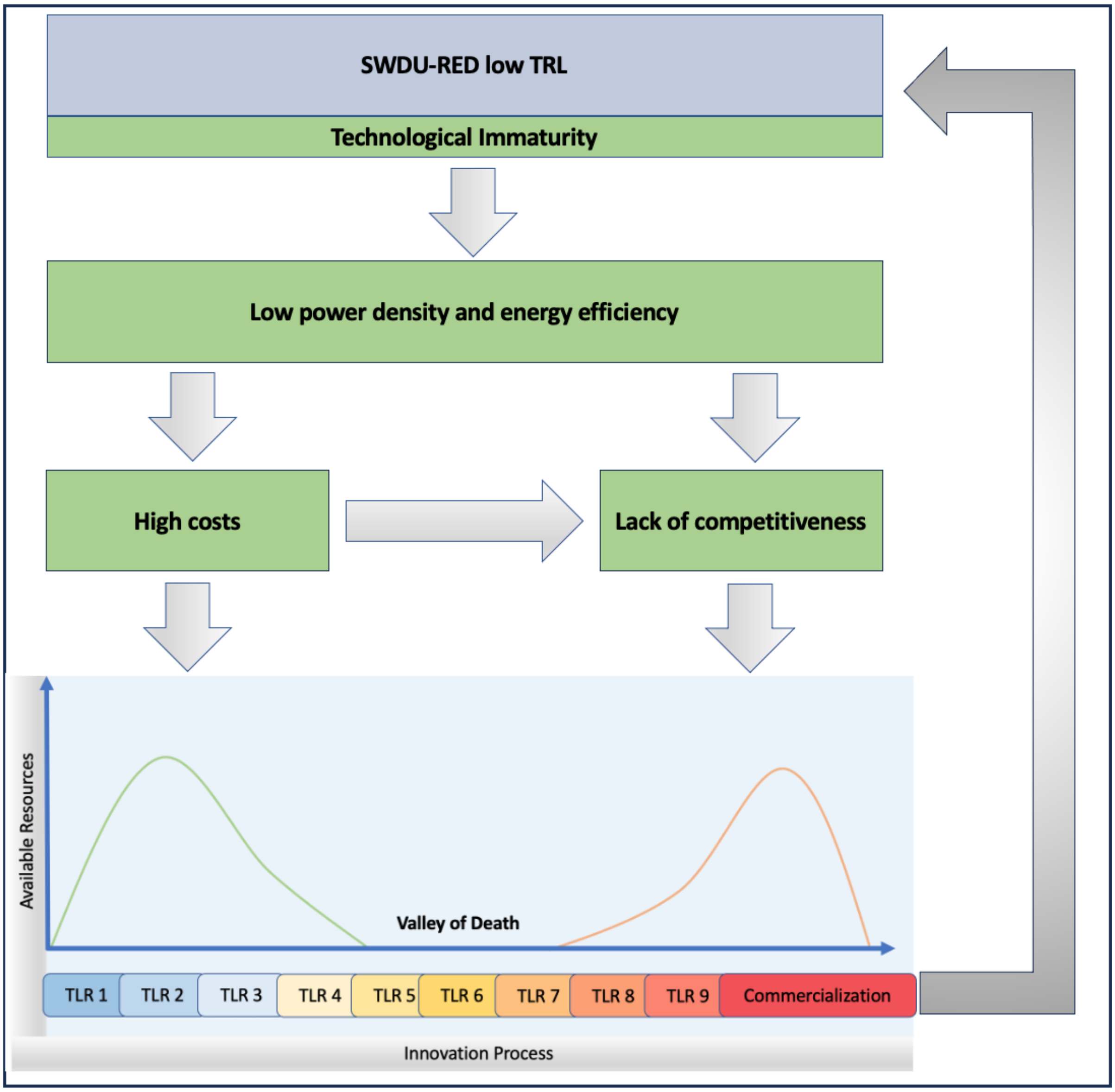


Figure 22: Interlinkage of the four main barriers against SWDU-RED, its TRL and the Valley of Death, own illustration.

5.3 The Future of RED

As suggested by the previous sections, there are still large efforts necessary to elevate SWDU-RED to a level on which commercialization and wide-spread diffusion of SWDU-RED become a possibility or as stated by Pawlowski et al. (2020, p.19): "There is an enormous margin of progress for future research". However, as it has been established in the previous section, this research and development would likely be highly cost intensive over an extended period which might be discouraging to potential investors. Further, the results of the systematic literature review suggest that there is strong competition by PRO. As stated earlier, PRO might have significant advantages compared to RED, especially in an application that combines desalination with salinity gradient energy. This outcome implies that co-location of desalination units with PRO (SWDU-PRO) will likely outcompete SWDU-RED.

However, while SWDU-RED might not progress to commercialization because of the interrelated technical and economic barriers in its way, there are numerous other RED applications that may be more promising than SWDU-RED.

For example, Mercer et al., (2019) have conducted an exploration into the combination of membrane distillation and reverse electrodialysis as an eco-friendly sanitation approach, aiming to supply clean water and electricity using urine and waste heat. Further, (Y. Zhang et al., 2019) describe the approach to couple microbial fuel cells, a technology that utilizes electroactive bacteria that is capable of producing electricity from degrading organic matter, with reverse electrodialysis in order to combine wastewater treatment with energy production.

However, regarded as the most promising among these applications by the author of this document is the usage of a closed loop heat-engine RED application for industrial waste heat valorization:
In a RED heat engine, RED is being operated in a closed loop (Tamburini et al., 2017). That means that the feed solutions do not leave the system. After the high salinity and low salinity feed solutions have been mixed in the RED process, they are separated again through condensation and evaporation (ibid). Subsequently, the feed solutions are mixed again, generating energy continuously. Via this process, industrial waste heat can be utilized for electricity or hydrogen production via electrolysis at the electrodes of the RED stack (ibid.).

The industrial waste heat that can be utilized in this process ranges between 40 and 100 degrees which is within a temperature range that can be used by no other currently established waste heat recycling process (Olkis et al., 2018). Consequentially, this approach might have the potential to fill a niche and make use of energy that has to date dissipated without adding value to society (ibid.).

This application might be useful for example for the Rotterdam harbor area because it is a location with abundant waste heat (Baas, 2011). Previously there has been an attempt to establish a so-called heat grid at the Rotterdam harbor where local businesses utilize the waste heat of other industries (ibid.). However, there had been economic concerns about this approach because there was the fear that a malfunction in one industry sector might cause the stop of heat flux to other businesses (Baas, 2011; Krakhella et al., 2019).

However, RED-heat engines could make this energy usable without making businesses dependent on each other. Further, the Rotterdam harbor is currently aspiring to become a global hydrogen hub (Luscuere & Luscuere, 2021) and as mentioned previously RED-heat engines are capable of producing hydrogen. Therefore, the employment of RED heat engines at the Rotterdam harbor appears highly logical.

To summarize, in light of the current limitations and barriers against SWDU-RED and the fierce competition of PRO, other RED applications such as RED heat engines might be more suitable for commercialization than SWDU-RED.

6. Conclusion

The systematic literature review on the economic and technical barriers to upscaling and commercializing SWDU-RED can significantly contribute to spatial planning by identifying challenges and assessing the feasibility of upscaled commercial employment of this technology. The review offers valuable insights for planners from an innovation study perspective to make informed decisions about incorporating RED into sustainable energy strategies and optimizing resource allocation in a spatial context.

To conclude, the integration of reverse electrodialysis (RED) with seawater desalination units (SWDU-RED) seems in theory like it has a large potential for partially decarbonizing the desalination industry by valorizing desalination brine. However, four major technical and economic barriers, each consisting of several sub-barriers, against the upscaling and commercialization of SWDU-RED have been identified in this work with a systematic literature review:

(1) Low power density and energy efficiency,
(2) High levelized cost of energy,
(3) Technological immaturity,
(4) Lack of competitiveness of SWDU-RED and strong competition

These main barriers are highly interrelated and have a reciprocal influence on each other. The poor power densities and energy efficiencies give rise to a high levelized cost of energy. These two adverse factors are caused by the technological immaturity of SWDU-RED and have a negative influence on the competitiveness of SWDU-RED against other approaches. The mutual influence of these main barriers on each other may cause SWDU-RED to not progress to a maturity that makes commercialization feasible. Therefore, SWDU-RED might fall victim to the so-called Valley of Death, a funding gap between the early stages of development of a technology and its commercial adoption. For SWDU-RED to progress beyond the Valley of Death, substantial long-term investments would be necessary.

However, during the literature analysis, it became apparent that the co-location of pressure retarded osmosis with desalination units (SWDU-PRO) can deliver higher power densities than SWDU-RED. Therefore, it is likely advisable, to focus investments on SWDU-PRO instead of SWDU-RED. However, there are other promising RED-applications such as RED heat engines for the utilization of industrial waste heat that seem promising. Therefore, it is recommended to conduct similar research on the economic and technical barriers of further novel RED-applications, as well as SWDU-PRO to elucidate their potential for commercialization. Additional research is also advisable into institutional barriers of salinity gradient energies.

7. Limitations

Boolean-operator based search queries are made to suit clearly defined topics and underperform when there is a lack of indexed, standardized terms and clearly defined concepts within the field of research in question (Zwakman et al., 2018). Therefore, it is recommended to balance precision and sensitivity in the literature search process. The usefulness of a literature review based on a search query with Boolean operators is constraint by the adequacy and completeness of the search terms connected to the operators. The search sensitivity can be increased by identifying as many relevant search terms as possible. However, if the identification of search terms is arbitrary, transparency and replicability of the research process are no longer given. Thus, the inquiry for suitable search terms needs to be structured, logical and replicable to not undermine the precision of the Boolean search query. Because of this, an iterative mixed-method approach is needed and careful documentation of the process is key. (Zwakman et al., 2018)

Therefore, the original intention for conducting the systematic literature review was to mitigate the inherent bias within the initial collection of articles in this preliminary exploratory search, which was accomplished through the implementation of the "pearl-growing" technique. Pearl-growing is a common method in literature reviews for enlarging the collection of articles that are applicable to a predetermined research question (Schlosser et al., 2006). From these publications, keywords were to be identified to serve as a basis for the subsequent search. In this manner, the corpus of articles that are connected to the research questions should have expanded. Further, it was planned to diminish the bias of the initial article set further through direct forward- and backward citation tracking were applied to the publications that emerged out of the pearl-growing process. By using forward- and backward citation analysis, the expansion of the literature corpus is supported by the judgment of other researchers (Zwakman et al., 2018). Backward citation tracking is commonly used for determining further relevant articles by utilizing the reference list of a publication that is already included within the article set for the literature review (Hirt et al., 2021). Similarly, forward citation tracking consists of identifying articles that cite the initial article from the previously known corpus of literature (ibid.).

However, due to the large number of publications that were found with the initial explorative search query already, it was not possible to conduct pearl growing or citation tracking. Therefore, the analyzed body of literature is not comprehensive and the selection of publications is inherently biased.

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