Barriers to osmotic power plants

Exploring the potential of reverse electrodialysis power plants in shaping our future energy landscape:

Examining current barriers that hinder an upscaling

A Master's Thesis

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I. Abstract

This thesis examines the potential of osmotic energy as a sustainable and innovative renewable energy source while addressing the main research question:

Which current barriers to osmotic energy, while focusing on reverse electrodialysis (RED), can be identified from a holistic planning perspective that could hinder an upscaling process, especially in the context of the Netherlands?

A strong focus on RED power plants as a case study and in the spatial context of the Netherlands is fundamental to this thesis. Drawing upon insights from literature, documents, and interviews, it identifies various facets of osmotic energy's diffusion, based on the insights from Innovation Diffusion Theory. It explores in this frame its relative advantages, compatibility with sociocultural factors, complexity, trialability, and observability.

While acknowledging its benefits, such as environmental benefits, reliability, infrastructure compatibility, and public acceptability, the thesis balances these aspects against identified key barriers to the upscaling of osmotic energy on multiple levels, including substantial funding requirements, economic considerations, regulatory complexities, potential water resource conflicts, diverging interests, limited political awareness, and the necessity of becoming competitive in the renewable energy market.

Based on that, this thesis provides valuable insights from a holistic planning perspective into current barriers in the upscaling process, while offering an up-to-date and holistic perspective for policymakers, researchers, and stakeholders in the renewable energy sector.

Key words: Osmotic energy, barriers, upscaling, renewable energy, RED

II. Acknowledgements

I want to express my deep appreciation for the exciting challenge posed by my research into the future energy source: Water. I am very grateful to all the individuals who supported me throughout this journey.

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The double degree master program, "Water and Coastal Management," offered in collaboration between the University of Oldenburg and the University of Groningen, significantly enriched my knowledge and kindled my interest in research in water-based energy. The opportunity to study abroad has been a truly transformative experience, and I am profoundly thankful.

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Marc Siemens

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III. List of Abbreviations

AEM	Anion Exchange Membranes
CEM	Cation Exchange Membranes
CO2	Carbon Dioxide
DMEC	Dutch Marine Energy Centre
ED	Electrodialysis
EWA	Dutch Energy from Water Association
EZK	Dutch Ministry of Economic Affairs and Climate Policy
IEM	Ion Exchange Membranes
IMIEU	Institute for Infrastructure, Environment and Innovation
INES	International and European Alliance for Osmotic Energy
IPCC	Intergovernmental Panel on Climate Change
KWH	Kilowatt-hour
LCOE	Levelized Costs of Energy
MFC	Microbial Fuel Cells
OTEC	Ocean Thermal Energy Conversion
PEOU	Perceived Ease of Use
PRO	Pressure Retarded Osmosis
PU	Perceived Usefulness
RED	Reverse Electrodialysis
RED2	Renewable Energy Directive
ROI	Return on Investment
SDG	Sustainable Development Goal
SGP	Salinity Gradient Power
TRL	Technology Readiness Level
UN	United Nations

1. Introduction

The energy transition is a response to the urgent need to address climate change by reducing greenhouse gas emissions and transitioning to a low-carbon economy. Since the legally binding international treaty on climate change, the Paris agreement from 2015, every participating nation must contribute to the goal of limiting global warming to far less than 2°C (Horowitz, 2016). To fulfil the goal of a carbon free society, we must transform, among others, our energy sector (Similä, 2022). This transformation contains a deep change of the current energy system and its infrastructure, with all its difficulties (De Boer & Zuidema, 2015).

This poses a great challenge to countries that rely heavily on fossil fuels in, among others, the energy sector, and induced a change in the energy supply system. In Europe, the energy transition is mainly driven by wind and solar energy (Buchholz & Brandenburg, 2018). But while the share of wind and solar power in the energy mix increases, there are new problems occurring. Fossil power plants have the advantage that they can be adjusted depending on the current energy demand. Wind and solar power are in a contrast very fluctuating, power can only be provided when the sun is shining, or the wind is blowing (Gross et al., 2007). Until today this fluctuation is mainly compensated by fossil power plants and a few energy storages, and therefore not desirable for the overall energy transition (Emblemsvåg, 2022).

Energy storage systems, which can store excess (renewable) energy when it is produced and then release it when needed, are still in their early stages, and it requires significant investment to further develop and implement these techniques (Hossain et al., 2020). Today's mainly used pumped storage hydropower systems and similar facilities are likely not sufficient to fulfil this demand of carbon free energy today, or possibly in the future, since the technique is not usable in flat lands like the Netherlands (Lu et al., 2018).

Beside the negative impacts on the climate, the war in Ukraine has resurrected a debate about energy dependency on fossil fuels from autocratic nations and the possible impacts on the European economy (Rodríguez-Fernández et al., 2022). After a reorientation of the European energy sector away from Russian energy supply followed by high price fluctuations on the marked the focus lays now on the expansion of renewable energies in Europe (WirtschaftsWoche, 2022).

Consequently, there is a focus on, and a need for, technologies that can help solve these problems. Osmotic power plants in general, and particularly reverse electrodialysis (RED) power plants, are very promising in this regard (Chae et al., 2023). This technique uses the salinity gradient between fresh and salt water for energy production and has the benefit to produce energy on demand (Jendeavor, 2014). The seawater and freshwater resources used in the process are, in many regions, almost infinite and readily available, making it a sustainable source of energy. Of great importance is that these power plants do not emit any greenhouse gases or other pollutants during electricity generation, making it a clean and environmentally friendly source of energy (Mei & Tang, 2018).

But despite the advantages of osmotic power plants, and the need for such technology, there is no large-scale implementation of these powerplants soon expected (Chae et al., 2023). Although major milestones in improving the technique were accomplished in the 2000s (Veerman & Vermaas, 2016), there are worldwide only a few osmotic energy pilot plants running. In the Netherlands is only one pilot plant using the RED technique in operation, which is currently at technology readiness level (TRL) 7 and has been built in 2013 (Veerman & Vermaas, 2016).

While current research in the field of osmotic energy and RED has a strong focus on technological aspects (see Figure 3). The upscaling and subsequent implementation of eco-innovations (including osmotic energy when following the most common definition by Carrillo-Hermosilla et al., (2010)) remains generally constrained by multifaceted barriers from different sources (Del Rio et al., 2010).

Barriers refer to obstacles or challenges that impede the achievement of a desired goal or objective. Biesbroek et al. (2011) defines barriers in a climate change context as *"(…) those conditions and factors that actors experience as impeding, diverting, or blocking the process of developing and implementing (…) strategies."* (Biesbroek et al., 2011, pp. 2). These obstacles can e.g., be social, economic, political, technological, or environmental in nature and can arise at various stages of the planning process (Painuly, 2001). Barriers can prevent the successful implementation of a project or plan, leading to delays, increased costs, or, in worst case, even the abandonment of the project altogether.

Additionally, societal systems are under constant change (Banathy, 2013) and the sustainable energy marked is constantly evolving (Al Ali et al., 2019), barriers that might have occurred in the past could already be overcome or no longer of importance. On the other hand, new barriers could have emerged over time (Eisenack et al., 2014). One example is the public opposition against local wind parks in Bavaria, Germany, resulting in a fast and significant policy change within 4 years by the state government from a before rather ambitious expansion of wind energy towards a strong deceleration of this expansion (Langer et al., 2016). It is consequently important to provide an up-to-date assessment of barriers.

In this line, the Intergovernmental Panel on Climate Change (IPCC) stated in 2nd Assessment that: "*Accelerated development of technologies that will reduce greenhouse gas emissions and enhance greenhouse gas sinks — as well as understanding the barriers that inhibit their diffusion into the marketplace — requires intensified research and development by governments and the private sector.*" (IPPC, 1995; pp. 42).

To facilitate its integration into the energy marked, identification of these barriers is essential. Therefore, this thesis aims to close the gap of a holistic identification of current barriers from a planning perspective that can hinder the upscaling of such a technique. The main research question can therefore be formulated as:

Which current barriers to osmotic energy, while focusing on reverse electrodialysis (RED), can be identified from a holistic planning perspective that could hinder the upscaling process, especially in the context of the Netherlands?

Furthermore, to elucidate the overarching research question, the research additionally focusses on these sub-questions:

1. *What are the benefits of this technology that could position it favourably within the ongoing energy transition and in the societal context?*
2. *Which barriers can be identified that potentially hinder a subsequent large-scale implementation in the future?*

Subsequently, this thesis aims to discuss and evaluate the identified barriers from an innovation diffusion perspective and juxtapose them with the benefits this technology can provide. This offers current insights and perspectives to the existing body of knowledge and allows a holistic classification of the current position of osmotic energy and RED within the given circumstances. Additionally, it provides potential decision-makers, actors, and planners in this field with valuable insights necessary to make informed decisions about incorporating osmotic energy and RED into sustainable energy strategies.

1.1 Academic Relevance

The relevance of this technology, especially for RED, is also reflected by the increasing number in publications on this topic which show an increase of rounded 582% from the year 2010 to 2022 (Fig. 1). For the same timeframe the overall number of publications on Dimensions.ai increased by rounded 100% (Fig. 2). This trend is supported by the “UNESCO Science Report 2020” which shows a stronger growth rate in publications for the cross-cutting category energy between 2015 and 2019 than for the total amount of publications (UNESCO, 2020), although the numbers are different and not easily comparable to Dimensions.ai.

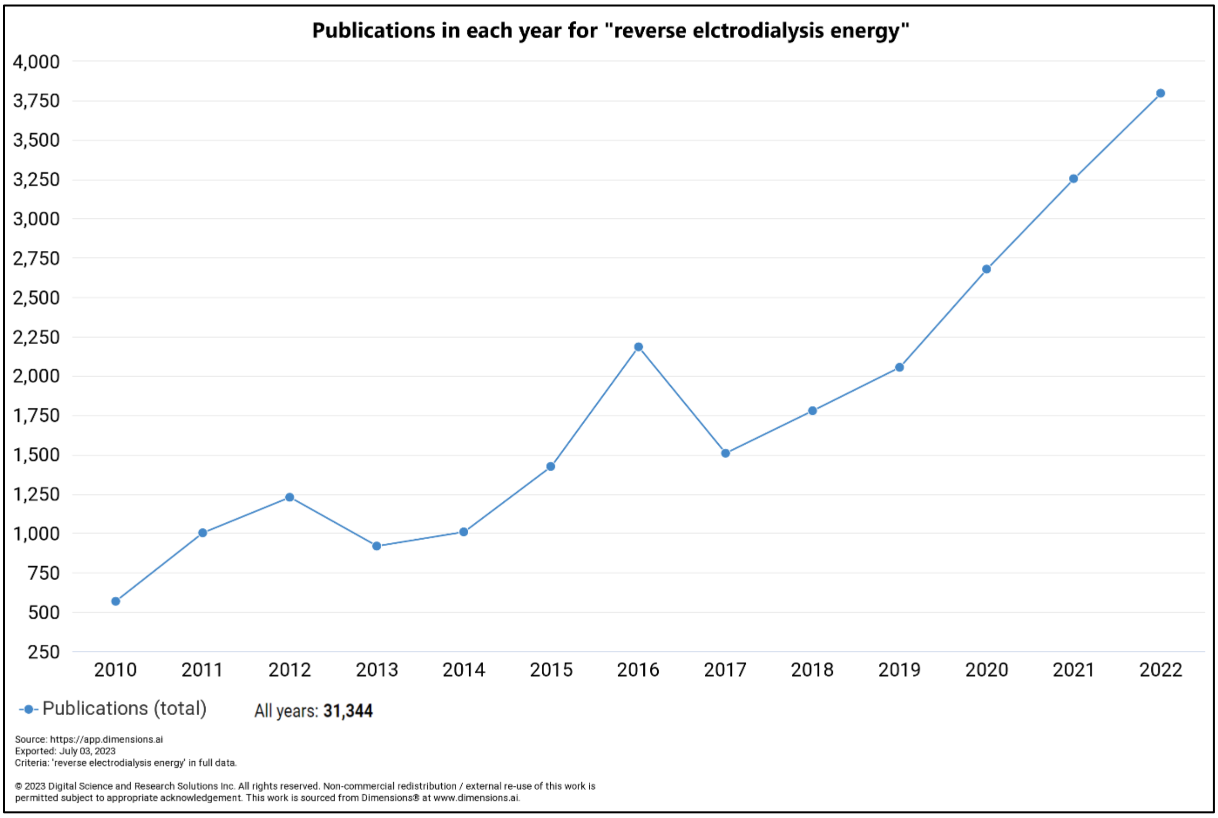

Figure 1: Publications in each year for the search term "reverse electrodialysis energy" on Dimensions.ai; Retrieved: 03.07.2023.

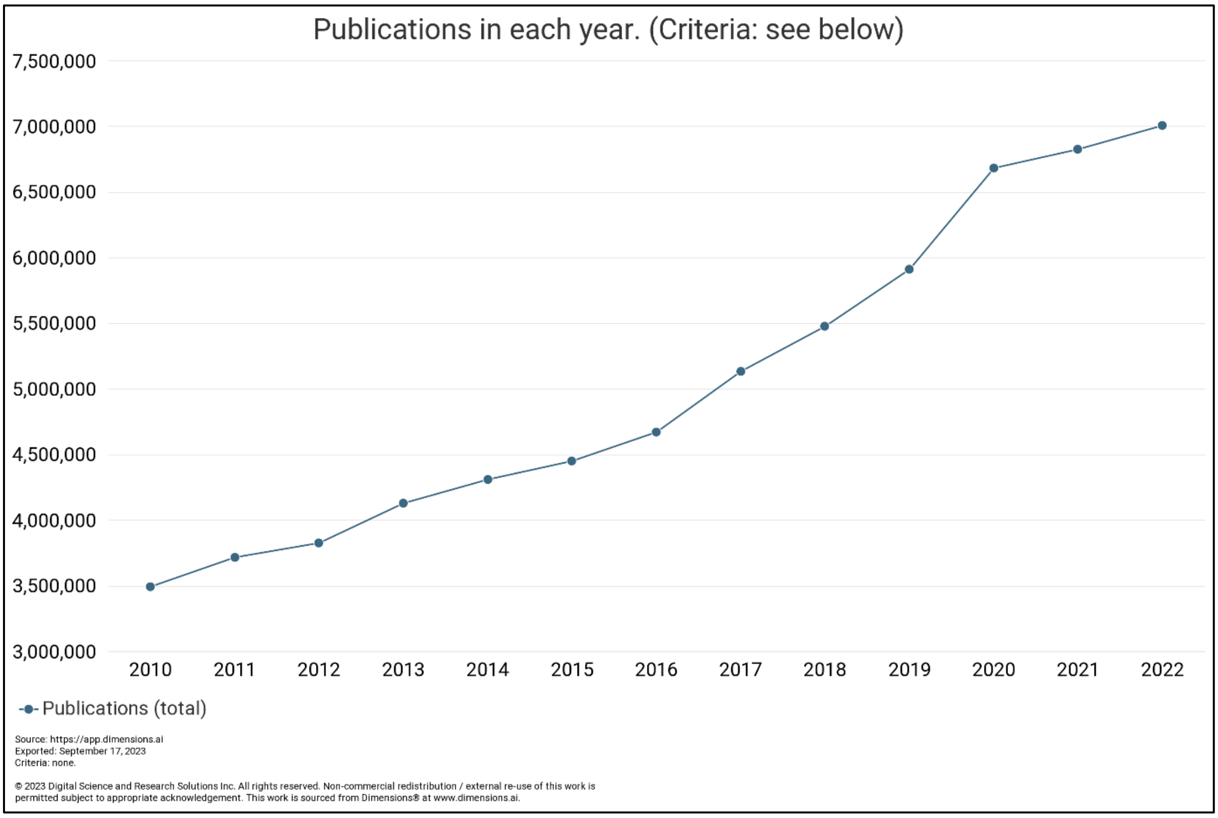

Figure 2: All publications in each year from 2010 to 2022 on Dimensions.ai; Retrieved: 17.09.2023.

However, the literature focusses mainly on engineering and chemical sciences, possibly due to the research needed to further develop the technology. Additionally, environmental, and biological publications are well represented, likely due to the research on impacts of this technology on the environment. Contrary to this, publications from economical, societal or management perspectives are underrepresented (Fig. 3). Comparable patterns, but with significantly less publications, emerge when applying the search terms: “reverse electrodialysis barriers upscaling”, “salinity gradient power barriers upscaling” or “osmotic energy barriers upscaling”, indicating a lack of research in this field (Applied on Dimensions.ai, Retrieved: 15.09.2023).

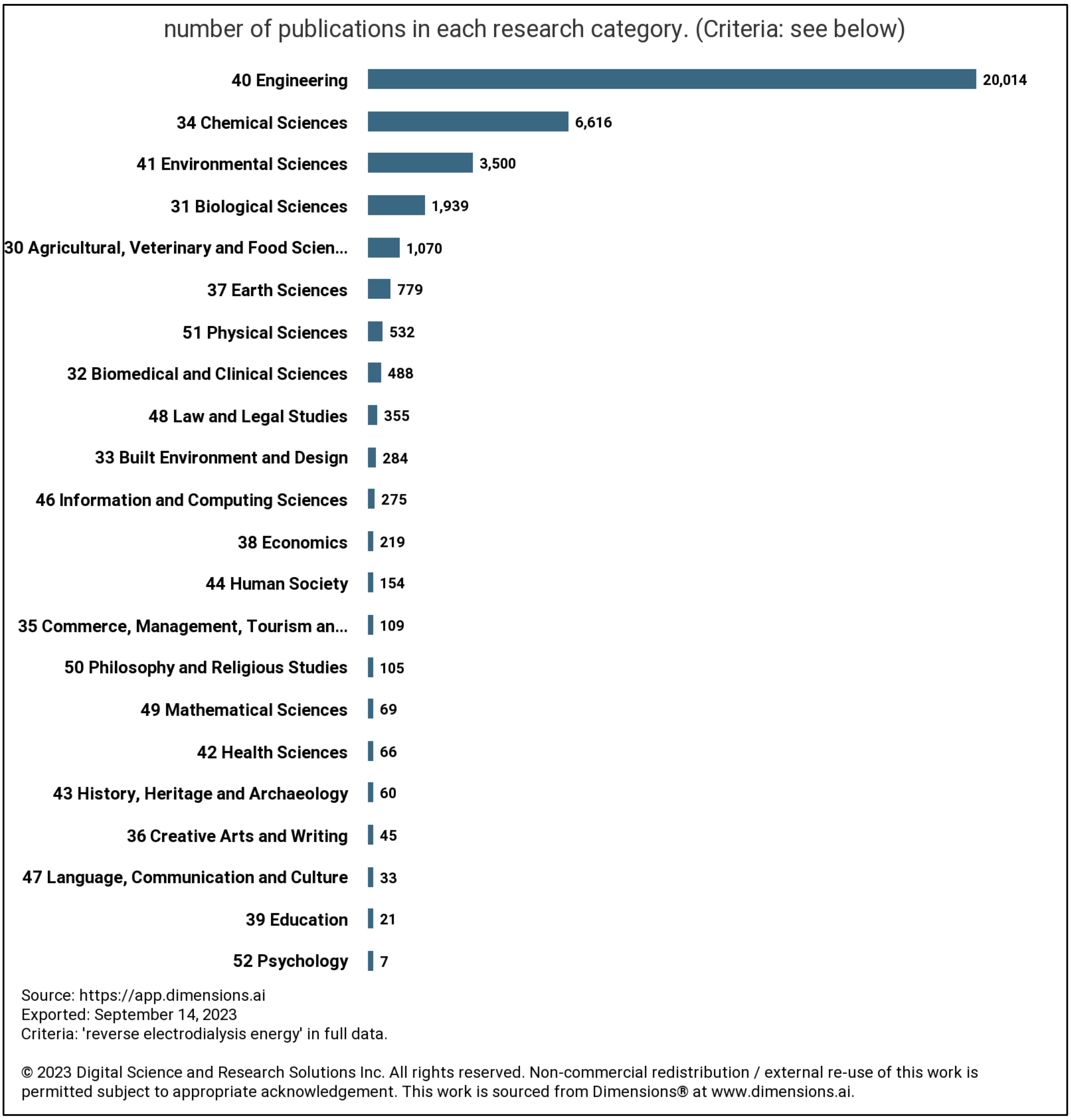

Figure 3: Number of publications in each research category for the search term "reverse electrodialysis energy" on Dimensions.ai; Retrieved: 14.09.2023.

In this line, Roldan-Carvajal et al. (2021, pp. 11) concluded for osmotic energy, that *"Indeed, there is certainly ample scope for more social, political, environmental, commercialization strategies and financial research to overcome the diffusion barriers and deploy future pilot plants."*

Consequently, this research contributes valuable insights from a planning perspective to the existing knowledge base, enabling a holistic assessment of the current status of osmotic energy and RED within the prevailing context.

1.2 Societal Relevance

The UN's 2030 agenda seeks to attain sustainable development by addressing social, economic, and environmental challenges (UN, 2015). This agenda is driven by 17 Sustainable Development Goals (SDGs) to guide the ongoing global transformation towards sustainability and is *"ground-breaking and unprecedented in its scope (…)"* (Bornemann & Weiland, 2021; pp. 96). Consequently, the achievement of these SDGs holds paramount societal significance.

Osmotic energy has the potential to contribute to the fulfilment of some of these goals, partly overlapping with the goals of the ongoing energy transition, as described in more detail in chapter 2.

Osmotic energy is an energy source that aligns with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) (Mora & de Rijck, 2015). By generating electricity from the difference in the salt concentration between freshwater and saltwater, osmotic energy offers a clean energy solution that can help reduce greenhouse gas emissions and combat climate change (Chae et al., 2023). This technique does not have a negative impact on air quality, aligning with SDG 11.6 (Sustainable Cities and Communities) by promoting clean and healthy urban environments.

Developed countries currently take the lead in creating and adopting osmotic energy pilots and plants and can therefore support the scientific and technological capacity of developing countries (Mora & de Rijck, 2015). This aligns with SDG 12.1 (Sustainable Consumption and Production) and SDG 12.a (Supporting Developing Countries' Scientific and Technological Capacity).

Beyond energy production, as described more in chapter 2.2.3, osmotic energy can be utilized for more efficient water purification and desalination, contributing to SDG 6.1 (Clean Water and Sanitation) (Rahman et al., 2022). Additionally, several more applications for this technology are being researched, such as storage systems, which will likely benefit from the further development of osmotic energy and the underlying components.

Given the significant societal importance of achieving the SDGs, the potential contributions of osmotic energy to multiple SDGs simultaneously are inherently of great societal relevance. However, the path towards the upscaling and commercialization of osmotic energy is likely impeded by substantial barriers. Understanding the nature of these barriers and their interconnectedness, while acknowledging the multifaceted origin of barriers, is essential. It serves as a crucial foundation for informed assessments regarding the feasibility and advisability of commercializing osmotic energy. This underscores the societal relevance of this thesis.

2. Literature

Chapter 2.1 further discusses barriers as key concept in this thesis. Chapter 2.2 serves as a foundational component by providing crucial background information relevant to the topic of osmotic energy, with a strong focus on RED as it serves as a case for this study. It initiates with an exploration of RED, diving into its historical evolution, fundamental principles, and current research efforts for future applications that make use of the RED technique. Based on this, the review turns in chapter 2.3 to the role of osmotic energy within the broader context of the ongoing energy transition to unravel benefits that this technology could provide to fulfil the goals, as well as downsides of the technology. In chapter 2.4 the innovation diffusion theory will be introduced, designed to facilitate the analysis of barriers encountered in the field of osmotic energy. Subsequently, in chapter 2.5 an analysis tool will be developed.

2.1 Defining Barriers

As discussed, identifying, and addressing barriers is a critical component of effective planning and is essential to achieve successful outcomes. The IPCC discusses the barriers in their 3rd assessment in a detailed manner, proving the importance of barriers in transition frameworks (IPCC, 2001).

Painuly (2001) states that "*Some barriers may be specific to a technology, while some may be specific to a country or a region*" (Painuly, 2001, pp. 75). Therefore, not the same barriers apply for different technologies or a different spatial context and must be examined for every technology and region. Therefore, as stated, this thesis focuses on RED power plants in the spatial context of the Netherlands.

The barriers that hinder the achievement of a goal can be examined and evaluated on various levels (Painuly, 2001). Figure 4 shows the different levels ranging from barrier categories to certain dimensions of barriers. However, to align with the holistic perspective of this thesis, this study will discuss barriers only up to level 3.

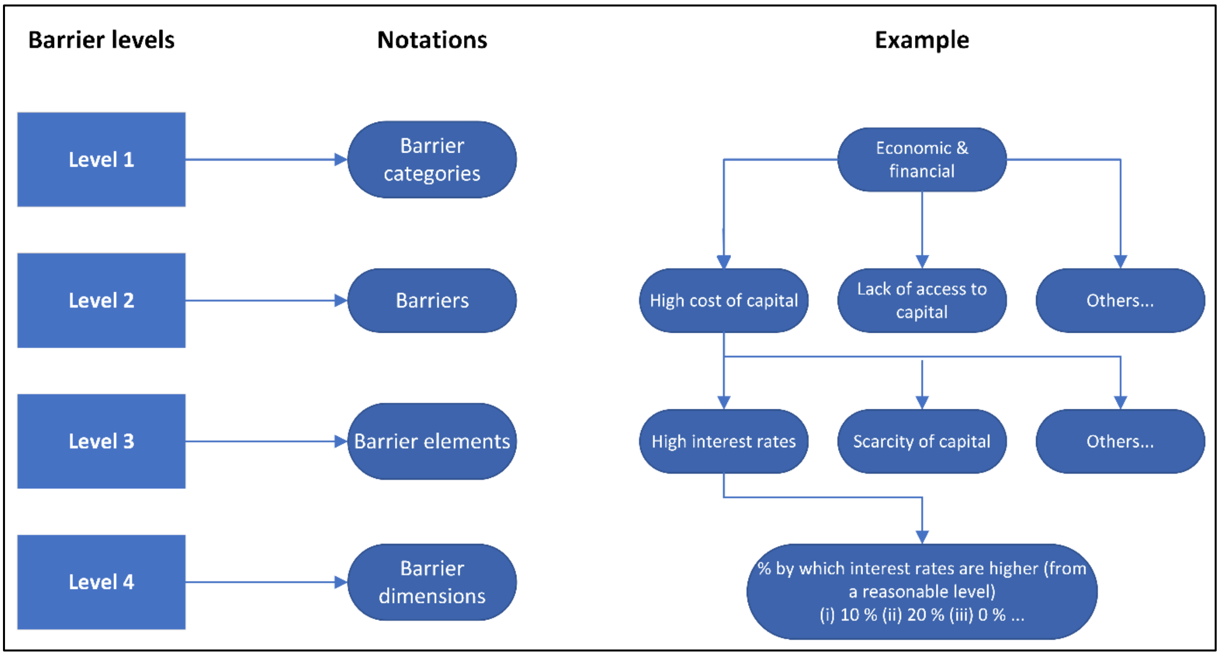

Figure 4: Description of barriers through their different levels (own illustration based on Painuly (2001))

2.2 Introducing Osmotic Energy

2.2.1 History

Electrodialysis (ED) is a process that utilizes electrical energy to transport ions against their chemical potential, while RED generates electrical energy from the diffusion of ions in the opposite direction. ED involves the use of an external power source to separate ions, whereas RED utilizes solutions of different concentrations to generate electricity. Maigrot and Sabates (1890) introduced the concept of ED in 1890 to remove impurities in sugar production. Over the years, ED found applications in various fields where salt removal was crucial.

In 1952, Manecke (1952) proposed the use of ED to store electrical energy in a device called the "Membranakkumulator". By employing Ag/AgCl electrodes and a KCl electrolyte, he demonstrated the possibility of reusing the stored energy through reverse operation. Richard Pattle later realized that the combination of river water with seawater could serve as a power source in a "hydroelectric pile", harnessing the osmotic pressure difference between the two (Pattle, 1954). Murphy (1958) further developed this concept in 1958 with the invention of "osmionic demineralization", combining an ED desalinator with a RED generator. This idea has been employed by a Canadian company for desalination facilities (Sparrow et al., 2012).

The 1970s witnessed increased interest in finding sustainable energy sources due to the publication of "*Limits of Growth*" by Meadows et al. (1972) and the global oil crisis in 1973.

Norman (1974) proposed the hypothetical "osmotic salination energy converter" in 1974, followed by Loeb's (1975) introduction of "pressure retarded osmosis" (PRO) in 1975. PRO utilized membranes permeable only to water, unlike RED, which employed ion-permeable membranes. Loeb continued to research PRO and played a significant role in its development until his passing in 2008 (Veerman & Vermaas, 2016).

Weinstein & Leitz (1976) improved the power density of RED in 1976, and Wick (1978) estimated the global potential of salinity gradient power (SGP) to be 2.6 TW, equalizing current electricity consumption. In the second oil crisis, researchers explored various methods to harness SGP, such as Olsson, Wick, and Isaacs' (1979) "vapor pressure differences utilization". Forgacs (1982) suggested several applications for ED and RED, some of which were realized later, including energy storage and reuse, solar energy conversion, and power generation using waste effluents.

The new millennium brought increased interest in RED, sparked by Valeriy Knyazhev's (2001) description of a real sea and river water-operated RED system in Russia. The Wetsus institute in the Netherlands initiated the osmotic energy project, resulting in numerous publications and doctoral theses on SGP (Veerman & Vermaas, 2016). Significant milestones in RED technology included increased power density, control over the negative effects of multivalent ions through membrane design, mitigation of fouling through feed water reversal and air injection, and the development of capacitive electrodes for RED (Veerman & Vermaas, 2016). In 2013, REDStack B.V., a company born out of these efforts, established an RED pilot on the Afsluitdijk in the Netherlands (Veerman & Vermaas, 2016), which serves as a case for this research. Later, the REAPower project, funded by the European Union, aimed to harvest salinity power from high-salinity feed waters, resulted in scientific articles and an operational RED stack with a nominal power of 1000 W (Tedesco et al., 2015).

2.2.2 Basic Principle of RED

As already stated, RED is a technology that harnesses the chemical potential difference between saltwater and freshwater to generate energy. It utilizes ion exchange membranes (IEMs) to facilitate this process. In a RED apparatus, a stack of IEMs is arranged, with compartments to feed water between them, and electrodes placed on each side (Fig. 5 (A)). Two types of membranes are used: Cation Exchange Membranes (CEMs), which allow only positive ions to pass through, and Anion Exchange Membranes (AEMs), which allow only negative ions to pass through. This selective permeability of the membranes creates a voltage difference when there is a concentration difference across them (Veerman & Vermaas, 2016).

By stacking multiple CEMs and AEMs alternately and supplying high-concentration salt solution (High) and low-concentration salt solutions (Low) in the compartments between the membranes, the voltages across the membranes accumulate. As a result, the overall stack voltage increases proportionally to the number of cell units. Each cell unit consists of a CEM, high compartment, AEM, and low compartment. When an external load is connected to the electrodes, ions are transported from the high salt solution to the low salt solution, and the ionic current is converted into electrical current at the electrodes. To facilitate the electricity generation from mixing saline solutions, a reversible redox reaction is often employed, as depicted in Figure 5 (B) (Veerman & Vermaas, 2016).

However, Nazif et al. (2022) states that typical commercially available IEMs are generally inappropriate for RED due to low-power density, lack of cost-effective IEMs, and membrane fouling under real life conditions, which are major problems from a technological perspective that can limit the commercialization of RED and could therefore represent barriers in this regard.

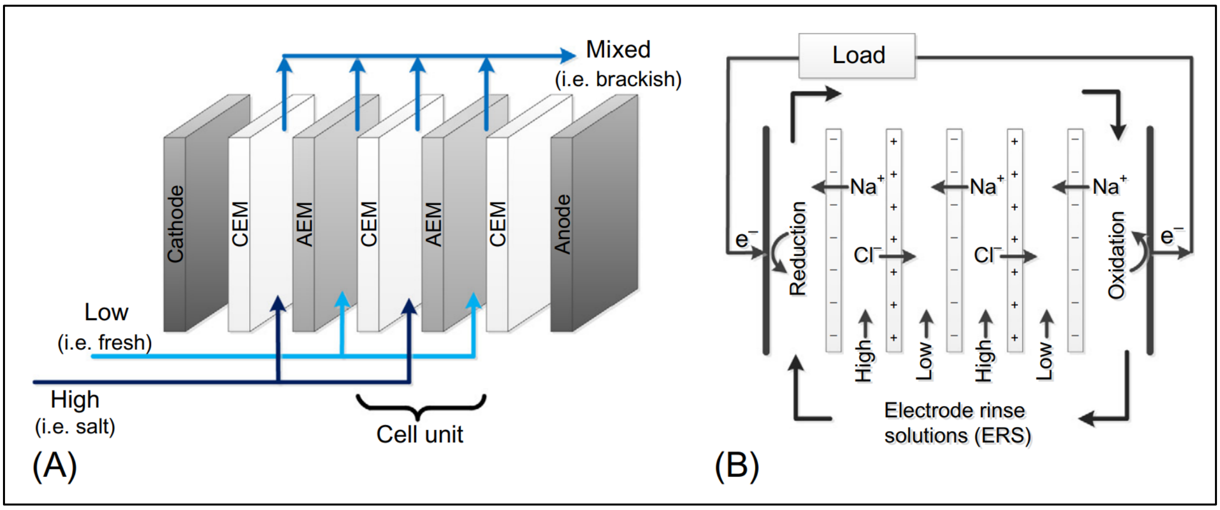

Figure 5: Industrial engineering principle of RED (Veerman & Vermaas, 2016).

2.2.3 Possible Applications

The RED technology can be used at every location where a salinity gradient between two waterbodies and a sufficient amount of water is available. Approximately 0.98 terawatts (TW) of the total global osmotic energy potential are considered extractable (Tufa et al., 2018). However, it is irrelevant if the salinity gradient is from an artificial source or occurs from natural givens. This enables the combination of industrial facilities that have brine as a by-product, such as desalination plants combined with RED power plants. In general, a higher gradient between the brine and the freshwater means a higher energy yield in each amount of water.

The most promising (future) application types beside the already mentioned power production will briefly be described to highlight further benefits of this technology.

Integrated Systems

If an unmodified RED stack is connected to other units, it creates integrated systems. On the other hand, in hybrid systems, the RED stack itself is modified. One example is a hypothetical production unit described by Brauns (2008) that combines the generation of electrical energy and drinking water. Seawater is first desalinated, and the resulting brine is further concentrated through evaporation using solar heating. The vapor is then condensed, transferring heat to a stream of cold seawater, which produces additional potable water and warm seawater. In this system, a RED generator is fueled by the gradient between the concentrated brine and warm seawater streams.

Another application involves utilizing the brine waste from seawater desalination units. Instead of directly discharging the brine, which can be harmful to marine life, it is used together with seawater for a RED system. This has dual advantages: generating energy and diluting the brine before discharge. Korean research institutes have investigated the use of concentrated feeds in combination with desalination technologies, such as capacitive deionization (Jande and Kim, 2014). Other sources of low salinity feedwater include sewage treatment effluent or river water that is not suitable for direct production of potable water (Li et al., 2013).

Integrated Closed Systems

Most of the examples mentioned so far involve open systems, where seawater and river water are used as feed water obtained from the environment, and the effluent is discharged into the sea. In contrast, closed-loop systems operate in a closed environment, eliminating the need for open feed intakes or external discharge. There are two practical types of closed-loop systems: energy storage systems and heat-to-power units.

In the context of energy storage, Forgacs (1982) proposed the concept of an ED-RED cycle for temporary electrical energy storage in salinity gradients. Recently, some research groups have investigated this technique. It involves storing electrical energy in saltwater and freshwater, which offers a higher energy density compared to hydropower and could serve as a safe and environmentally friendly alternative to traditional batteries (Veerman & Vermaas, 2016).

Another interesting option is the generation of electrical power from waste heat. This concept utilizes a closed-loop RED stack for energy generation and incorporates a thermally driven regeneration step to restore the initial salinity gradient of the feed solutions. An example described by Luo et al. (2012) involves the use of ammonium bicarbonate solutions, where the volatile salt can be removed through heating in the regenerator.

Hybrid Systems

While the gas-evolution reactions of H2, O2, or Cl2 in a RED stack have generally been considered undesirable due to safety concerns and energy consumption, there have been some notable exceptions and novel applications explored by researchers. Seale (2006) and Logan et al. (2014) patented the idea of using RED for hydrogen production. Scialdone et al. (2014) successfully reduced chromium (VI) to the less toxic chromium (III) in the cathode compartment, and oxidized acid orange 7 dye in the anode compartment of a RED stack (Scialdone et al., 2015).

Furthermore, RED stacks have been combined with microbial fuel cells (MFC) in various ways, with notable contributions from the group of Bruce Logan at Pennsylvania State University. Examples include boosting the power of MFCs (Cusick et al., 2013), production of acid and alkali (Zhu et al., 2013), hydrogen production and/or CO2 sequestration (Zhu et al., 2014; Luo et al., 2013), and methane production (Luo et al., 2014).

In summary, the RED technology can possibly be used in a wide range and in combination with different techniques and will possibly benefit from the further development of this technique, however the practical implementation is so far limited, suggesting that challenges for an implementation in practice are still present.

2.3 Positioning Osmotic Energy in the Energy Transition Context

The term “energy transition” in today’s understanding refers to the global transition from fossil fuels to renewable energy sources and the implementation of more energy-efficient technologies and practices (Davidsson, 2015). The transition aims to address the challenges of climate change, energy security, and economic competitiveness by reducing greenhouse gas emissions, enhancing energy security, promoting economic growth, improving public health, and driving technological innovation (Gründinger, 2017). It involves changes in the energy supply system, such as the expansion of renewable energy sources, energy storage, and smart grid technologies, as well as changes in energy demand patterns, such as energy efficiency measures and the adoption of low-carbon technologies in transportation, buildings, and industry. The energy transition is a complex and multi-faceted process that involves a range of stakeholders, including governments, businesses, civil society, and individuals (Gründinger, 2017).

2.3.1 Defining Energy Transition

An energy transition refers to a comprehensive change in technologies and practices that are necessary to replace an existing energy source with a different one. The IPCC defines a transition as follows:

"*The process of changing from one state or condition* (equilibrium) *to another in a given period of time. Transition can occur in individuals, firms, cities, regions, and nations, and can be based on incremental or transformative change*" (IPCC, 2022).

The term "energy transition" has a long history and has been used in various contexts. It was initially used to describe the transition from traditional biomass energy, such as e.g., coal, to modern fuels such as oil and gas in the mid-twentieth century. In the 1970s, the term gained more prominence because of the oil crises and the growing awareness of the environmental and social impacts of fossil fuels (Basosi, 2020).

In the 1980s and 1990s, the concept of energy transition began to expand beyond a focus on replacing one type of fuel with another, to encompass broader transitions in energy systems and the integration of renewable energy sources. During this time, the term was increasingly used to describe the transition from centralized, fossil-fuel-based energy systems to the growing field of decentralized, renewable energy systems (Melosi, 2017).

In the early 2000s, the concept of energy transition gained renewed attention in response to concerns about climate change, energy security, and the growing economic potential of renewable energy technologies (Melosi, 2017). The term has since become a key focus of energy policy development and research, as countries around the world seek for ways to accelerate the transition to a low-carbon, sustainable energy system.

One prominent practical example is the transition from a pre-industrial era that depended on traditional biofuels, wind, water, and human labour, to an industrial era marked by extensive mechanization by steam power and consequently the utilization of coal (Fig. 6) (Solomon & Krishna, 2011).

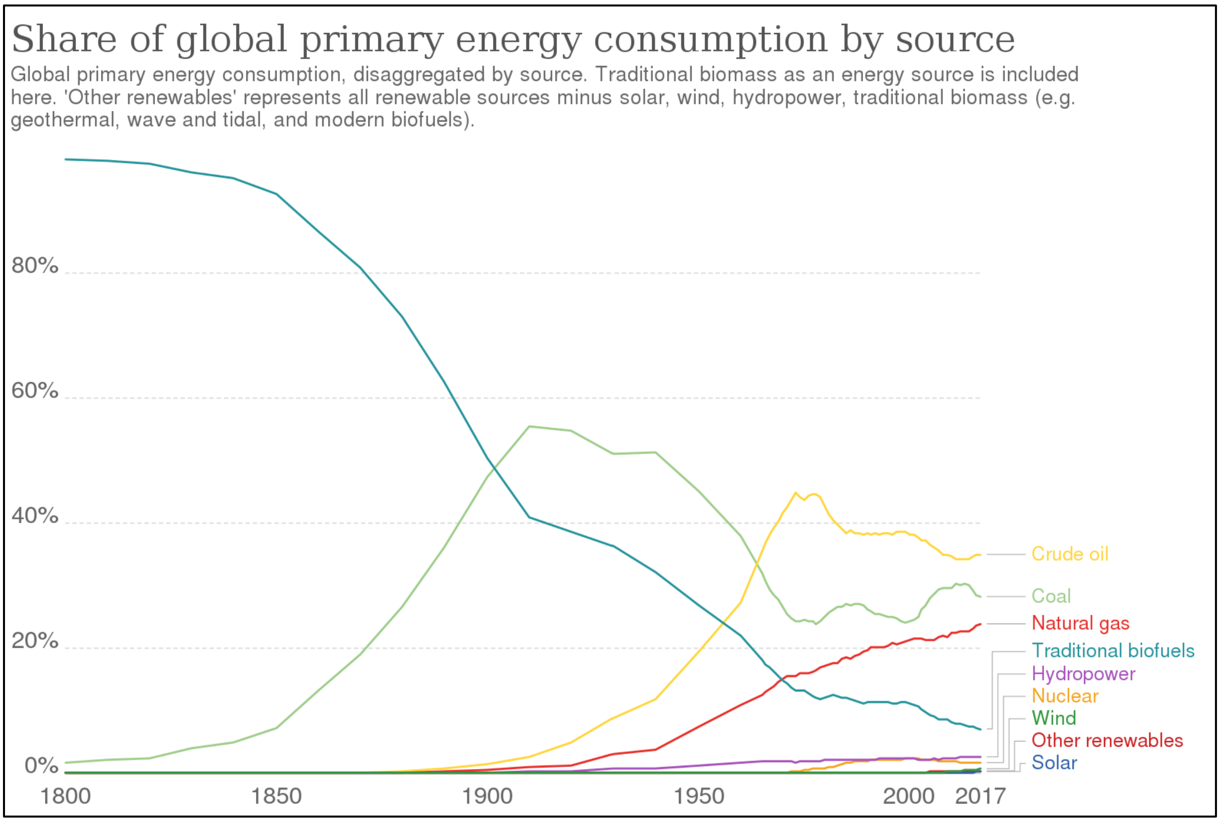

Figure 6: Share of global primary energy consumption by source. (https://ourworldindata.org/grapher/global-primary-energy-share-inc-biomass, Retrieved: 07.05.2023).

2.3.2 Drivers of Today's Energy Transition

Climate change is one of the most important push-factors for the energy transition (UN Energy, 2021). The burning of fossil fuels such as coal, oil, and gas releases large amounts of carbon dioxide and other greenhouse gases into the atmosphere, which contribute to global warming (see Fig. 7). The global energy sector is currently the main emitter of greenhouse gasses (UN Energy, 2021). This leads to a range of environmental and social impacts, including more frequent and severe weather events, sea level rise, changes in precipitation patterns, and ecological disruption.

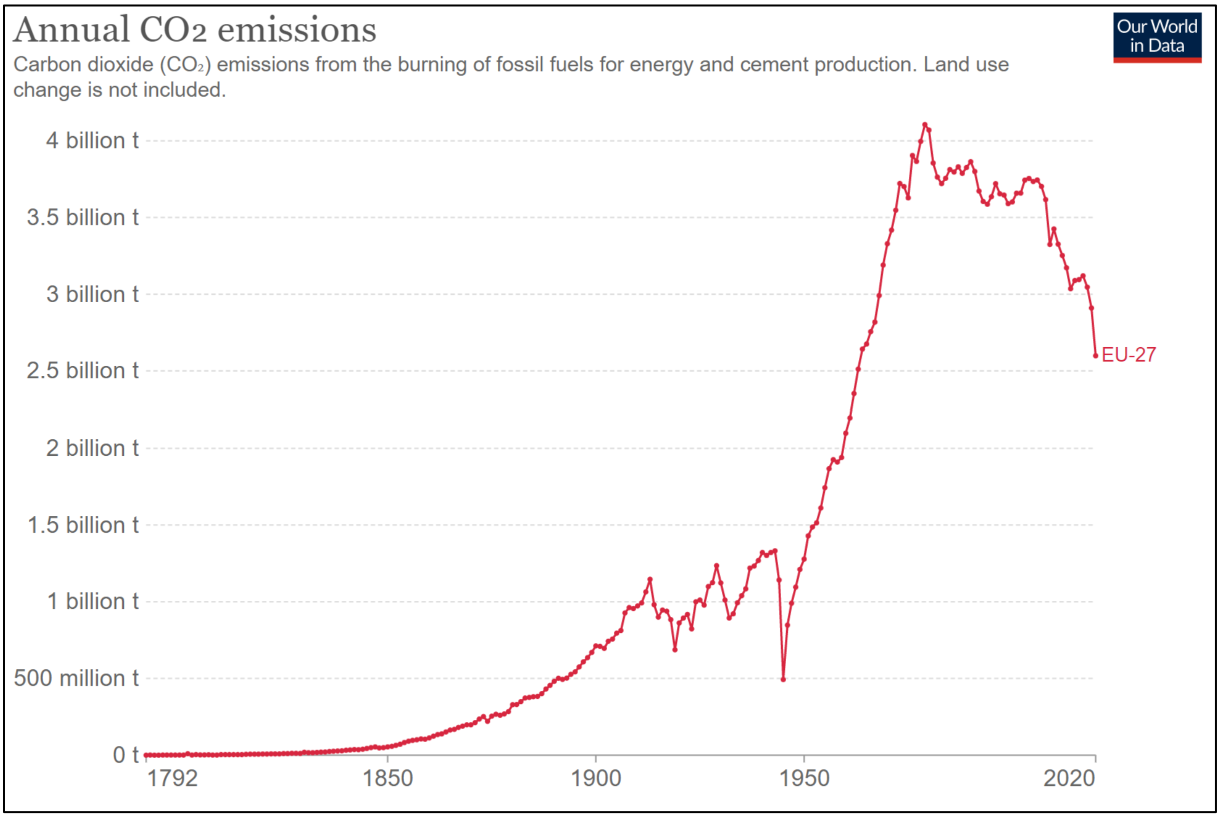

Figure 7: Annual CO2 emissions from the EU 27 states. (https://ourworldindata.org/co2-and-greenhouse-gas-emissions, Retrieved: 07.05.2023)

To mitigate the impacts of climate change, there is a high consensus among scientists, policymakers, and the public that urgent action is needed to reduce greenhouse gas emissions (UN Energy, 2021). This has led to a global transition towards renewable energy sources, such as solar, wind, hydro, and geothermal power, which emit little or no greenhouse gases during their operation.

As discussed earlier, RED power plants use the salinity gradient between fresh and salt water to generate electricity on demand, making them a reliable and flexible source of renewable energy (Mei & Tang, 2018). This can help address some of the challenges faced by wind and solar power, which are intermittent and dependent on weather conditions. Namely they are baseload capable and could provide electricity production in the case of bad weather conditions for solar and wind power, the so called "Dunkelflaute". A part that is currently realised by fossil power plants which emit greenhouse gases.

However, it must be noted that renewable energy alternatives are not fully emission free, production, installation, maintenance and decommission still emit greenhouse gases. Acuna Mora & de Rijck (2015) stated in a life cycle analysis that e.g., solar power emits 90g CO2-

equvalents per kwh and RED emits <10g CO2-equivalents per kwh. But compared to 1004g CO2-equivalents per kwh for energy from coal this can still be considered as a significant improvement.

Secondly, **energy security** is an important push-factor for the energy transition (UN Energy, 2021), especially in Europe. It refers to the reliable and affordable supply of energy to meet the needs of our society. Historically, Europe has been heavily reliant on fossil fuels, particularly oil and gas, from a few dominant suppliers (see Fig. 8). This has created concerns about energy security, especially in modern times with the background of the war in Ukraine and the use of fossil fuels as political leverage by Russia (Rodríguez-Fernández et al., 2022).

This dependence on fossil fuels from a few sources has two major drawbacks. Firstly, it can make countries vulnerable to supply disruptions due to political instability, conflicts, or natural disasters in the supplier countries. Secondly, the prices of fossil fuels can be volatile, leading to uncertainty and potential economic impacts (Bluszcz, 2017). But without a consistent and uninterrupted flow of energy, our modern society would cease to function effectively.

The energy transition aims to increase energy security by diversifying energy sources and reducing dependence on fossil fuels. This can be achieved through the deployment of renewable energy technologies, which provide a more decentralised and diverse energy supply. For example, solar-, wind energy, and new innovations like RED power plants, can be generated locally, reducing dependence on imported fossil fuels in the energy sector (Carfora et al., 2022).

The use of RED power plants can improve energy security by reducing dependence on fossil fuels, particularly those which are imported from politically questionable regions. The abundant availability of sea- and freshwater water as a resource, especially in the Netherlands, reduces the vulnerability to energy supply disruptions and price volatility.

However, large-scale energy infrastructure projects necessitate access to cost-effective generation technologies, such as solar panels, wind turbines and osmotic energy (Sandor et al., 2018). These technologies, in turn, rely on specialized manufacturing facilities and raw materials supplied through robust and dependable supply chains (Sandor et al., 2018). Imposing trade duties or sanctions has the capacity to raise costs or limit access to these energy technologies, especially in countries lacking control over the entire supply chain

(Sandor et al., 2018). Such actions could potentially disrupt the global market, or the market in affected countries, for these technologies, potentially leading to reduced deployment of renewable energy systems and a decreased utilization of indigenous renewable resources.

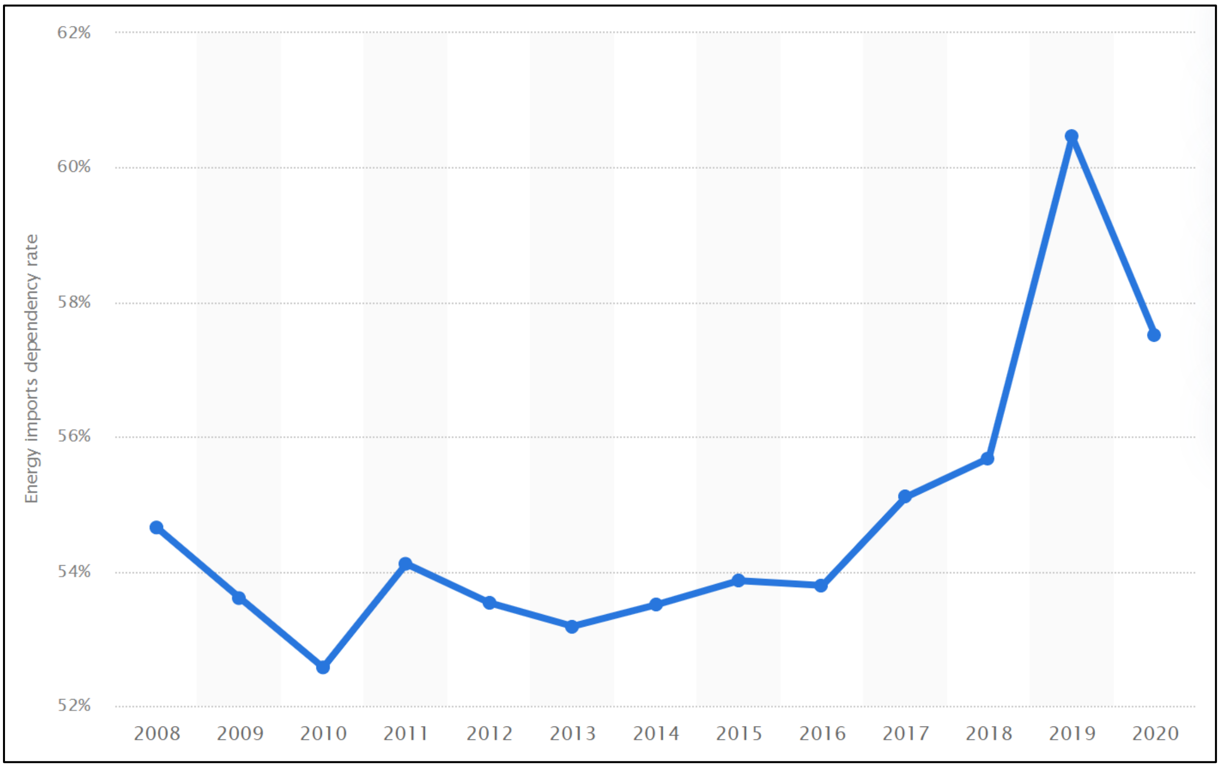

Figure 8: Dependency rate on energy imports in the European Union (EU-28) from 2008 to 2020; (https://www.statista.com/statistics/267588/dependency-on-energy-imports-in-the-eu/, Retrieved: 07.05.2023)

Thirdly, **economic competitiveness** is a pull-factor for the energy transition (UN Energy, 2021). The transition to a low-carbon economy can create new economic opportunities and drive economic growth, which can make countries more competitive globally.

The deployment of renewable energy technologies can create new industries and jobs in these regions through manufacturing, installation, operation, and maintenance. For example, the production of wind turbines has become a major industry in Europe, providing employment opportunities and boosting economic growth. In the last decades, there was a significant increase in employment in the environmental economy, which grew by 49% compared to the overall economy, which only grew by 6% (see Fig. 9). The growth in the number of jobs in the environmental economy can be attributed to the management of energy resources, specifically the production of renewable energy sources such as wind and solar power, as well as the manufacturing of equipment and installations that promote energy efficiency and conservation (Eurostat, 2017).

However, it's worth noting that the Employ-RES study (Ragwitz et al. 2009), which found that the promotion of renewable energy will create a net increase in jobs in Europe, acknowledged that the total effect of renewable energy on employment is strongly dependent on energy cost increases, with higher costs potentially dampening the employment increase. Energy prices are therefore an important factor for net job creation from renewables.

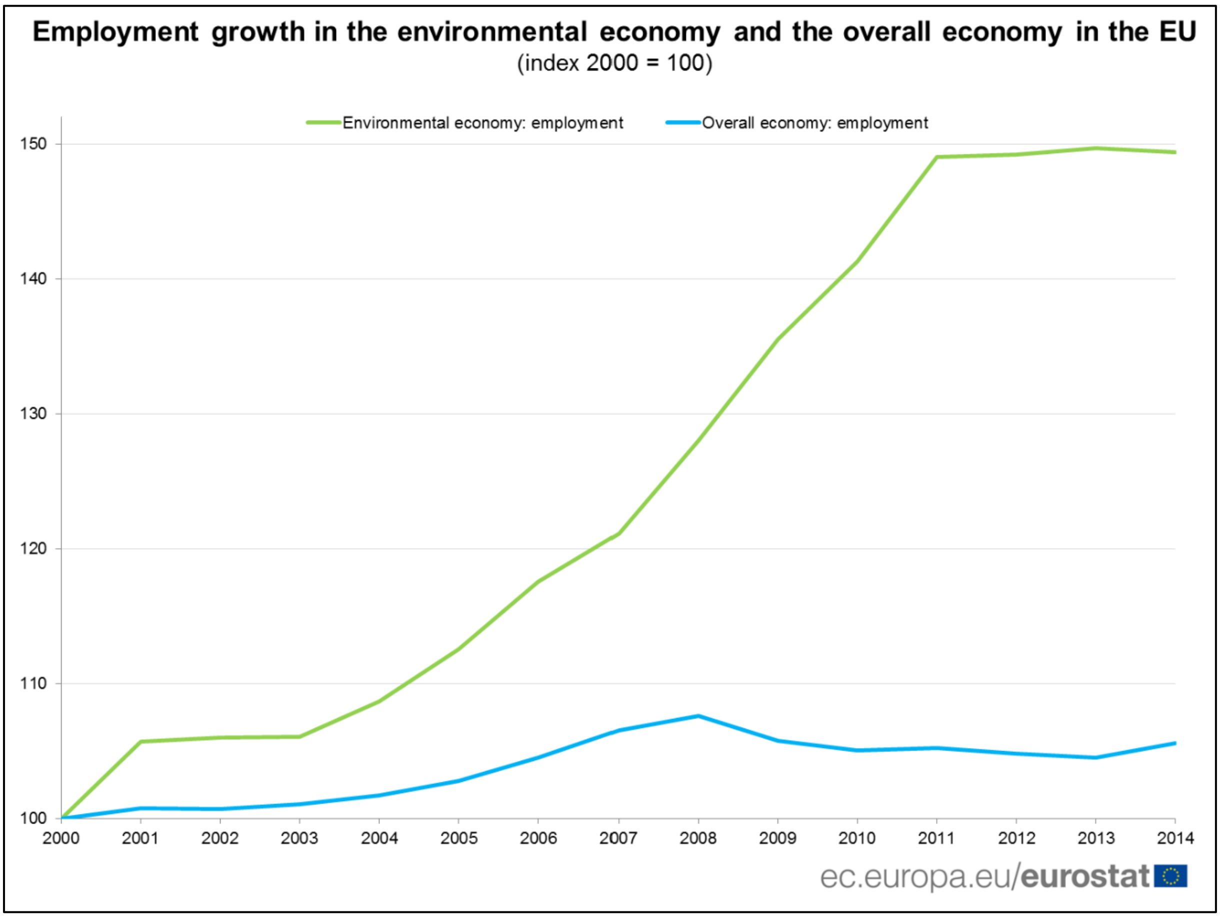

Figure 9: Employment growth in the environmental economy compared to the overall economy in the EU. (https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20170529-1, Retrieved: 07.05.2023)

Lastly, **public health** is a push-factor for the energy transition (UN Energy, 2021). The combustion of fossil fuels in electricity generation contributes to air pollution, which can have significant negative impacts on public health. This includes, for example, respiratory and cardiovascular diseases, as well as premature death (see Fig. 10) (Markandya & Wilkinson, 2007). Additionally, electricity generation from nuclear sources is connected to high risks for public health in case of failure as well as additional uncertainties in terms of permanent disposal of nuclear waste (Liljenzin & Rydberg, 1996).

The use of renewable energy technologies, especially solar, wind and wave power, can help to reduce air pollution and improve public health. They do not emit any harmful pollutants or greenhouse gases during operation, which can lead to cleaner air and a healthier society (Markandya & Wilkinson, 2007). RED power plants can further improve public health by reducing air pollution and greenhouse gas emissions if this technique replaces fossil power plants or power plants responsible for baseload provision. This can contribute to the achievement of climate and environmental goals, while also improving the quality of life through reduction of harmful emissions.

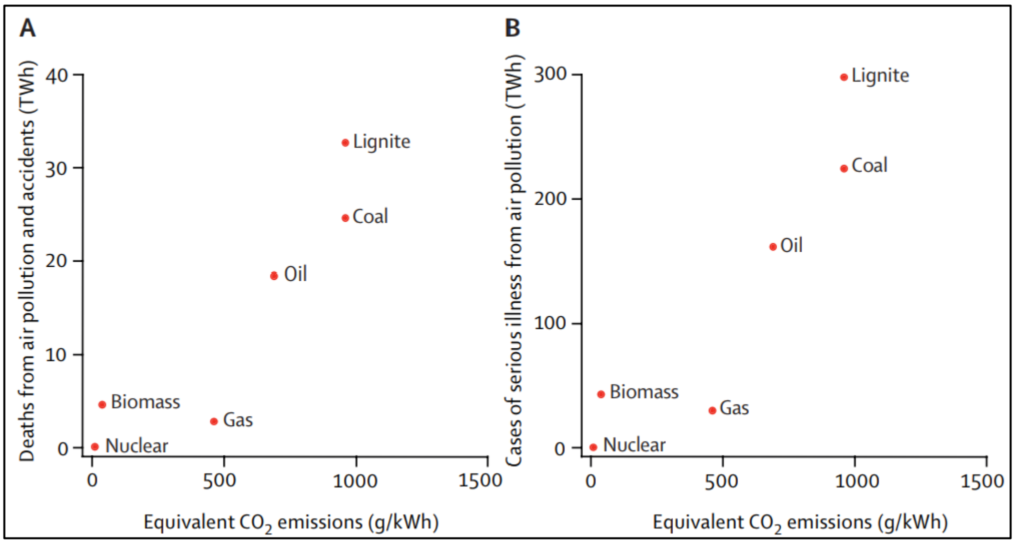

Figure 10: Health effects of electricity generation per TWh (A) deaths from air pollution and accidents involving workers or the public; (B) cases of serious illness attributed to air pollution. (Markandya & Wilkinson, 2007)

These drivers have widely been acknowledged by the governments around the world and led to the implementation in the sustainable development goals of the United Nations (UN):

> *"Energy sector goals for 2030 have generally been defined in SDG7:*
>
> • *7.1 Ensure access to affordable, reliable, sustainable, and modern energy for all.*
>
> • *7.2 Increase substantially the share of renewable energy in the global energy mix.*
>
> • *7.3 Double the global rate of improvement in energy efficiency"* (UN Energy 2021, pp. 9).

RED power plants could contribute to the energy transition by providing a different way to generate clean and renewable electricity with several benefits that are in line with the goals of the energy transition. As discussed earlier, RED power plants are a reliable and flexible source of renewable energy. This can help address some of the challenges faced by wind and solar power, which are intermittent and dependent on weather conditions. Namely they are baseload capable and could increase electricity production in the case of bad weather conditions for solar and wind power, the so called “Dunkelflaute”. A part that is currently realised by fossil power plants.

However, until today there is no upscaling of RED power plants visible. One pilot plant in the Netherlands has been built in the year 2013, and the funding for a second pilot (extension) plant granted approval in 2023 (Klein, 2023). Considering this, there are barriers beside the mentioned benefits that hinder the further development and upscaling of this technology.

Building on the potential of RED power plants to address renewable energy challenges and contribute to the energy transition, it is crucial to understand why their upscaling remains limited despite their promising attributes. To delve deeper into this thematic, the innovation diffusion theory will be discussed. This theory offers a structured framework to understand how innovations are adopted and therefore integrated into social systems. By examining the fundamental dynamics of diffusion, we can identify specific barrier categories influencing the path of this technology.

2.4 Innovation Diffusion Theory

Diffusion of Innovations, a theory proposed by Rogers (1995), explores the spread and adoption of new ideas, technologies, or practices within a social system. The theory suggests that the adoption process follows a predictable pattern and involves the interaction of different types of individuals. It is today widely acknowledged as a reference book for diffusion theory (Miller, 2015; Sahin, 2006; Robinson, 2009).

Rogers (1995) theory highlights five key attributes as most important influence on the rate (speed) of adoption of innovations, such as the perceived relative advantage of the innovation, its compatibility with existing values and practices, the complexity of its use, the ability to try it on a limited basis, and the level of observability of its benefits (Rogers 1995).

2.4.1 Rate of Adoption

According to Rogers (1995) the rate of adoption refers to the speed (and extend) at which an innovation is adopted by individuals within a social system. It is measured by the number of individuals who adopt the innovation within a specific time. Several factors contribute to the rate of adoption, including the previously mentioned attributes of the innovation (relative advantage, compatibility, complexity, trialability, and observability). These attributes explain a significant portion of the variance in the rate of adoption: "*… 49 to 87 percent of the variance in rate of adoption is explained by the five attributes …"* (Rogers, 1995; pp. 232).

In addition to the five attributes, other variables such as the type of innovation-decision, the nature of communication channels, the characteristics of the social system, and the efforts of change agents also influence the rate of adoption. Innovations that require individual decisions are generally adopted more quickly than those adopted by organizations. The more individuals involved in the decision-making process, the slower the rate of adoption. Altering the unit of decision-making to involve fewer individuals or in an authoritarian way can accelerate the adoption rate (Rogers, 1995).

Rogers (1995) emphasises that communication channels used to diffuse an innovation also affect its rate of adoption. The complexity of the innovation and the communication channels interact to influence the adoption rate. The nature of the social system, including its norms and the interconnectedness of its communication networks, plays a role as well.

Lastly, the efforts of change agents in promoting an innovation also have impact on the rate of adoption. However, the relationship between change agent efforts and adoption rate is not always direct and linear. The most significant response to change agent activities typically occur when opinion leaders are adopting the innovation (Rogers, 1995).

While all these factors contribute to the rate of adoption, the five attributes of innovations are the most important for the speed and extend an innovation will be adopted and will thus serve as a basis for this study. (see Fig. 11) (Rogers, 1995; Rogers, 2003).

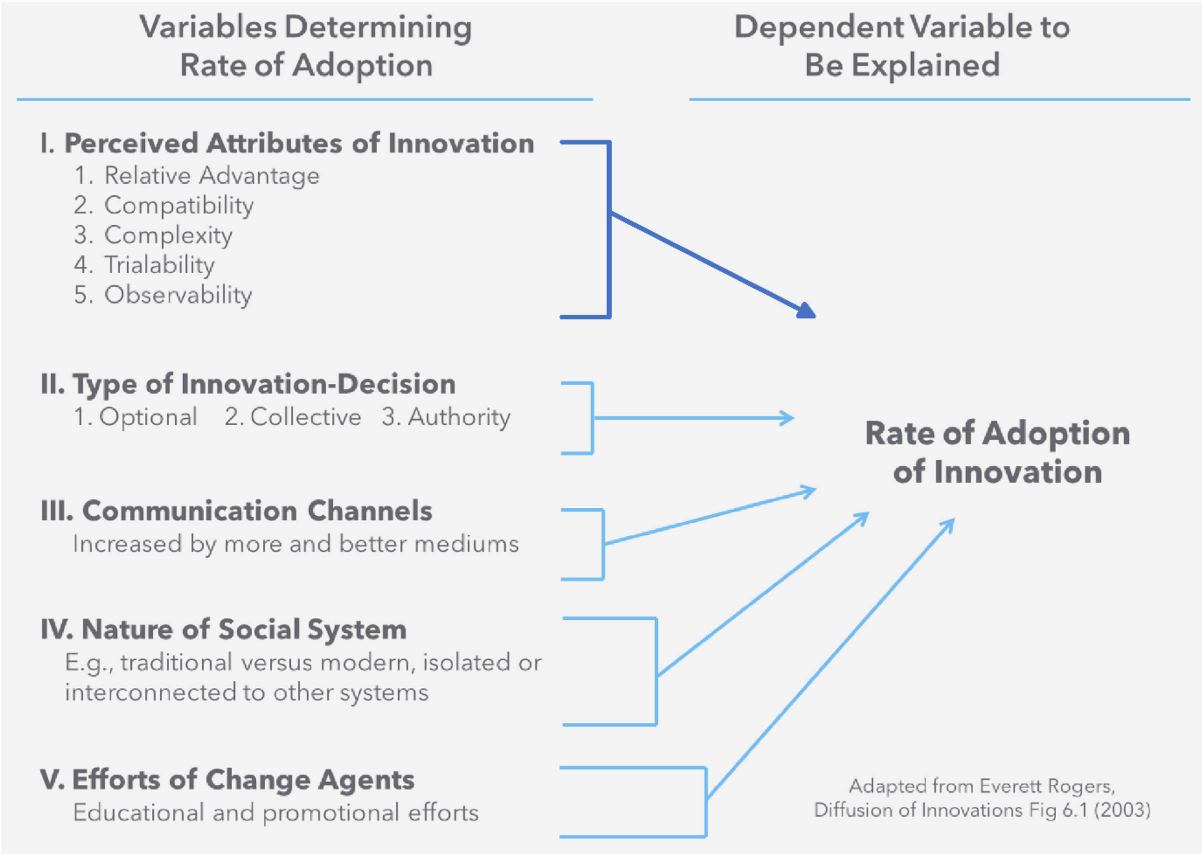

Figure 11: Variables that influence the rate of adoption; I. will be used as a background for this thesis (adapted from Rogers, 2003)

2.4.2 Key Attributes

The diffusion of innovations theory from Rogers (1995) identifies five key attributes that influence the rate and extent of adoption. These factors interact and influence each other during the adoption process. Innovations that score high on these factors are more likely to be adopted, while those that score low may face barriers or resistance to adoption. It's important to note that the significance of each factor may vary depending on the context and the characteristics of the innovation and the adopters involved. Therefore, the significance of each attribute for RED power plants must be evaluated throughout the research process.

Relative Advantage

Relative advantage is the perception that an innovation is better than the technology it replaces. It can be measured in terms of economic profitability, social status, or other factors important to adopters. Innovations that result e.g., in lower production costs and consumer prices, tend to be adopted more rapidly (Rogers, 1995).

"Learning by doing" is a term used by economists to describe a phenomenon where new products undergo a sequence of technological advancements, resulting in lower production costs and subsequently to a marked advantage. These improvements enable a more efficient manufacturing process, leading to cost savings that are eventually passed on to customers (Arrow 1962). This mostly leads to a more rapid rate of adoption (Rogers, 1995). One provided example by Rogers (1995) is the pocket calculator, which demonstrates how its relative advantage increased significantly as its price dropped dramatically in a few years due to technological advancements in transistor technology.

A controversy exists regarding the relative importance of profitability compared to other perceived attributes of innovations. Some economists argue that economic variables, particularly profitability, are the primary determinants of technological change and adoption rates. However, it is argued that economic factors alone are important, but not the sole predictors of adoption (Rogers, 1995).

Social status for example is a significant motivating factor for individuals when adopting innovations. Certain innovations, such as new smartphone models or expensive cars, obtain their value primarily from the social prestige they confer upon the adopters. However, when they become widely adopted, its social value diminishes, leading to the emergence of newer trends. It is crucial to recognize that economic factors alone do not predict the rate of adoption, as every innovation inherently carries some degree of status conferral (Rogers, 1995). However, the author proposes the hypothesis that the social status is non the less important for adopters of this technology, but that RED power plants on a bigger scale are too expensive sole for this purpose.

Subsidies

Actors or institutions that want to promote an innovation often utilize incentives or subsidies to encourage the adoption and accelerate the rate of change. These subsidies serve the purpose of enhancing the relative advantage, in an economic sense, of the new innovation. Incentives can take the form of direct, or indirect monetary or non-monetary rewards provided to individuals or systems with the aim of promoting specific behavioural changes. Typically, these changes involve adopting the innovation being promoted. An example is the subsidization of wind and solar energy in Germany in the beginning of the broader implementation phase to enhance the competitiveness of the technologies (Nicolini & Tavoni, 2017).

Subsidies can have a huge influence on the rate of adoption of a technology but must also be viewed critically. When subsidies are exhausted, the relative economic advantage diminishes unless the technology has become independently competitive within the subsidy timeframe. For the example of wind (Jansen et al., 2020) and solar energy, the technologies became competitive and are now the cheapest on the market (Kolb et al., 2020).

Compatibility

Compatibility refers to the extent to which an innovation aligns with the existing values, past experiences, and requirements of potential adopters. When an idea is perceived as more compatible, it reduces the level of uncertainty for potential adopters (Rogers, 1995). Compatibility can be evaluated based on three aspects: (1) alignment with sociocultural values and beliefs, (2) consistency with previously introduced ideas, and (3) fulfilment of client needs for innovations (Rogers, 1995).

Alignment with Sociocultural Values and Beliefs

The lack of compatibility between an innovation and prevailing cultural values can hinder its adoption (Rogers, 1995). For Example, in a society where the predominant cultural value places a high emphasis on preserving the natural landscape and minimizing human intervention in natural environments, the introduction of large-scale renewable energy projects may face significant resistance. Despite the potential benefits of renewables in generating clean energy, the innovation could be hindered by its incompatibility with the cultural value of preserving natural landscapes. Referring to the case of wind energy in Bavaria, Langer et al. (2016) found out that acceptance tends to rise when renewable energy systems are not visible and do not directly alter the landscape, indicating that visual disruptions frequently contribute to reduced acceptance within the population.

It is therefore difficult to promote an innovation that is against the prevailing sociocultural values and beliefs, even if the innovation would provide a benefit for a societal system (Rogers, 1995).

Consistency with Previously Introduced Ideas

Compatibility plays a crucial role in the adoption of innovations, as it is not only influenced by deeply ingrained cultural values but also by previously accepted ideas. The compatibility of an innovation with prior ideas can either accelerate or hinder its rate of adoption. Existing practices serve as the familiar benchmark against which the innovation is evaluated, for the purpose of reducing uncertainty. The rate of adoption of a new idea is influenced by the old idea it replaces (Rogers, 1995).

However, if a new idea perfectly aligns with current practices, it may not be considered an innovation by potential adopters. In other words, the higher the compatibility, the less significant the change appears to be. Nonetheless, introducing a highly compatible innovation can be highly valuable if it serves as a steppingstone for subsequent, less compatible innovations introduced in a sequential manner (Rogers, 1995).

Rogers (1995) notes that it is important that negative experiences with one innovation can create resistance toward future innovations. This phenomenon, known as innovation negativism, occurs when the failure of an innovation conditions potential adopters to reject subsequent innovations. When one idea fails, individuals become careful of embracing future innovations.

Complexity

"*Complexity is the degree to which an innovation is perceived as relatively difficult to understand and use*" (Rogers, 1995; pp. 230). While certain innovations are easily to understand by potential adopters, others may be more complicated. The perceived complexity of an innovation by individuals within a social system is inversely correlated with its rate of adoption (Rogers, 1995; Pelz, 1985).

Karakaya & Sriwannawit (2015) stated that the complexity of interaction between people and PV systems can hinder the adoption. The perception of adopters has a significant impact on their decision regarding whether to adopt a new technology or not and could therefore also be a factor that applies to osmotic energy.

Trialability

Trialability refers to the extent to which an innovation can be experimented with on a limited basis (Rogers, 1995). Innovations that can be tried gradually or in small steps are more likely to be adopted quickly compared to those that cannot be easily divided. When an innovation is trialable, it reduces uncertainty for potential adopters. However, the ease of trialability can vary among different innovations. Rogers (1995) suggested that the perceived trialability of an innovation is positively related to its rate of adoption.

Observability

Observability refers to the degree to which the results or outcomes of an innovation are visible and can be easily communicated to others. When the benefits or advantages of an innovation are easily observable by potential adopters, it tends to have a higher rate of adoption (Rogers, 1995).

However, the author proposes the hypothesis that complexity, trialability and observability are of less relevance than relative advantage and compatibility for the upscaling of osmotic energy. Observability and trialability may already be covered by the pilot plant as a proof of concept and complexity of an innovation may apply more heavily to end-users than to industrial facilities.

2.5 Analysis Tool

The innovation diffusion theory primarily examines how innovations are adopted and spread within a social system, including the attributes influencing this process. This theory, along with the literature previously introduced, can assist in identifying categories of barriers that affect the speed and extent of adoption.

As the innovation diffusion theory shows, relative advantage involves comparing the innovation with existing solutions or technologies (Rogers, 1995). If an innovation doesn't offer clear economic benefits, such as cost savings, increased efficiency, or improved profitability, potential adopters may perceive it as economically disadvantageous compared to their current practices (Caves, 1984). Therefore, economic conditions can act as a barrier.

Additionally, Socio-economic barriers and technological barriers can be considered as closely interlinked (Rae et al., 2023; Palm & Thollander, 2010; Sherriff, 2014; Chmutina & Goodier, 2014). For instance, technical barriers associated with a renewable energy technology can result in reduced energy efficiency, subsequently leading to increased electricity generation costs.

Mankins et al. (2009) states that technical barriers have a direct influence on the adoption costs of the technology while referring to the technology readiness level (TRL). Technology Readiness Levels (TRLs) are a structured metric and measurement system used for evaluating the maturity of specific technologies and facilitating consistent comparisons of maturity across various types of technology (Mankins, 1995). It spans from TRL 1, representing the initial concept, to TRL 9, indicating full implementation. It can therefore be used as a factor to determine the costs and risks of advancing the technology to the requisite level for use (Straub, 2015), linking back to economic considerations. Therefore, technological aspects can be considered as a barrier.

Inherent to the technology of osmotic energy is the need for salt- and freshwater as resources (Chapter 2.1.2). Osmotic energy is primarily feasible in specific geographical locations where saltwater and freshwater mix, such as coastal areas or estuaries. As discussed, barriers are location specific (Painuly, 2001) and therefore spatial barriers must be examined.

Accompanied by this selection of a location for osmotic power plants are regulatory requirements. The site's location dictates the specific governmental jurisdictions involved (Kahn, 2000). Copping (2018) concluded that current regulatory requirements are high for the marine renewable energy industry. Lengthy permitting timelines are acknowledged by Copping et al. (2020) as challenges that need to be overcome to accelerate innovation and commercialization of this industry. But due to these circumstances, location-specific limitations occur and need to be considered as potential barriers, since they can influence the relative advantage over competitors on different locations.

The attribute compatibility refers to the degree to which an innovation aligns with the existing values, practices, and needs of potential adopters in a societal context (Rogers, 1995). When an innovation is perceived as incompatible with conventional or customary practices and ideologies, it can face resistance from the public (Segreto et al., 2020). In example, referring to the case of wind energy in Bavaria, Langer et al. (2016) found out that acceptance tends to rise when renewable energy systems are not visible and do not directly alter the landscape, indicating that visual disruptions frequently contribute to reduced acceptance within the population. Therefore, social acceptance needs to be considered when identifying barriers to osmotic energy.

In line with the argumentation of value and beliefs and their impact on the adoption of innovations are environmental concerns. Based on the literature review concerning osmotic energy, it is evident that environmental issues and challenges frequently intersect with ongoing discussions, particularly within the context of the energy transition (Nasirov et al. 2018). In this line, but not limited to a transition towards a carbon free energy generation, Lorimer (2017) highlights the overall environmental zeitgeist as a pervasive element of our era. Therefore, environmental aspects hold significant importance.

Although it serves as a suitable framework to examine diffusion of innovations, classic diffusion theory is not without its critics. Detractors argue that it tends to overlook the role of institutional influences in the decision-making process, leading to a perception of classic diffusion studies as overly rationalized (Strang & Macy, 2001). Frost & Egri (1990) highlight the essential role of political strategy in both advancing and inhibiting innovation. In this line Bretznitz (2007) acknowledges the importance of politics and their strategies on innovations as well as their strong interrelations, therefore a political dimension was added.

The conceptual framework aims to provide a tool, which can also be viewed as a set of criteria or a classification of possible barriers (Fig. 12), to categorize the current challenges faced in upscaling and subsequent large-scale implementation of this innovative form of renewable energy. The transition toward greater utilization of renewable energies, especially osmotic energy, can be seen as the overarching goal of this effort.

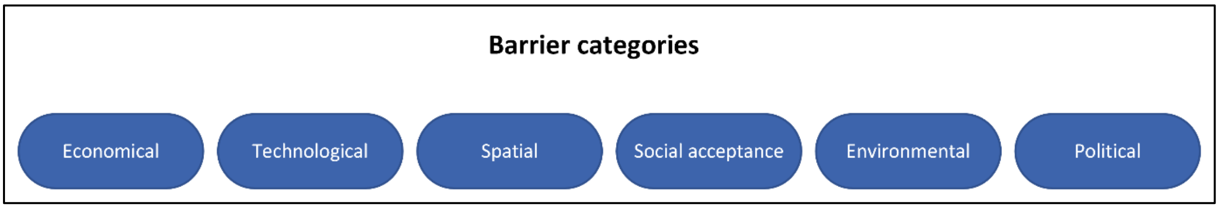

Figure 12: Barrier categories for the further evaluation of barriers (own illustration)

3. Methods

In this chapter the used methodology to collect data will be discussed. For this research a qualitative approach has been chosen to provide insights in barriers that likely hinder an up-scaling, as well as to what extend the key attributes are of significance for this technology.

3.1 Research Strategy

The research strategy is divided into multiple steps (see Fig. 13). Firstly, the case as an appropriate basis of the thesis was selected. Selecting cases for this research is associated with several difficulties. Energy production from osmotic energy on a large scale is a rather new approach, and the method of reverse electrodialysis in this context is currently only applied in a few small-scale pilot plants. Therefore, this study will primarily focus on RED with an emphasis on its application in the Netherlands and within the European context. However, it is important to acknowledge that general barriers and challenges identified in this research are likely to have implications on a global scale for the future implementation of RED, and osmotic power plants in general.

In a second step initial background analyses were conducted to identify and provide insights into various aspects, including current policy plans, the existing state of the technology, ongoing environmental and governmental debates, and potential possibilities of implementation.

In a third step, a conceptual framework and analysis tool for this thesis was elaborated, following the identification of stakeholders. Interview partner were identified through a literature review, based on recommendations from relevant actors, and by contacting umbrella organisations.

Subsequently, expert interviews were conducted. However, some challenges occurred as possible interview partners were not willing to participate in research on a master's thesis, mainly on a (national) governmental level, within the ministries. On the other hand, private companies and nonprofit organisations were highly ambitious in participating.

In a last step the results from the interview process were discussed utilizing relevant literature.

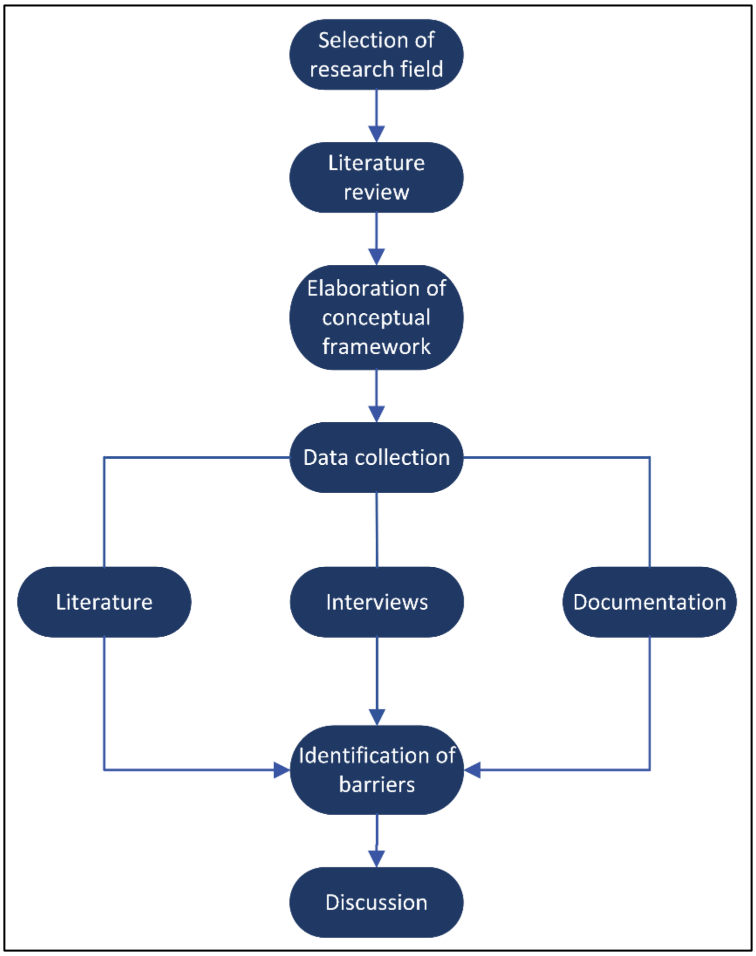

Figure 13: Overall research strategy for this thesis (own illustration)

3.2 Methodology

Qualitative research is one of the main research methodologies and focuses on understanding and interpreting people's experiences, behaviours, beliefs, opinions, or social interactions. Unlike quantitative research, which relies on numerical data and statistical analysis, qualitative research uses non-numerical data such as expert knowledge or observations to gain a deeper understanding of the research topic. It is often used to explore complex phenomena, social processes, and the context and relationships in which they occur, which cannot be covered by numerical data alone (Aspers & Corte, 2019).

To gather the required data for this research, several methods were employed. Initially, a comprehensive literature review was conducted. This review helped identify gaps in existing literature. To address these gaps and gain deeper insights into the innovation, expert interviews were conducted. Additionally, document and literature screening, (if possible) with a focus on recent sources, was performed to address specific queries from different sources of data. Finally, the obtained results were analysed and discussed (see Figure 13).

3.3 Empirical Research

The data for this qualitative research was collected through semi-structured interviews. Conducting interviews was chosen as the primary method to gather information, supported by a document and literature screening, due to the limited availability of relevant literature on some aspects.

Through these interviews, the research aimed to obtain a wide range of information, from the fundamental aspects of the technology to detailed discussions about potential barriers, challenges, and future perspectives. Notably, this study sought insights from stakeholders at different fields, with many of them being strongly involved and on leading positions in the context of osmotic energy and RED (Tab. 1).

Semi-structured interviews are designed to include a set of predetermined questions while allowing room for exploration beyond the initial inquiries (Berg, 2004). In semi-structured interviews, the interviewer follows a flexible interview guide with a set of predetermined questions or topics but also has the freedom to explore additional questions or delve deeper into certain areas based on the participant's responses. This approach allows for a balance between standardization and adaptability, making it a popular choice in many research settings.

To identify the most significant stakeholders in the osmotic energy sector, a stakeholder analysis was conducted beforehand. Drawing from the results of the stakeholder analysis, experts who possess valuable insights from different viewpoints into the domain of osmotic energy were contacted for interviews.

Table 1: Categorisation of interview partners

No.	Name	Organisation	Category
1	A1	REDStack	Private
2	A2	Dutch Marine Energy Centre (DMEC)	Private/nonprofit
3	A3	Dutch Energy from Water Association (EWA) & Bluespring	Private
4	A4	Province of Friesland	Governmental
5	A5	Institute for Infrastructure, Environment and Innovation (IMIEU) & International and European Alliance for Osmotic Energy (INES)	Private/nonprofit

3.4 Interview Process

Relevant experts were personally contacted via email, or after introduction from other participants, to request their participation in the interviews. In some instances, umbrella organizations were approached to connect with the appropriate experts in this field. Before each interview, the purpose and background of the research were communicated to the participants. The initial interview guide (see Appendix A) was customized for each individual interview, as some specific questions might not be relevant to their expertise.

All interviews were conducted either by telephone or video conference, as suggested by the candidates, or due to significant geographical distances between the participants and the author. The language used for the interviews was English, except for one that was held in the German language, and each interview was transcribed. The transcriptions include every relevant question that was asked and the corresponding answers, along with any other relevant information shared by the interviewees.

However, small talk and off-topic discussions that were not important to this research were not transcribed, as they did not contribute to the study's objectives. Similarly, introductory details about the author, the study program, or detailed information about the research were also left out from the transcripts. Additionally, topics unrelated to renewable energies, osmotic energy, or the general energy debate were excluded from the transcriptions. It is important to note that these exclusions were limited and applied only to minor parts and certain sections of the interviews.

3.5 Ethical Considerations

Ethical considerations play a fundamental role in research as they not only enhance the credibility of the study but also safeguard the rights and well-being of the individuals involved (Clifford et al., 2010). Ensuring ethical conduct throughout the research process is crucial to maintain the integrity of the study and uphold the principles of research ethics. To uphold these ethical principles, a series of measures were implemented throughout the research process.

Prior to conducting interviews, all interviewees were informed about the research's aims, objectives, and how the gathered data would be utilized. This process ensured that participants were informed about the research's purpose and the use of their data. Participants were encouraged to seek clarifications or raise any concerns they might have had regarding their involvement.

At the outset of each interview, participants were informed how the gathered data would be utilized and were asked for their explicit permission to record the interview. This procedure emphasized transparency and allowed participants to have agency over their involvement in the research. All data collected, including interview transcripts, underwent thorough anonymization to protect the identities of participants. Participants were assigned pseudonyms in the research findings.

After interviews were conducted and transcripts were generated, the interviewees were provided with the transcripts. This step offered participants the opportunity to review the transcripts and provide feedback in case of inaccuracies or any concerns about how their responses were represented.

These ethical considerations were essential not only to uphold the credibility of the research but also to respect the autonomy and rights of the participants. By ensuring transparency, informed consent, and participant involvement in the research process, ethical standards were maintained throughout the study. This reinforces the trustworthiness of the research outcomes and contributes to responsible research practices.

4. Results

In this chapter the gathered data from the interview process, relevant documents and literature will be presented, including relations to possible advantages and disadvantages over existing technologies, while focussing on barriers that could hinder an upscaling now or possibly in the future. The results will be classified according to different categories examined in the analysis tool.

4.1 Technological Maturity

A1 asserts that from a technology standpoint, there are no significant research challenges remaining. The technology development mainly involves scaling up the equipment, which requires design engineering, mechanical engineering, and process engineering. He categorizes the remaining development work as more applied and industrial in nature, not requiring extensive research efforts. The technology is considered scientifically ready for upscaling to Technology Readiness Level (TRL) 8, as evidenced by the operational TRL of 7.

A2 emphasizes that energy projects, including osmotic energy, progress incrementally. While the basic principle of energy production has been demonstrated by the existing pilot plant, the next steps involve substantial upscaling to megawatt levels. He notes that the stepwise approach is crucial for learning and adapting to challenges that emerge within larger installations. The process is viewed as gradual, with each stage of development leading to new insights and the construction of larger and more sophisticated plants.

A3 expresses scepticism about the notion that the research is complete, and the technology is ready for immediate upscaling. He suggests that practical challenges still need to be addressed. He questions why there hasn't been more progress if everything is indeed already accomplished. This perspective indicates that there might be complexities or gaps that need attention before an upscaling can be performed.

Collectively, these interviews shed light on the readiness of RED technology for further upscaling. While there is agreement that the principles have been proven, there are differing opinions on the extent to which research and development have been completed but showed a tendency towards the readiness for upscaling to TRL 8.

This is supported by the 2023 Projectplan for the pilot plant on the Afsluitdijk (REDStack et al., 2023), which emphasises the stack production and an assembly line as ongoing efforts towards the desired upscaling efforts. The status report of ocean energy in the European Union (Tapoglou et al., 2022) states that the technology is still in its conceptual stage and is notably less advanced compared to tidal, wave, or ocean thermal energy conversion (OTEC) technologies. However, it emphasises that extensive research is actively underway, data collection is in progress, and laboratory testing is being conducted. IRENA (2023) follows this argumentation and states that REDStack's next goal is the installation of a TRL 8 plant. Chae et al. (2023) highlights the necessity of an ongoing development towards more efficient membranes to archive economic advantages.

The expert interviews highlight the importance of gradual progress, ongoing problem-solving, and addressing practical challenges before achieving fully matured power plants.

4.2 Environmental Considerations

The experts highlighted the critical environmental factors associated with osmotic energy plant construction and operation. They emphasized that while the plant mainly has effects on the surface area and water, its compact design minimizes land usage. In terms of environmental impacts through the operation of the power plant several factors need to be considered.

4.2.1 Ecological Impact and Mitigation

Both A2 and A3 emphasized, relating to a power plant on the Afsluitdijk, the unique composition of water in the Wadden Sea ecosystem. A3 highlighted that the Wadden Sea's water is already slightly brackish due to the influence of various rivers discharging freshwater into it. This creates a distinct salinity gradient compared to North Sea water. The natural tidal movement adds a flushing effect to the waters every six hours, which contributes to minimize the effects of an inflow of the excess waters from the power plant.

A2's perspective on the environmental impact in the Wadden Sea echoed the significance of water management. He highlighted the challenges related to pumping large volumes of water in and out of the system. Salinity control and prevention of unintentional harm to aquatic life emerged as primary concerns. A2 stressed the need for cautious water intake practices to avoid upsetting the delicate balance of the Wadden Sea's ecosystem. His insights emphasized the importance of understanding the potential consequences of large power plants, before upscaling RED plants to higher capacities.

A1 discussed the ecological aspects, detailing how the plant addresses water intake and discharge. He described the dual-step filtration process, involving pre-filtration to prevent fish and larger debris from entering, followed by rapid sand filtration. This process ensures minimal ecological impact, even in sensitive areas like the Waddensee. A1 also introduced the concept of reintroducing filtered flora and fauna into brackish water and creating a transparent, brackish water zone. This, he noted, could enhance fish migration, and support the aquatic ecosystems.

The project plan emphasizes the ongoing research on ecological impacts of the RED power plant during the withdraw, pretreatment and discharge process, while pointing out potential beneficial contributions to the surrounding ecosystems through e.g., discharge of brackish water for the optimisation of fish migration through the Afsluitdijk (REDStack et al., 2023).

Seyfried et al. (2019) concluded in a literature review that the construction of osmotic energy facilities may temporarily disturb marine habitats and organisms due to noise and sediment disruption. During operation, osmotic energy facilities have unique operational stressors related to treatment chemicals, water flow disruption, and effluent characteristics. Long-term impacts on marine life, water currents, and nutrient cycling may occur. The decommissioning phase's impacts depend on the decommission plan and may interact with previous construction and operation stressors, requiring careful planning to address concerns.

4.2.2 Membrane Cleaning and Fouling

In response to questions about membrane fouling, A1 referred to extensive research conducted by Wetsus and REDStack. He explained that while some fouling occurs within the stacks, the design of the system, membranes, and operational practices collectively minimize the impact. A1 clarified that no chemicals are used in membrane cleaning and emphasized that the design of the membrane stacks, involving water movement, polarity reversal, and other mechanisms, helps self-clean the membranes. This operational approach eliminates the need for chemical interventions. Gonzales et al. (2021) support this by reporting about chemical-free cleaning strategies using continuous circulation of clean water, indicating that the former use of chemicals for cleaning purposes is being addressed.

4.2.3 Impact of Polluted Water

A1 addressed concerns regarding polluted waters and their impact on the filtration system. He noted that e.g., some oil presence is tolerable, but excess amounts require effective pre-treatment systems. He cited the example of the Rotterdam harbour, where oil (comparably small amounts) tends to float on the water's surface and is less likely to pose a problem. However, in severely polluted environments like certain rivers in India, a more rigorous pre-treatment system is necessary to ensure effective filtration. As emphasised by A1, the technology could then contribute additionally to clean parts of the river.

The discussions primarily revolved around the ecological implications of using large quantities of water in these ecosystems, while changing the composition in terms of the salinity gradient. Considering these insights, experts like A1 and A2 suggest that the technology's design mitigate potential harm to ecosystems. Also, A5 considered the environmental effects as benign. But they highlight that already a lot of research has been done and, at the same time, the need for transparent and robust research to address potential concerns. Overall, while uncertainties remain, the prevailing sentiment leans toward the potential of RED power plants to be developed in an environmentally responsible manner, which is supported by the wide acknowledgement of environmental concerns in the project plan of the TRL 8 extension (REDStack et al., 2023) and an analysis of Papapetrou & Kumpavat (2016) about possible environmental impacts through the life cycle of an osmotic power plant.

4.3 Public Acceptance

The interviews with the experts shed light on the perceived public acceptance and complexity of the RED technology. Their viewpoints contribute to a comprehensive understanding of how this innovation might be received and understood by the broader public.

A2 expresses a positive outlook on the public acceptance of the technology. He anticipates higher acceptance due to the compact nature of the technology, like traditional power plants and being less visually intrusive. He acknowledges the importance of addressing the ecological footprint to avoid opposition from NGOs, but overall believes that the Public Acceptance for this technology should be quite favourable.

A3 also views the Public Acceptance as high. He highlights the concept's inherent beauty—generating electricity from the mix of seawater and freshwater. He suggests that people may find it difficult to imagine potential negatives, especially if the technology is placed in areas where landscape impact is minimal. While acknowledging the complexity, he draws parallels with understanding nuclear, solar, and wind power, indicating that public comprehension of the underlaying concepts might not significantly impact acceptance.

A4 points out that resistance to energy means, such as wind turbines and solar fields, is prevalent. She believes that the resistance is generally high across all energy solutions.

Academic literature regarding public acceptance of RED power plants and osmotic energy seems limited, Daniilidis et al., (2014) points out that social acceptance rises if RED power plants come closer to profitability. IRENA (2014) and Papapetrou & Kumpavat (2016) state that the concept of harnessing energy from salinity gradients is largely unfamiliar and lacks awareness, both among the general public and within relevant regional, national, and European authorities. Yip et al. (2016) states that in regions where freshwater is limited the public acceptance of this technology is possibly low.

In a broader perspective Sharpton et al. (2020) evaluated that the public acceptance of renewable energy is generally higher than energy generated from fossil fuels. Segreto et al. (2020) followed this assessment but differentiated between local and general acceptance, while local acceptance is generally lower if impacts of a technology are visible to residents.

4.3.1 Complexity and Understanding

A3 acknowledges that the technology is complex and might be challenging for the average person to comprehend fully. He draws parallels with the complexities of nuclear, solar, and wind power. While the mechanism involving salinity gradient and membrane interactions might be understandable at a basic level, similar to the mechanisms of wind and solar energy, he recognizes that explaining the technical intricacies of the conversion process to laypersons could be difficult but will likely not result in lower public acceptance.

Collectively, these interviews suggest that while the osmotic energy technology might be perceived as complex and challenging to fully comprehend, this complexity might not necessarily hinder its public acceptance. The experts' insights indicate that the innovative nature of the technology, coupled with effective communication of its benefits and minimal landscape impact, could potentially contribute to a favourable reception. However, ongoing efforts to address ecological concerns and effectively communicate the technology's benefits seem essential for fostering greater public understanding and acceptance.

4.4 Political Awareness

The insights garnered from the interviews provide a comprehensive understanding of the political awareness surrounding the RED technology, particularly in the context of the Netherlands. These viewpoints reflect the challenges and opportunities in terms of political recognition and prioritization of this technology.

A1 highlights the lack of political awareness and support for salinity gradient power in the Netherlands. Despite initial enthusiasm and parliamentary approval for funding, subsequent government actions have not aligned with the approved plan. The Minister of Energy and Climate's focus on other energy sources indicates a lack of political facilitation for this technology.

A3 offers a contrasting view, noting significant public and political awareness. The technology was recognized as an iconic project for the Netherlands, visited by the King and government officials. However, his perspective highlights that awareness does not necessarily translate into immediate policy support.

A4 discusses regional awareness due to the presence of a pilot plant but notes low national attention. She underscores the challenge of limited awareness for innovative water-based energy solutions, which are not yet widely considered suitable in the energy mix.

A5 identifies the absence of political priority for osmotic energy in the Dutch energy strategy. He underscores the potential influence of European regulations, such as the Renewable Energy Directive (RED2), in promoting innovation. He suggests that the directive could push the Netherlands to take osmotic energy more seriously even if it lacks national political priority.

The interviews collectively suggest that political awareness and prioritization for osmotic energy in the Netherlands are there but limited. While some recognition exists, it has not translated into robust policy support on a national level. The absence of inclusion in the national energy strategy, which is focused on wind, solar and nuclear power (NECP, 2019), further indicates a barrier. This is in line with a letter from the Minister of Economic Affairs and Climate Policy to the Speaker of the House of Representatives of the States General (Overheid, 2021), which states that revisiting the existing national policy or increasing national efforts in the domain of electricity from water is not recommended at this juncture. The cost projections for both small-scale and large-scale technologies surpass those associated with alternative renewable electricity options, such as offshore wind energy. Moreover, small-scale technologies, both presently and in the foreseeable future, exhibit limited potential at the national level for making substantial contributions to the sustainability of the country's electricity production (Overheid, 2021). Indicating political awareness but a lack of policy support.

Noteworthy is that the pilot plant on the Afsluitdijk and the planned TRL 8 extension got funding from the provinces (REDStack et al. 2023), reflecting the willingness to promote innovations, and shows political awareness and willingness. This will be further examined in the finance sub-chapter.

However, A5 identifies an opportunity within European regulations, suggesting that European directives might influence national policies and priorities.

4.4.1 Balancing of Interests

A1 points out the challenges associated with the practical execution of this technology, particularly within harbours. He underscores the necessity for infrastructure and water flow in such locations. Specifically, the case of Rotterdam brings to the fore a complicate predicament. Its integration might introduce logistical complications by causing delays for ships passing through locks, potentially affecting maritime operations. He emphasizes that certain locations, like flood protection systems and pumping stations, present more viable prospects for osmotic energy integration. These locations can circumvent the logistical barriers faced in harbours, offering smoother pathways to implementation.

He emphasized the distinction that osmotic energy's freshwater usage does not compete with other purposes such as irrigation, drinking water, or other processes. He clarified that their usage is positioned at the end of the freshwater consumption cycle, occurring just before the water naturally flows into the sea.

In a broader perspective and contrary to A1 insights, A4 highlighted potential barriers from a governmental standpoint. She pointed out that osmotic energy's reliance on freshwater could clash with other crucial needs, particularly in times of drought. As water scarcity becomes a growing concern, managing freshwater resources becomes pivotal. A4 also noted conflicting interests in water usage, such as in the case of the IJsselmeer region, where the future balance between energy requirements and freshwater conservation possibly needs to be carefully navigated.

Location-specific challenges, such as logistical conflicts with maritime operations, can hinder project approval. Additionally, concerns about freshwater scarcity and clashes with other water usages, like drinking water and agricultural needs, could potentially impact support for osmotic energy initiatives now and in the future (Yip et al., 2016). Balancing energy needs with environmental and logistical considerations is crucial for successful osmotic energy integration.

4.5 Spatial Considerations

A1 highlights that several studies have been conducted to assess the spatial potential of osmotic energy worldwide. These studies consider factors such as river flow rates, delta configurations, and continuous power generation capabilities. The reported capacities vary, with estimates ranging from 650,000 to 3 million megawatts of continuous power generation. The distinction lies in whether the focus is on low-flow conditions, which ensure year-round operation at maximum capacity. The feasibility of extraction is also influenced by environmental factors, such as maintaining sufficient water availability for aquatic ecosystems and human needs. The potential of different rivers varies, with some excluded due to geographical or logistical challenges, like the Amazon River's vast size and significant outflow amount of freshwater that creates a low salinity zone of around 300km around the river mouth and makes the implementation of RED power plants vastly uneconomically.

A5 emphasizes that the spatial potential of osmotic energy is significant and flexible. The technology can be implemented in diverse locations, including areas with highly saline and less saline streams. He mentions the possibility of using the technology inland, such as near salt factories or wastewater treatment plants, where brine or treated water can be utilized for power generation through the mixing process.

Collectively, these interviews indicate that osmotic energy has considerable spatial potential on a global scale. Literature acknowledges that practical potential is still significant, but comparably small compared to other renewables (Alvarez-Silva et al., 2016; Nijmeijer & Metz, 2010; IRENA, 2020). The technology can be applied to various types of saline water sources, including rivers, streams, and industrial facilities. However, the actual capacity and feasibility depend on factors like river characteristics, environmental considerations, and infrastructure requirements (Alvarez-Silva et al., 2016). The range of estimates for potential capacity underscores the need for further research, assessment, and strategic planning to fully leverage the spatial potential of osmotic energy technology.

4.5.1 Permitting

A5 emphasized that obtaining permits is essential for osmotic energy projects. He mentioned that even the pilot plant required seven permits from different organizations, but the second plant would be an extension of the pilot plant on the same site with the same permits and licenses.

The complexity of acquiring permits depends on the location, with nature protection areas posing longer procedures, while power plants in harbours would like to require less time. He also noted a forthcoming EU law to accelerate environmental permitting time to less than one year for renewables.

A5 emphasized the importance of permitting for REDStack. The Province of Friesland is a key permitting authority. Another authority is the Dutch Ministry of Transport and Public Works and the water management department, responsible for the area around the pilot plant.

The interviews emphasize the importance of permits for osmotic energy projects. The process is complicated, varying with location. Regional and national authorities play key roles in permitting. The TRL 8 expansion on the same site does not require additional permits.

Consistent with this, does the project plan categorize the risk of delayed permit acquisition as low (REDStack et al., 2023).

Papapetrou & Kumpavat (2016) emphasises in this regard that market and regulatory conditions as well as permits for construction and operation can pose significant challenges towards osmotic energy.

4.5.2 Integration in Current Energy Landscape

Grid connections are not considered a significant barrier for osmotic energy implementation. A1 explains that since osmotic energy functions as baseload power generation, plants would likely be located in industrialized areas with existing infrastructure like harbours or pumping stations. While major flood protection systems might necessitate grid connections, they would be integrated with the overall infrastructure development.

A2 believes that grid connections are relatively simple for osmotic energy compared to other installations. The spatial requirements are modest, and the technology's baseload nature makes it appealing for grid integration. Transmission grid operators like Tennet would welcome the predictability and continuous output of osmotic energy. The primary challenge lies in resource availability – the technology requires sufficient convergence of saltwater and freshwater flows.

A4 highlights grid congestion as a potential hurdle, especially in regions like the Province of Friesland. Existing grid congestion may hinder the allocation of electricity for new companies. For osmotic energy implementation, direct energy off-take agreements or collaboration with energy consumers could be explored to mitigate grid-related challenges.

A5 emphasizes the compatibility of osmotic energy with the current energy landscape. The technology offers constant energy output, distinguishing it from the variability of solar and wind sources. He also mentions a company utilizing RED for energy storage, which adds to the versatility of the technology.

The interviews collectively suggest that grid connections are not a major obstacle to osmotic energy implementation. Al-Shetwi et al. (2020) underline the need for baseload for the future grid system, when fluctuating energy sources like wind and solar be further developed. The technology's baseload nature, coupled with its potential for direct energy off-take agreements, makes integration into existing energy systems feasible. Grid congestion remains a concern in certain regions, necessitating innovative solutions and collaboration with grid operators (Brinkel et al., 2022). If major infrastructure projects need to be realised, like the reinforcement of the Afsluitdijk, the required infrastructure can directly be implemented in the overall planning. Literature in this regard is very limited, but Essalhi et al., (2023) indicate, that implementing osmotic energy can be more straightforward if nearby infrastructure is available.

4.6 Economical

In this chapter economic considerations and results from the interviews regarding the upscaling will be presented.

4.6.1 Supply Chain

A1 discusses a past challenge with the supply chain related to membrane development. Initially, they had a long-term agreement with Fuji Film to develop and manufacture membranes at a cost of €5, and with the goal of €2 per square meter. However, Fuji Film eventually halted the development due to the inability to achieve the agreed-upon cost. This led REDStack to rely on other membrane suppliers and, in the future, assemble the membranes themselves in license. While there is currently sufficient membrane availability for the TRL 9 demonstration plant, the long-term industrial application of hundreds of megawatts would require additional membrane manufacturing capacity, which REDStack is willing to set up under license from established membrane manufacturers.

A2 highlights the importance of a fully developed supply chain for upscaling. He mentions that the internalization of the supply chain, similar to the strategy of companies like Tesla, can be both an advantage and a risk. While having most of the value chain internalized can reduce dependence on external suppliers, it also requires significant financial resources. He notes that REDStack is following a similar strategy, which can be capital-intensive.

A5 believes that the supply chain is generally not a hindrance to development or upscaling. He mentions that while there may not be many manufacturers of the required membranes, their production is feasible. Despite the discontinuation of membrane development by Fujifilm, other manufacturers like Fumatech are still producing these membranes. A5 sees the availability of high-quality, low-priced membranes as the only potential bottleneck in terms of thy supply chain, but he's optimistic about the overall situation.

These perspectives collectively indicate that while there have been challenges related to membrane supply and development in the past, the overall supply chain for this technology appears to be manageable. There is optimism that the supply chain will be able to support the technology's development and potential upscaling, provided that high-quality and cost-effective membrane manufacturing is available.

IRENA (2014) stated in 2014 that upscaling process will require substantial dedicated resources. There has been a growing interest among water technology firms and membrane developers in enhancing membranes and other crucial technologies for salinity gradient power generation and energy recovery in desalination. To advance the commercialization of this technology, it would greatly benefit from increased participation by industrial players and companies with expertise in efficiently scaling up the latest advancements.

Additionally, IRENA (2020) states that the vast quantities needed are not commercially available, and regular replacement would be essential.

4.6.2 Competitiveness

A1 indicated that osmotic energy could potentially serve as a supplementary energy source rather than a direct competitor. Referring to a TNO report submitted to the Ministry of Energy and Climate, A1 disclosed projections for the levelized cost of energy associated with osmotic energy. For an initial upscaled 100 megawatts power plant, the estimated cost was between 11 and 12 € cents per kilowatt hour. However, when the technology matures and more power plants are established, this cost could decline to as low as five cents per kilowatt hour by the years 2040 to 2045.

A central emphasis was placed on comprehensively evaluating the levelized cost of energy, encompassing project preparation, licensing, environmental assessment, land expenses, and grid connectivity. In this light, A1 contended that apparent cost advantages of wind and solar projects might not be directly comparable to osmotic energy, which integrates more comprehensive cost considerations.

A1 also accentuated the continuous energy production capability of osmotic energy, which contrasts with the intermittent nature of solar and wind power generation. This continuous output could contribute significantly to grid stability, particularly during periods of limited wind and solar generation. Notably, he underscored the challenges of power storage for conventional renewables and the intricate decision-making involved in selecting an appropriate storage technology. He elaborated on the inefficiencies inherent in hydrogen storage, where substantial energy loss transpires during the conversion process, since green hydrogen plays a prominent role in today's energy debates.

Furthermore, A1 explored the relevance of osmotic energy in remote areas or on islands where fossil fuel accessibility is limited, or energy generation is expensive due to fossil fuels and their transport. He posited that osmotic energy could offer a cost-competitive and ecologically viable alternative to the high costs and environmental impacts associated with transporting and using fossil fuels.

A2 emphasized that historically, none of the renewable energy sources were initially market ready. Drawing parallels to solar energy, he highlighted how the market viability of solar power was achieved through substantial state-level investments, notably by California and Germany. These states disbursed substantial sums, amounting to several hundred million dollars, for TRL 8 & 9 installations, effectively rendering solar power market competitive. A significant portion of solar cost reductions, estimated at 40-50%, was attributed to these initiatives.

A2 noted that the journey towards cost reduction is pivotal for emerging renewable technologies, including tidal energy, osmotic energy, wave energy, and floating solar cells. He asserted that achieving cost reduction would depend on factors such as considerable carbon credits or Flexibility Load Benefits. However, he pointed out that these mechanisms might take too long to mature, potentially positioning the technology at a disadvantage relative to rapidly advancing alternatives like battery storage, which may be less energy-efficient but more cost-competitive due to progress driven by sectors such as the automotive industry.

The interview delved into the role of subsidy mechanisms like SDE Plus in the Netherlands, which could potentially expedite the cost reduction trajectory. A2 acknowledged the policy implications of such mechanisms, raising questions about whether the Netherlands possesses the resources to reap economic or energy system benefits from this technology. The Dutch

Ministry of Economic Affairs and Climate Policy (EZK) was cited as contemplating the potential advantages.

From a competitive standpoint, A2 highlighted osmotic energy's unique advantage in its rapid tunability. He underlined the technology's capability to adjust energy production within seconds, which provides a distinct competitive edge over solar and wind energy sources. Drawing an analogy to nuclear energy, he characterized this attribute as a significant asset. Despite potential higher costs, this flexibility compensates for the economic equation.

In terms of integration into the energy system, A2 highlighted that osmotic energy's characteristics make it more feasible to synchronize with existing energy infrastructures. This agility in energy modulation contributes to its competitiveness. However, he conceded that osmotic energy might carry somewhat higher costs, potentially offset by its agility and the strategic advantage it offers in certain energy contexts.

A3 began by acknowledging the significance of osmotic energy's potential: the ability to generate renewable energy from the salinity gradient between saltwater and freshwater, available consistently throughout the year. He drew a comparison to hydropower, another highly concentrated form of green energy, highlighting osmotic energy's advantage of continuous availability and abundant resources.

Regarding osmotic energy's scalability and economic viability, A3 stated that the current technology was not economically feasible due to high costs per kilowatt-hour, potentially exceeding €1 and eventually even reaching between €5 to €10 in the current pilot installation. The expectation is that economies of scale, achievable with megawatt-scale installations, reduce these costs. However, he emphasized the need to calculate the future value of energy, considering factors like storage costs and the evolving energy mix towards 100% renewables.

The interview addressed the issue of osmotic energy's competitiveness against wind and solar power, particularly during periods of low energy prices when these sources dominate. A3 agreed with this challenge and stressed the importance of calculating the economic viability of osmotic energy in the context of dynamic pricing, such as in times of "Dunkelflaute" (low or no wind and solar availability; approx. 14 days a year).

In response to competitors, A3 noted that tidal stream and ocean currents hold promise but have limitations. He mentioned wave energy as a possible competitor but only if it lags wind energy. However, osmotic energy stands out due to its high availability throughout the year.

A3 reiterated that osmotic energy's economic feasibility hinges on significant reductions in kilowatt-hour costs through economies of scale and improved system efficiency. He emphasized the need for a compelling narrative that demonstrates the system's potential to achieve economic value. He emphasises that future predictions about the composition of the energy market and the values of electricity require whole modelling studies and that the competitiveness of this technology in the future cannot easily be foreseen.

Regarding hydrogen, A4 emphasized its competitiveness in terms of attention and funding. Green hydrogen's scalability and water demand align it with osmotic energy, though her province prioritizes electrification over hydrogen investment.

The tidal kite, another innovation and possible competitor, was mentioned. It shares similarities with osmotic energy but faces comparable challenges, notably public awareness, and early-stage development. A4 recognized a higher competitive risk from hydrogen due to its broader applications and scale.

A5 highlighted that ocean energy, including osmotic energy like REDStack, is still striving for commercialization. He emphasized the advantageous environmental impact of osmotic energy, as it doesn't directly disrupt marine life and has benign environmental effects.

A5 acknowledged competition within the ocean energy sector and emphasized that the location specificity of these technologies is vital for competitiveness. He noted that osmotic energy's potential is substantial, particularly in well-suited locations like the Afsluitdijk or the saltier waters of the Mediterranean.

Regarding competitiveness, A5 mentioned competition with traditional renewables like solar and wind, which are evolving and becoming more cost-effective over time. He also indicated that osmotic energy, with its potential cost reduction to around six-to-eight-euro cents per kilowatt-hour, remains an attractive prospect.

When questioned about the technology's timeline for becoming competitive, A5 expressed optimism and mentioned the potential of combining saltwater utilization with power generation for circular economy benefits.

Regarding barriers to upscaling, A5 identified resource competition with other renewables as a key challenge.

The tendency for osmotic energy's competitiveness leans carefully toward promise, but it also reflects the intricacies of an evolving energy landscape. Its continuous energy production, unique attributes, and adaptability contribute to its potential competitiveness, yet hurdles related to cost reduction, emerging alternatives, and specific energy contexts require careful consideration.

Chae et al. (2023) noted that if contemplating the operation of large-scale RED plants, the financial consequences of IEM affordability remain a subject of ongoing debate. To rival established technologies in the energy market, there is a need for additional advancements in both membrane technology and economics. To ensure future competitiveness of RED technology in the energy market, achieving high power density and improving energy output efficiency are crucial factors while reducing the size of RED stacks in commercial applications (Altıok et al., 2022).

IRENA (2014) states that even if cost estimates for RED are subject to significant uncertainty, yet they appear relatively favourable when compared to cost projections for other ocean energy technologies that are further along in their technological development and considers membrane costs are considered as the main economic barrier.

Zoungrana & Çakmakci (2021) identified that the main challenge facing the practical implementation of RED in a natural environment is its low power density and the high levelized cost of energy (LCOE). The performance of RED processes is primarily influenced by factors like the properties of IEMs, spacers, feed solution characteristics, salinity, and the electrodes. To enhance RED performance and reduce the overall energy cost, there is a need for new, highly selective, conductive, and cost-effective membranes. Additionally, exploring alternative feed solutions such as wastewaters and brine from desalination plants, as well as hybrid approaches can lead to more cost-effective water treatment and salinity gradient power extraction.

4.6.3 General Market Conditions

A5 emphasizes the current favourable market conditions for osmotic energy due to heightened concerns about energy security and resource independence in Europe. The dependency on international energy suppliers, coupled with the desire for resource autonomy, has created an environment beneficial for innovative energy solutions. He points out the establishment of a lobbying group and successful lobbying efforts in Brussels, resulting in the recognition of salinity gradient power as a renewable energy source by the European Union. This acknowledgment indicates a positive regulatory framework for osmotic energy's integration into the energy mix, alongside wind, solar, and tidal energy.

A2 addresses the question of timing in relation to energy security, geopolitical situations, and subsidies for renewable energy. He acknowledges the challenges of developing technologies like osmotic energy that require substantial initial investments. Unlike solar and wind, which have comparatively lower startup costs, osmotic energy demands significant (time)resources for research, development, and implementation. In terms of government subsidies, he emphasises that today comparably more subsidies are available than 10 years ago, but the distribution changed.

A4 highlights the role of the Province of Friesland in supporting innovations and knowledge valorisation. While various schemes are in place to promote innovation, she acknowledges that some innovators may struggle to navigate the system. A4 also explains the influence of universities on innovation leadership in a region. Despite lacking a university, their province has made progress in innovation, moving from a moderate to a strong innovation region according to the European Innovation Scoreboard. In general, she emphasises that the conditions for innovations are beneficial in the Province of Friesland.

The interviews suggest that the current market conditions appear conducive to the introduction of innovative energy technologies like osmotic energy. Beside the overarching goal of a carbon free energy system, energy security concerns and a push for resource independence have created a receptive environment for such solutions. However, challenges related to funding, regulatory frameworks, and regional innovation capacities continue to influence the timing and success of technology implementation. The proactive efforts of lobbying groups, provincial support systems, and evolving regulations contribute to build favourable conditions for osmotic energy.

Jang et al. (2020) estimated that is osmotic energy becomes commercialized, it is anticipated that a substantial market worth approximately $16.4 trillion could emerge, primarily utilizing the world's top ten rivers as an energy source. This development is also projected to lead to a reduction in carbon dioxide emissions by approximately 12 million tons through the generation of 30 terawatt-hours of salinity gradient power.

Additionally, in chapter 2.3 general marked conditions within the energy framework were discussed.

4.6.4 Financing & Funding

A1 identifies a significant barrier to the future success of osmotic energy technology: Financing. While the technology is advancing towards TRL 8 level, the leap from a 20-kilowatt demonstration to a 100-megawatt power plant presents a massive financial challenge. Project financing, especially from banks, becomes difficult due to the substantial upfront investment needed. A possible solution involves creating a demonstration site for a smaller 3-to-5-megawatt plant as phase one of a larger project. However, the cost for this initial phase, which would not be recoverable from selling the produced energy, poses a considerable financial hurdle.

Regarding the market and subsidies, A1 highlights the historical precedent of wind and solar energy, which were initially subsidized but eventually became market competitive. He draws attention to the changing landscape in Europe, where the focus has shifted away from subsidies for new innovations in the Netherlands due to the increasing availability of wind, solar, and nuclear power. He highlights that the financing barrier is exacerbated by the lack of available funds in the Netherlands for such substantial projects. The existing innovation funds in Europe are competitive, with various technologies vying for support.

Private capital companies, while potential partners, are more inclined towards cooperate finance than project finance. The magnitude of the initial investment required for the larger project makes it unattractive from a financial perspective, considering the uncertainties involved. The potential for financial recovery would only come with the completion of the 100-megawatt plant, making it a significant risk.

A1 contrasts the European context with India, where the Ministry of Renewable Energy might be more amenable to subsidizing the demonstration plant.

A2 notes that the EU's Innovation Fund provides a suitable avenue for funding large-scale projects. He emphasizes the need for a strong consortium involving energy companies to increase the chances of success, following A1 assessment about the competitiveness regarding this fund. Additionally, he mentions the potential for national or regional funds to contribute to projects after the initial upscaling.

A3 acknowledges the challenge faced by projects like REDStack in securing funding from national and local sources. He points out that while the project is recognized as an icon project, the financial figures may not align with the expectations of (potential) funders. A3 suggests that a key factor in securing funding is transparent communication. He notes that presenting a laser-sharp and realistic scale-up plan is essential. However, he highlights that previous overpromising and underdelivering might have led to a loss of support.

A3 emphasizes the importance of open communication about both successes and failures in technology development. He suggests that sharing challenges and failures with the public is crucial in gaining their support, particularly in public-private partnerships. He notes that public funding is often provided with the expectation of celebrating success. A3 advocates for embracing failures as part of the learning process and acknowledging them to show progress. He underlines that communication around challenges is necessary for technology development and building trust with stakeholders.

A4 acknowledges that the initial pilot plant received funding from the province of Friesland, and there was an application for the funding of the TRL 8 extension. She mentions, in line with A5, that, while the funding from the Waddenfund, a fund supported by the provinces around the Wadden Sea, is approved. The decision-making process for the upscaling funding from the province is ongoing.

She acknowledges the absence of national government funding and the technology's exclusion from the overall energy strategy of both the government and the provinces. A4 explains that, while the regional government has invested millions in the project, the resources are insufficient to fully support the upscale. She emphasizes the importance of national government involvement due to the scale of funding required.

A4 suggests that the technology's readiness for implementation might be a key consideration for its inclusion in energy strategies. She notes that, while the innovation aligns with the focus on electrification, it is not mature enough for immediate implementation. A4 acknowledges the potential for change through additional funding but also highlights the need for alignment with government and marked perspectives.

A5 also notes that REDStack succeeded in obtaining funding from the Waddenfund. However, the prospects of securing European innovation funds are characterized as highly competitive as well. Other opportunities from the European Commission are still in progress, reflecting the rigorous nature of acquiring these funds. A5 also touches on the perception that innovation funds might not always be readily accessible to small and medium enterprises, adding a layer of complexity to the funding landscape. The status of pending replies from DG CLIMA, the responsible stakeholder for European Commission innovation funds, is highlighted as an ongoing consideration.

Regarding the main barriers inhibiting the upscaling of osmotic energy technology, A5 underscores funding as a predominant obstacle. He emphasizes the need for increased risk capital to support the technology's growth. While risk capital is not uncommon in Europe, A5 points out that obtaining it can be challenging, indicating a potential gap in financial support for emerging technologies like osmotic energy.

All experts unanimously identify funding as a primary challenge. These interviews underline the magnitude of the funding required to upscale from a TRL 8 (9) demonstration to a fully developed power plant. This step demands substantial upfront investment, making project financing, especially from traditional sources like banks, a considerable challenge. The experts highlight the financial gap between smaller demonstration phases and larger-scale implementation without immediate revenue generation.

The interviews shed light on the competitive nature of European innovation funds. While securing funding from such sources is a possibility, it is highlighted that these funds are fiercely contested, especially for emerging technologies. The accessibility of these funds, particularly for small and medium-sized enterprises, is also noted as a challenge.

Transparent communication emerges as an important aspect for securing funding and support. One interviewer suggests that a history of overpromising and underdelivering could erode stakeholder trust and reduce support. Openly sharing both successes and failures is encouraged as it demonstrates progress, commitment, and a willingness to learn from challenges. This communication strategy is viewed as essential for building public-private partnerships and gaining financial backing.

The role of national governments and regional support mechanisms is stressed as pivotal in overcoming financial barriers. While regional governments, such as the province of Friesland, have provided initial funding (REDStack et al. 2023; Provinsje Fryslân, 2023), their resources may be insufficient for the upscaling of osmotic energy technology to marked maturity. National government involvement is seen as important due to the substantial funding needed. The energy strategy of the national government does not focus on innovative energy concepts such as osmotic energy, but rather on established renewables and nuclear power (NECP, 2019).

The need for increased risk capital for emerging technologies, and osmotic energy, is emphasized. However, competitiveness with other emerging technologies plays a role in influencing funding decisions and support for novel technologies.

The interviews collectively highlight funding as a major barrier to the upscaling of the osmotic energy technology today. The competitive landscape of innovation funds, the role of government involvement, and the challenges of securing capital are critical factors shaping the technology's journey towards commercial viability.

In this line IRENA & OEE (2023) identified recurring challenges observed in the implementation of ocean energy solutions caused by inadequate funding prospects and a scarcity of market exposure.

From a general view on the current stage of the upscaling process (TRL 7-8) Nemet et al. (2018) describes a dilemma regarding innovations, private investment incentives in large-scale demonstrations are lacking, and the history of governance support in such projects has been poor, creating a valley of death for innovations in the upscaling process. In this line Karakaya et al. (2014) states that two substantial obstacles must be addressed to facilitate the adoption of eco-innovations: market unpredictability and uncertain investment returns.

4.6.5 Other

According to A1, there is no shortage of skilled labour hindering the development of the technology and within his company. He argues that while there might be concerns about a lack of technical expertise in some fields, companies engaged in sustainable technologies can find suitable candidates. A1 believes that many individuals prefer working in sustainable industries over sectors like military or the fossil fuel industry. Therefore, he sees no significant barriers related to the availability of skilled labour.

A3 points out a potential barrier related to marketing and branding. He suggests that companies like REDStack could improve their image and presentation. He observes that elements like the company's logo, website, and overall visual identity could be enhanced to better convey their innovative and pioneering image. A3 highlights the need for a compelling visual experience on the company's website, comparable to the branding approach of Tesla, to effectively communicate their vision.

While A1 emphasizes that there is no lack of skilled labour due to the attractiveness of sustainable technologies, A3's insights underscore the importance of effective marketing and branding strategies. A strong visual identity and engaging online presence can contribute to building confidence and interest in the technology among potential stakeholders.

A2 states that scaling up energy technologies, while potentially conferring a beneficial status on owning companies, often presents significant cost challenges. For instance, establishing a 10-Megawatt solar farm may cost a few million dollars, but scaling up to larger capacities involves may costs in the range of hundreds of millions to billions, making it impractical for mere PR purposes, supporting the initial hypothesis of the author.

4.7 Future Perspectives

In this chapter the future perspectives of the interview partners regarding osmotic energy and RED will be presented.

A1 envisions a positive future for the osmotic energy technology. He anticipates the construction of a demonstration (TRL 9) plant after next year and a 100 MW plant by 2028. He envisions potential large-scale implementations, especially in Korea, where the technology's attributes align well with the nation's energy goals. He expresses enthusiasm about collaborating with the major national power company and sees the technology's potential to contribute significantly to Korea's energy landscape.

A4's perspective on the future of osmotic energy is cautious yet pragmatic and points out that her views aren't official policy. She acknowledges the uncertainty inherent in predicting technological trajectories. Highlighting the challenge of moving from startup to scale-up, she emphasizes the importance of market adoption. She suggests that beyond funding hurdles, technologies like osmotic energy face the challenge of finding investments beyond the startup phase. A4 underlines the evolving nature of the energy landscape, noting that the energy mix in 2050 remains unpredictable due to technological advancements.

A5's perspective on the future of osmotic energy is optimistic. He sees the technology poised for commercialization and emphasizes the role of competition with other renewables. A5 mentions the potential impact of the updated Renewable Energy Directive in Europe, which could give osmotic energy a significant push by requiring member states to address it. He considers the successful completion of ongoing European projects, like IntelWATT and Indesal, as crucial for the sector's advancement. A5 sees REDStack's progress, including the Waddenfund subsidy, as promising signs for the technology's growth.

4.8 Identified Key Results

The results emphasize the critical role of funding as a predominant barrier to the upscaling of osmotic energy, and REDStack (A1; A2; A3; A4; A5; IRENA & OEE 2023). While the funding for an TRL 8 extension seems securable (A1; A4; A5; RedStack et al., 2023; Provinsje Fryslân, 2023), the transition from a TRL 8 pilot plant or TRL 9 demonstration plant to a large-scale (100-megawatt) power plant demands a substantial financial investment, that will probably not be regained by selling the produced energy until the technology reached marked maturity (A1). Additionally, the competitive landscape for acquiring necessary funds poses a significant challenge. Innovation funds, particularly those offered by the European Commission, are highly sought after and competitive. This competition makes securing funding a complex process, especially for small and medium-sized enterprises like REDStack (A2; A3; A5).

The scarcity of risk capital in Europe adds to the complexity (A5). While risk capital is not uncommon in Europe, the outcomings reveal that obtaining it for emerging technologies like osmotic energy remains challenging (A5; Nemet et al., 2018). The rather unpredictable nature of emerging technologies coupled with the substantial investment required likely creates hesitation among private capital companies, contributing to the difficulty in securing financial support (A1). This presents a paradox where the need for investment is high, but the readiness of investors to provide risk capital is limited (A5).

The market competitiveness of osmotic energy is another dimension revealed through the gathered results. With the rise of established renewable technologies like wind and solar, osmotic energy seemingly enters a fiercely competitive arena, in a technological as well as political dimension (A2; A3; A4; A5; Overheid, 2021; Zoungrana & Çakmakci, 2021). Stakeholders recognize the potential of osmotic energy to contribute to the market and the interviews highlight that osmotic energy is on the brink of commercialization, but its success depends on how well it presents compelling advantages in a competitive price range, which is not possible to estimate for the future (A2; A3; A5; Chae et al. 2023; Altıok et al., 2022; IRENA, 2014).

The European Union's updated renewable energy directive, which potentially includes osmotic energy in the renewable energy definition, is deemed important (A5). If implemented, this directive would force member states to engage with osmotic energy if sites are available, giving it a push towards recognition and adoption (A5). However, even with this potential recognition, osmotic energy's ability to compete effectively against established renewables remains a pivotal question, especially considering the dynamic shifts that the energy sector undergoes over time (A2; A3).

The practical execution of osmotic energy technology faces challenges related to infrastructure and site selection. Implementation within harbours, while promising (A1; A5), also introduce complexities (A1). The need for specific water flows, integration within existing maritime processes, like the potential for delays in ship passage through locks in Rotterdam, contribute to logistical challenges (A1). Alternative sites like flood protection systems and pumping stations offer alternatives, potentially sidestepping these logistical barriers (A1). However, the actual capacity and feasibility depend on a multiplicity of factors (Alvarez-Silva et al., 2016)

The interviews emphasize a significance for permits regarding osmotic energy projects and renewables in general (A1; A4; A5; Papapetrou & Kumpavat, 2016; Copping 2020). The diversity of locations requires navigating through varying levels of complexity in obtaining permits (A1; Kahn, 2000). Locations designated as nature protection areas demand more extensive procedures, while sites within existing infrastructures, like harbours, likely require shorter permitting processes (A1). Regulatory changes, such as the European Union's proposal to shorten environmental permitting times for renewable energy projects, are expected to impact future developments in a positive way (A5).

Water resource conflicts arise as a potential barrier, particularly in regions experiencing water scarcity, now and in the future (A5; Yip et al., 2016). Although the powerplants are last in line (A1), balancing these conflicting demands on water resources becomes pivotal, necessitating careful consideration and management to avoid resource depletion and conflicts (Yip et al., 2016).

The political and societal dimensions are crucial determinants for technology integration. Political actors may have reservations about the implementation of osmotic energy due to factors like political standpoints (A1; A5; Overheid, 2021) infrastructure changes, or conflicting interests in water usage (A4; Yip et al. 2016). Public acceptance, although rated positive for this technology (A2; A3; Sharpton et al., 2020), can become significant factors influencing the feasibility of large-scale implementation (A4; Segreto et al., 2020).

The evolving energy landscape may present a challenge for the incorporation of osmotic energy. With shifting priorities and emerging technologies, the energy mix and focus may change over time (A3; A4). The interviews underline the need for adaptability and the possibility that the role of osmotic energy might fluctuate within the larger energy transition, indicating the requirement of constant reassessment of its relevance and alignment with future energy needs.

5. Discussion

In this discussion, the identified benefits and barriers associated with osmotic energy and RED will be juxtaposed. This aims to provide a multifaceted understanding of osmotic energy, while acknowledging the insights of innovation diffusion theory and within the context of the ongoing energy transition. Therefore, this study discusses its relative advantage, compatibility with sociocultural values and beliefs and factors related to its complexity, trialability, and observability.

5.1 Relative Advantage

Osmotic energy presents several potential advantages that could position it in a positive way within the realm of renewable energy and were therefore highlighted throughout this thesis and within the acquired data. One of the primary strengths of this technology are the environmental benefits (A1). Unlike fossil fuels or nuclear energy, osmotic energy produces minimal to no greenhouse gas emissions and no radioactive waste, aligning well with the global efforts to combat climate change (Mei & Tang, 2018).

Secondly, the steady and reliable nature of osmotic energy production offers another advantage (Chae et al., 2023; Mei & Tang, 2018). Unlike solar or wind energy, which are dependent on weather conditions, osmotic energy can generate power consistently, making it a potentially stable contributor to the energy mix through its baseload characteristics (A2; Al-Shetwi et al., 2020). This aspect could be especially valuable in ensuring a continuous and reliable energy supply, addressing the fluctuant nature of wind and solar energy (A1; A2).

Thirdly, the compatibility of osmotic energy with newly build infrastructure, such as flood protection systems and pumping stations, could benefit its integration (A1; A2; A4; A5). Logistical challenges faced by other renewable energy sources that require extensive infrastructure development, such as offshore wind parks, are not directly visible as this type of power plant can be implemented in existing harbour structures.

Moreover, osmotic energy's potential to be harnessed in various geographical locations with saltwater and freshwater, as well as the combination with new technologies, broadens its applicability (A1; A5; Alvarez-Silva et al., 2016). This adaptability enhances its attractiveness as a renewable energy solution that can be customized to fit different regional needs, such as on islands or in remote areas, potentially aiding its diffusion.

Finally, the public acceptance for this technology is considered as high, since these powerplants are not visible in the landscape like wind turbines or solar fields and neither do they produce radioactive waste like nuclear energy (A2; A3). The story of mixing two water bodies and producing energy out of it was highlighted as potentially favourable for the public acceptance.

However, these relative advantages need to be weighed against the significant barriers that osmotic energy currently faces. One of the most prominent barriers, highlighted from most interviewees, is funding (A1; A2; A3; A4; A5; IRENA & OEE, 2023). The results reveal that RED, and osmotic energy projects in general, demand substantial financial investments. While initial funding has been secured from regional sources for the pilot plant and its TRL 8 extension, the complexity of obtaining adequate financial support for scaling up remains a challenge. This funding gap could impede the technology's advancement beyond the pilot phase.

The renewable energy sector is highly competitive, with established sources like wind, solar and nuclear energy dominating the market (NECP, 2019). Osmotic energy competes for attention and partly funding within this landscape (A3; A4; A5). The results suggest that osmotic energy's success may depend on its ability to carve out a distinct niche, e.g., the baseload provision, effectively communicate its advantages compared to existing renewables (A3) and lower its levelized cost of energy (Zoungrana & Çakmakci, 2021; Chae et al., 2023).

As already mentioned, implementing osmotic energy within harbours or other specific locations introduces infrastructure and logistical challenges (A1). The need to navigate complex regulatory frameworks and obtain permits from multiple organizations, especially in sensible areas (A1), can slow down project progress, thereby limiting its potential for quick diffusion (Papapetrou & Kumpavat, 2016).

The requirement for freshwater in osmotic energy production raises concerns about water resource conflicts in the future (A4). As water scarcity becomes a pressing issue in many regions, osmotic energy's freshwater usage could potentially clash with other vital needs such as agriculture and drinking water supply (Yip et al., 2016).

Political awareness is another important factor, since the focus of the current national government in the Netherlands lays on the established sources of renewable energy, wind and solar, and nuclear energy (A4; Overheid, 2021). Osmotic energy is not mentioned in the national energy strategy or the energy strategy of the provinces (A5; NECP, 2019). However, the interviews suggested that this could be the case if this technology is fully developed and competitive to the other renewables. One interviewer also highlighted the importance of the European Union and their upcoming renewable energy directive since the member states must consider osmotic energy in their strategies once it is acknowledged in this directive (A5).

Osmotic energy demonstrates relative advantages that position it favourably within the renewable energy landscape, but faces, at the same time, considerable barriers. The success and extend of its diffusion into the marked will likely be influenced by how effectively the existing barriers will be managed.

5.2 Compatibility

5.2.1 Alignment with Sociocultural Values and Beliefs

Osmotic energy aligns with the sociocultural value of environmental responsibility. It offers a sustainable energy source and, according to the results, provides an environmentally feasible solution as it doesn't impact the local flora and fauna to a larger extent (A1; REDStack et al., 2023). Compared to fossil fuels, it is reducing greenhouse gas emissions, and therefore minimizing environmental harm typically associated with the traditional energy generation. Sociocultural values related to climate change adaptation align with osmotic energy in this sense. The need for sustainable energy solutions to combat climate change make osmotic energy relevant for the ongoing energy transition.

Osmotic energy, if implemented on a larger scale, has the potential to align with values of energy independence and security. It diversifies the energy mix, reducing dependence on fossil fuels and therefore external energy sources (Carfora et al., 2022). As the interviews show, this aligns with the goal of the European Union and the member states for more energy independence, especially in hindsight of the war in Ukraine and the impacts on the European energy market.

Osmotic energy facilities are comparably compact and likely submerged, located in remote areas or within already industrialised sites, like harbours, limiting their visibility to local communities (A1). This aligns with sociocultural values related to landscape degradation (Segreto et al., 2020), mainly originating from debates around wind turbines, which are highly visible in the landscape (Langer et al., 2016). The interviews highlight that transparent communication about the technology's benefits, challenges, and environmental contributions is important to foster this alignment (A3).

However, the alignment with economic values varies. While osmotic energy can create economic opportunities through job creation and technology development, its financial feasibility and competitiveness compared to other energy sources can hinder its alignment with these values.

As already partly discussed throughout this study, osmotic energy aligns with several sociocultural values and beliefs, such as environmental responsibility, resource efficiency, technological progress, energy independence, and adaptation to climate change. However, the alignment with economic values depends on factors such as funding and cost competitiveness. Effective communication and engagement with the public are important for enhancing alignment with sociocultural values and to gain public awareness and acceptance.

5.2.2 Consistency with Previously Introduced Ideas

The interviews suggest that osmotic energy aligns well with the idea of a sustainable energy production. This alignment with well-established principles makes it an attractive candidate within the renewable energy paradigm, and therefore simplifying its integration into existing energy infrastructure. While osmotic energy is acknowledged as environmentally sustainable, it's essential to acknowledge the potential ecological implications of large-scale power plants (A2). The osmotic energy process involves changes in the flow of freshwater and seawater, which could have possible impacts, positive or negative, on aquatic ecosystems due to the outflow of large amounts of brackish water (A2; Seyfried et al., 2019). Therefore, despite its alignment with sustainability goals, careful environmental impact assessments are necessary to ensure its true ecological compatibility for large scale implementations.

Osmotic energy possibly also aligns with the idea of multifunctional infrastructure (A1). By integrating energy generation in coastal defence systems, it serves a dual purpose. This aligns with contemporary urban planning and infrastructure design trends, where structures are planned to deliver multiple benefits (Hansen & Pauleit, 2014). However, it's necessary to recognize the complexity of integrating energy generation with other infrastructure functions. In the case of Rotterdam, it is visible that logistical and operational challenges can outweigh the benefits, leading to a resistance from stakeholders (A1). Thus, while the idea aligns with contemporary planning trends, the practical implementation may be more challenging than anticipated.

However, it's important to understand that new innovations also bring risks and uncertainties (Teece et al., 2016). The technology's capabilities for large-scale deployment, although the interviews gave a positive view (A1), remains a question mark, as it has never been done before. As with any innovation, there are potential setbacks that need to be navigated.

In summary, osmotic energy shows good consistency with previously introduced ideas and concepts. These attributes collectively position osmotic energy as a concept well-aligned with contemporary energy and sustainability ideas. However, critical considerations must accompany these alignments, marked challenges, practical implementation challenges, technological uncertainties, and complex international dynamics all warrant attention.

5.3 Complexity, Trialability, Observability

Osmotic energy's complexity primarily resides in the underlying technology and processes. End-users, such as energy companies, may not need an in-depth understanding of this complexity to adopt the technology (A2). Instead, they can rely on specialized providers and experts in the field. This is underlined by the statement from A3 who refers to the complexity of nuclear energy and sees no impacts on the acceptance due to complexity concerns. Additionally, as the technology matures and more successful implementations occur, best practices and standardized procedures can emerge, simplifying the adoption process.

While the technology and the upscaling itself is complex, this may not be a significant hindrance to diffusion, as the technology development could be considered as advanced and because of less relevance for the “end-user” (A2), supporting the initial hypothesis.

Trialability may not be of large importance for osmotic energy due to the existence of pilot plants. REDStack's pilot plant and the upcoming TRL 8 extension, for instance, serve as concrete proof of concept, which was highlighted by A2. These pilot plants provide, in the longer term, a high level of technical assurance, while addressing complex technical challenges associated with osmotic energy. Pilot plants also undergo environmental assessments, helping to minimize concerns related to water quality and ecosystem impacts (A1). Given the long-term commitment and resource-intensive nature of establishing pilot plants in suitable locations, they become critical resources and reducing the need for additional trials by the end-user. In essence, the presence of pilot plants offers technical validation, environmental insights, and scalability data, making smaller trials less important for the development and commercialization of osmotic energy.

In terms of observability, it acts comparably to trialability, the existence of a pilot plant makes it possibly of less importance for the end-user because this pilot plant serves as a physical and tangible representation of the osmotic energy technology. Pilot plants are under scientific guidance (A1). This scientific research allows for the comprehensive assessment of the plant's performances and impacts. This transparency enhances observability by offering stakeholders insights into the technology's capabilities and limitations.

6. Conclusion

In search of understanding the potential of osmotic energy, particularly in the context of RED, this study relied on an identification of the benefits and barriers associated with this innovation. The overarching research question guiding this thesis was to identify the current barriers to osmotic energy, focusing on RED, within an up-to-date holistic planning perspective, and to assess how these barriers might impede the crucial upscaling process, particularly in the Dutch context, which were extensively discussed in the previous chapter.

Additionally, the study aimed to identify the benefits osmotic energy brings to the ongoing energy transition and society. In doing so, this thesis aimed to provide a holistic understanding of the current position of RED within the complex circumstances of our energy landscape.

Osmotic energy demonstrates a mixed potential in terms of relative advantage as it provides several outstanding benefits but at the same time substantial barriers. A good potential in terms of compatibility could be identified, which positions it as a concept well-aligned with contemporary energy and sustainability ideals. However, overcoming the barriers necessitate ongoing consideration and strategic planning. To unlock its full potential, addressing funding challenges and ensuring cost competitiveness are imperative steps.

Osmotic energy's alignment with sustainability goals and its potential to address pressing energy and environmental challenges can act as a catalyst for diffusion. Sociocultural factors and beliefs regarding sustainable energy solutions may override concerns, pushing stakeholders to invest in and support osmotic energy initiatives.

6.1 Limitations

This thesis covers a broad spectrum of topics related to osmotic energy. However, due to the nature of a master's thesis, the depth and breadth of the analysis are limited. While the thesis provides a qualitative exploration of the various aspects of osmotic energy, a comprehensive research study would involve a more in-depth analysis of each topic. For example, a detailed examination of specific barriers, such as regulatory challenges or technological limitations, would require dedicated research and data collection. In practice, conducting such an analysis might involve a more extensive review of the literature, engagement with a wider range of experts and stakeholders, and potentially interdisciplinary research to fully grasp the complexities of the subject, which can be subject for further research.

The analysis and discussion in this thesis are primarily qualitative. They rely on expert opinions and discussions but lack quantitative data and statistical analysis. In a comprehensive study, quantitative data would be essential to support and validate the claims and assumptions. For instance, assessing the financial viability of osmotic energy, especially in the future, would require detailed financial modelling, cost-benefit analysis, and consideration of variables like energy market prices and government incentives. Quantitative studies often involve surveys, data collection, and statistical tests to determine the statistical significance of findings. This analysis does not provide a statistical dimension which would be of value in a formal research study.

This thesis does not extensively consider external factors that can significantly impact the prospects of osmotic energy. The global energy landscape is dynamic and influenced by factors such as changes in oil prices, geopolitical events, or market trends. These external factors can affect the competitiveness of osmotic energy and other renewable technologies. Breakthroughs in related fields, such as materials science or energy storage, can influence the feasibility and competitiveness of osmotic energy. However, as this applies to many parts of the global marked, this is not inherent to osmotic energy alone.

Lastly, real-world decisions about osmotic energy would involve input from a wide range of stakeholders, such as government agencies, energy companies, research institutes, environmental organizations, and local communities. This thesis does not cover the diverse perspectives and interests of all these potential stakeholders.

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V. Appendix A

Interview Guide

This section contains the general interview guide developed for the study. However, each interview was customized to suit the specific respondent. Depending on the interviewee, a unique set of questions was curated, and individual inquiries were adapted accordingly. The adaptable nature of semi-structured interviews allowed for additional questions to be formulated when specific points of interest arose.

1. Can you introduce yourself and the institution you are working for?
2. Which stakeholders are involved in the salinity gradient sector in the Netherlands, especially for salinity gradient power on a private and government level?
3. What do you think are today´s main technological barriers that could hinder an up-scaling of this technology?
4. Does the technology have a relative advantage over its competitors? For example, in an economical or technological sense?
5. Is there a marked demand in today's energy landscape?
6. Are the financial resources for this technology sufficient? Who is funding this technology?
7. How convenient is it to implement this technology in the current energy landscape?
8. How would you classify the spatial potential of this technology?
9. Which other spatial barriers, such as e.g., grid connections, could hinder the implementation of this technology?
10. Is there political (and social) awareness about the existence and potential of this technology?
11. How would you consider public acceptance for this technology?
12. How would you consider the complexity of the technology in terms of comprehensibility?
13. Does the technology provide a beneficial social status for the company that possibly owns this kind of powerplant?

14. Does a lack of other resources, such as skilled labour or supply chains, hinder the development?
15. Are there any environmental factors during construction and operation that must be considered?
16. Would you consider the benefits of this technology as more important than the current barriers from a societal perspective?
17. Can you identify further barriers?
18. What are your future perspectives for this technology?