SeaHydrogen

Position paper: Integral Nexus Approach for the Production of Hydrogen at Sea

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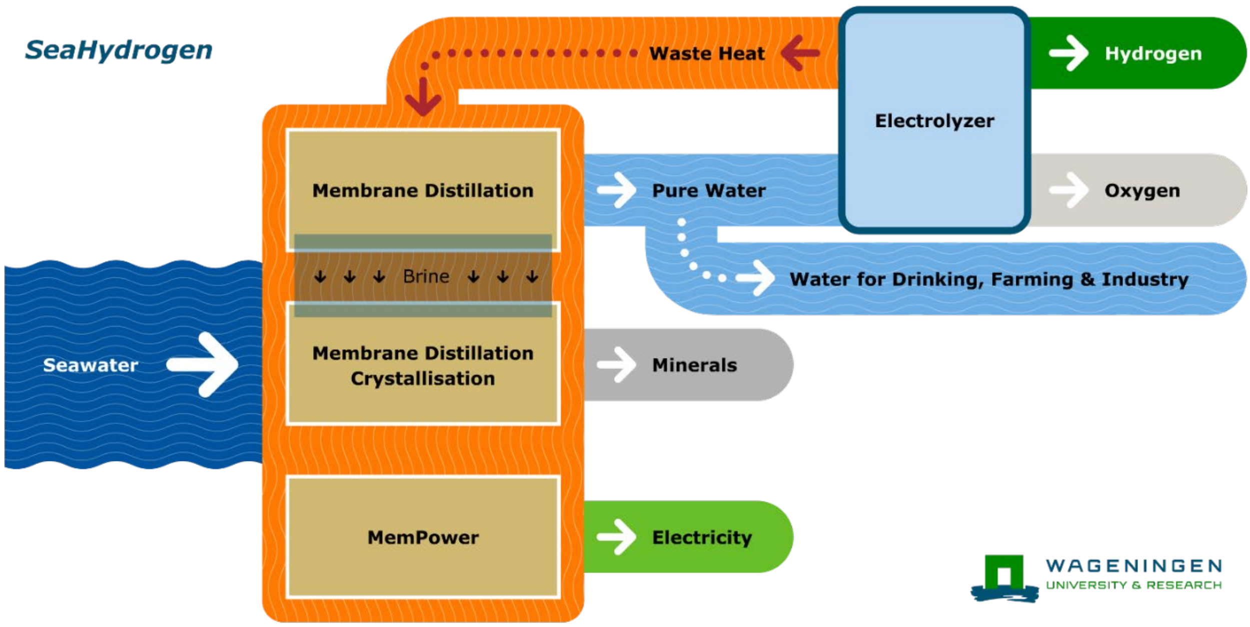
Executive Summary

This position paper presents an innovative and integrated concept for hydrogen production from seawater: *SeaHydrogen*. This concept combines the use of an electrolyzer for hydrogen generation, membrane distillation for ultrapure water production, and the treatment of seawater brines to enhance water yield and extract valuable salts. Additionally, a novel membrane distillation technology, known as MemPower, can convert excess waste heat from the electrolyzer into electricity. This integrated Nexus approach, as visualised below, not only promotes sustainable hydrogen production but also maximizes resource utilization, including waste heat, to produce hydrogen, oxygen, electricity, and valuable minerals from seawater.



1 Introduction

The current global energy landscape is marked by a growing demand for clean and sustainable hydrogen production. Hydrogen, as a versatile energy carrier, offers a promising solution for transitioning towards a greener future. However, traditional hydrogen production methods are not without their challenges, including the efficient utilization of resources and waste heat. In response to these challenges, we propose an innovative and integrated concept for hydrogen production from seawater, which we refer to as the "Nexus Approach."

1.1 Background information

Hydrogen (H_2) production is predominantly reliant on electrolyzers in today's energy landscape. However, this method presents inherent challenges that demand innovative solutions:

- Waste heat generation: The electrolysis process generates a substantial amount of waste heat. Effectively managing this waste heat is essential and typically involves the implementation of extensive cooling systems. Unfortunately, a significant portion of this thermal energy is dissipated without being harnessed.
- Dependency on drinking water: Electrolyzers depend on copious amounts of drinking water as their primary feedstock. This reliance introduces competition with other essential applications and exacerbates the strain on our already precious drinking water resources.
- Environmental impact: The conventional approach of hydrogen production contributes to environmental challenges. The process consumes substantial amounts of energy, often derived from non-renewable sources, leading to increased greenhouse gas emissions.

To address the second challenge, an alternative approach is to produce drinking water from seawater through Reverse Osmosis (RO). Nevertheless, while RO is a common method, it comes with its own set of limitations (ref):

- Limited water production: While RO is effective at desalting seawater, it may only remove about half of the water because of osmotic pressure limitations (i.e. high pressure operation). This also results in relatively large brine streams. Proper disposal of this brine can be an environmental challenge, as it must be managed to prevent harm to marine ecosystems.
- Electricity dependency: The operation of RO systems necessitates a substantial amount of electricity.
- Chemicals usage: RO operations often require the addition of chemicals, such as antiscalants, which can have adverse environmental implications

As governments and policymakers worldwide acknowledge the pivotal role of hydrogen in shaping the future economy, ambitious targets are set. For instance, the Netherlands aims to achieve a substantial hydrogen production capacity of 8 GW in the near future (2032). However, this pursuit is accompanied by an increase in waste heat generation and a growing burden on the drinking water system (see Figure 1), emphasizing the need for innovative and sustainable approaches.

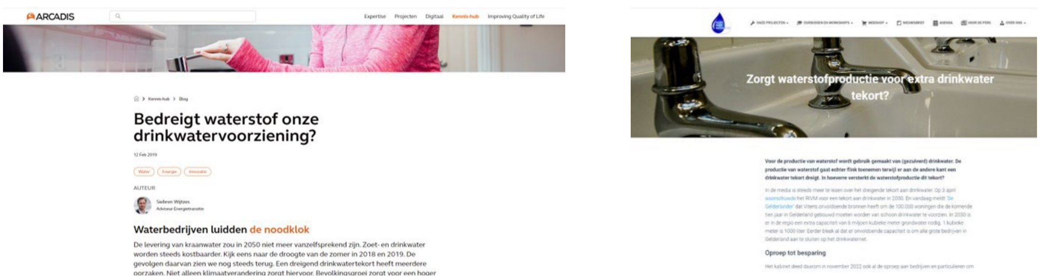


Figure 1 Some Dutch press messages (ref1, ref2) reporting about increasing pressure on water resources due to hydrogen production.

1.2 Statement of the position to be defended

Our position is rooted in the belief that the existing challenges associated with hydrogen (H_2) production from drinking water and seawater demand a comprehensive and innovative solution. We advocate for the adoption of the Nexus Approach, which integrates multiple technologies to address the shortcomings of traditional hydrogen production methods and promotes sustainability, resource utilization, and waste heat management.

Our position can be summarized as follows: We assert a Nexus Approach, combining the use of an electrolyzer for hydrogen production, 3 generations of membrane distillation for ultrapure water generation, treatment of seawater brines, and conversion of waste heat into electricity, respectively. This offers a transformative and sustainable solution for hydrogen production from seawater: *SeaHydrogen*. This approach effectively utilizes waste heat from electrolyzers and reduces the amount of cooling duty, minimizes the dependence on drinking water, increases the availability of fresh water, reduces the amount of brine produced, extracts valuable minerals from seawater resources, and produces electricity.

Key points in our position are:

- Hydrogen production using conventional electrolyzers results in significant amounts of waste heat, competition for drinking water resources, and environmental challenges.
- The Nexus Approach maximizes the utilization of waste heat from the electrolyzer, reduces energy consumption, and minimizes the need for drinking water as feedstock.
- Membrane distillation technologies play a crucial role in the Nexus Approach, enabling the production of ultrapure water, the treatment of seawater brines, and the conversion of waste heat into electricity.
- Our position aligns with the growing recognition of hydrogen as a key component of the future economy, requiring innovative solutions to meet ambitious production targets.

In essence, our stance is a call to action, advocating for the adoption of an integrated and sustainable concept that overcomes current challenges and fosters a more efficient, environmentally responsible, and resource-conscious hydrogen production landscape.

1.3 Significance of the topic

The significance of the topic of hydrogen production from seawater, particularly within the context of the Nexus Approach, cannot be overstated. This innovative concept holds profound importance for a multitude of reasons:

- **Global energy transition**: As the world struggles with the imperative of transitioning to cleaner and more sustainable energy sources, hydrogen emerges as a key player. Hydrogen is a versatile energy carrier that can significantly reduce greenhouse gas emissions, making it pivotal in achieving global climate goals.
- **Resource efficiency**: The Nexus Approach aligns with the fundamental principle of resource efficiency. It addresses the challenge of waste heat generation, a prevalent issue in electrolysis-based hydrogen production, by utilizing this surplus thermal energy for various applications, including freshwater production and electricity generation. This resource optimization not only enhances the overall efficiency of hydrogen production but also minimizes energy waste.
- **Reduced environmental impact**: The traditional method of hydrogen production often involves significant carbon emissions, energy consumption, and chemical usage. By promoting membrane distillation and reducing the dependence on electricity and chemicals, the Nexus Approach offers a more environmentally friendly alternative. This contributes to reduced environmental impact, aligning with global sustainability goals.
- **Enhanced water resource management**: Competition for drinking water resources is a growing concern, particularly in regions facing water scarcity. The Nexus Approach mitigates this challenge by reducing the demand for drinking water as a feedstock. By efficiently utilizing seawater, it lessens the strain on already stressed water supplies, ensuring sustainable water resource management.
- **Economic opportunities**: Beyond environmental and resource benefits, the Nexus Approach opens doors to economic opportunities. The extraction of valuable minerals from seawater brines, along with electricity generation, presents potential revenue streams. This integrated concept can stimulate economic growth and diversify income sources.

- **National and international energy goals**: Many nations, including the Netherlands, have set ambitious targets for hydrogen production, viewing it as a linchpin for the future economy. The Nexus Approach offers a practical means of scaling up hydrogen production to meet these targets and support the transition to a hydrogen-based economy.

In summary, the significance of the topic lies in its capacity to address critical challenges in hydrogen production from seawater while advancing the principles of sustainability, resource efficiency, environmental responsibility, and economic growth. The Nexus Approach holds the potential to shape the future of clean energy production and contribute to a more resilient and sustainable world.

2 Problem Statement

2.1 Lack of fresh water sources

More and more we see reports of water shortages in The Netherlands (ref). According to Vitens we will lack 6 million m^3 of water sources to provide 100.000 new built houses with drinking water in the province of Gelderland in 2030 (ref). This is an unknown phenomenon for The Netherlands, expecting to be a progressive issue.

With an upcoming hydrogen economy, the pressure on fresh water sources will even increase and that is worrisome. The planned 8 GW hydrogen capacity in 2032, requires about 11 million m^3 of pure water (ref). If drinking water is used as a source for this, it will claim 1% of the total drinking water capacity of The Netherlands every year. This is twice the deficit of water amount already lacking in Gelderland in 2030. In the present planning of drinking water production the water need for hydrogen electrolyzers has not taking into account and we just lack enough fresh water sources for it.

2.2 Green hydrogen production downsides

As the government of The Netherlands is aiming for a green hydrogen economy with a production capacity of 8 GW in 2032 (ref), there is a large demand for pure (demineralised) water as feedstock for the electrolyzers. Given the abundance of seawater, it could be the favored resource for supplying hydrogen electrolysers with pure water. The current method involves utilizing conventional Reverse Osmosis (RO) systems for this purpose. Future plans are also based to produce this water by using RO systems. This linear approach is visualised in Figure 2.

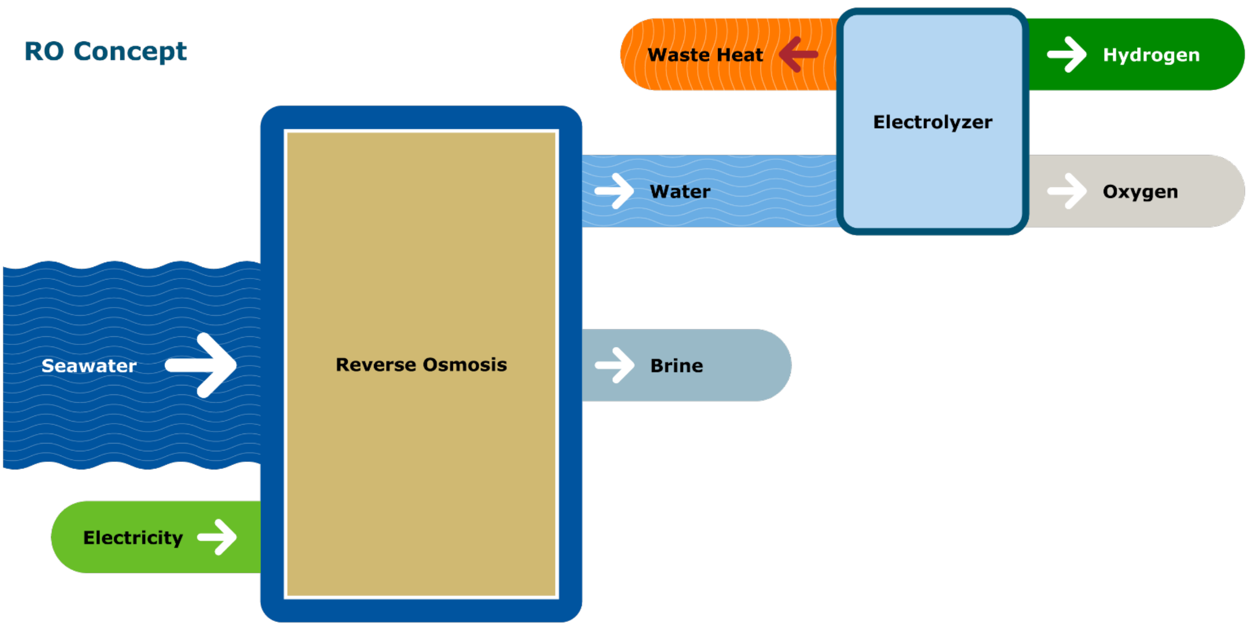


Figure 2 The planned linear approach for hydrogen production from seawater based on the RO-concept.

However, there are some drawbacks related to applying RO on seawater:

- The electricity consumption for RO is significantly larger compared to using freshwater, due to the elevated salt content in seawater. This leads to a higher carbon footprint.
- Membrane fouling, where impurities and particles accumulate on the surface of the membrane, is a common issue in RO. Seawater contains various contaminants, such as algae, bacteria, and organic matter, which can foul the membranes over time and ask for regular maintenance and cleaning of the membranes
- The RO process generates brine water flows, and as of now, there is no practical solution available. Discharging it into the ground or freshwater environments is not viable, as it could lead to the salinization of valuable freshwater sources. Moreover, discharging (higher density) RO concentrates into the sea has been observed to elevate local salinity levels and impact marine life.

Another concern related to hydrogen electrolyzers is the generated waste heat. There are currently no plans to repurpose the low-grade heat, which is around 80 - 85 °C. Utilizing it for purposes like building heating requires proximity, which may not be feasible in offshore hydrogen production scenarios. Presently, the only proposed approach is to cool down the heat, requiring additional water, and thereby dissipate it.

The next statistics and facts are illustrating the current challenges:

1) Waste heat generation: Presently, hydrogen production through electrolyzers (alkaline or PEM electrolysers (ref) generates a significant amount of waste heat. This excess thermal energy often goes underutilized or is dissipated into the environment. This is a pressing concern given the increasing demand for sustainable energy production. This waste heat represents a lost opportunity for improving the overall energy efficiency of the hydrogen production process.
    - Quantitatively: in conventional electrolyzer-based hydrogen (with an energy density of 120 MJ/kg H_2 = 33.3 kWh/kg H_2), approximately 20% of the input electricity is converted into waste heat. This translates to substantial energy loss that can be harnessed more efficiently. An average 1 megawatt (MW) electrolyzer operating for one hour, producing 30 kg H_2, generates around 0.2 megawatt-hours (MWh) of waste heat, which could be better utilized for other applications.

2) Drinking water dependency: The reliance on vast quantities of drinking water as a feedstock for electrolysis poses a dual challenge. First, it exacerbates competition for drinking water resources in regions already facing water scarcity, putting additional strain on these precious supplies. Second, it hinders the scalability of hydrogen production, as an expanded operation would significantly escalate the demand for drinking water, potentially leading to resource shortages and conflicts.
    - Quantitatively: A single 1 MW electrolyzer, operating continuously for one year (8760 h/y), will consume at least over 2365 cubic meters (m^3) of drinking water (based on a minimum water consumption rate for electrolysis of about 9 kg H_2O/kg H_2, which may be expressed as 0.27 m^3/MWh). This demand could lead to competition for drinking water in regions with limited freshwater resources. The projected increase in hydrogen production capacity, such as the Netherlands' target of 8 GW, could amplify this water demand, potentially leading to water scarcity in certain areas.

3) Environmental implications: Conventional hydrogen production methods are associated with adverse environmental consequences. They require substantial energy consumption, often derived from fossil fuels, resulting in increased greenhouse gas emissions. Additionally, some methods involve the use of chemicals, such as antiscalants in reverse osmosis processes, which can have detrimental effects on the environment and aquatic ecosystems.
    - Quantitatively: The electricity consumption for conventional hydrogen production methods results in significant carbon emissions. Producing 1 kg of hydrogen through traditional methods emits approximately 9-12 kilograms of carbon dioxide (CO_2). In addition, the use of chemicals, such as antiscalants in reverse osmosis, can lead to the discharge of chemical waste. It's estimated that for every 1 m^3 of desalinated water, about 1-2 kilograms of antiscalants are used for RO, contributing to environmental concerns.

4) Resource underutilization: Traditional approaches focus solely on hydrogen production without capitalizing on the wealth of resources available in seawater. Valuable minerals and brines from seawater remain largely untapped, representing a missed opportunity for economic growth and resource diversification.
   - Quantitatively: Seawater contains a wealth of valuable minerals, with an estimated 3.5% of the world's dissolved salts. The underutilization of these resources represents an economic loss. The annual global production of salt (primarily NaCl) from seawater for various industries exceeds 300 million tons, showcasing the untapped potential.

5) Inefficient freshwater production: In cases where reverse osmosis is used to desalinate seawater for drinking water production, the process can be inefficient, consuming excessive electricity and producing a concentrated brine waste stream that poses disposal challenges.
   - Quantitatively: In a reverse osmosis desalination process, the energy consumption can vary but is typically around 3-4 kilowatt-hours (kWh) per cubic meter of freshwater produced. This translates to a significant electricity demand for freshwater generation. The concentrated brine waste stream produced during reverse osmosis processes can be as much as 50% of the initial seawater volume, highlighting the inefficiencies in freshwater production.

In light of these critical issues, this position paper advocates for the adoption of the Nexus Approach, which integrates various technologies to address these challenges comprehensively and promote sustainability, resource utilization, and waste heat management in hydrogen production from seawater. The problem statement underscores the urgency of reevaluating and innovating hydrogen production methods to align with global sustainability goals and the transition to cleaner energy sources.

3 Our Proposal: The Nexus Approach

As an alternative route experts of Wageningen Food & Biobased research (WFBR) advise to establish an integrated system using the SeaHydrogen concept. With this approach, waste heat of the electrolyzers will be utilized to produce pure water and electricity, and to gain valuable minerals from seawater. Calculations prove that more pure water can be produced than is needed for the hydrogen production, so reducing fresh water shortages instead of inducing them. As an additional advantage of using the residual heat, less cooling of the electrolyzer is needed, limiting additional use of water.

Hydrogen production from seawater demands a fresh perspective, one that converges innovation, sustainability, and resource optimization. The Nexus Approach is our answer to the challenges posed by conventional methods, promising a transformative solution that reshapes the landscape of hydrogen production. In this chapter, we introduce the Nexus Approach, its key components, and how it effectively addresses the issues outlined in the problem statement.

3.1 Introduction to the Nexus Approach

The Nexus Approach is not merely a concept but a paradigm shift in hydrogen production. At its core, it combines the strengths of various technologies to create a holistic solution. We will delve into the fundamental principles and components of the Nexus Approach, illustrating how it aligns with the goals of sustainability and efficiency. This circular approach is visualised in Figure 3.

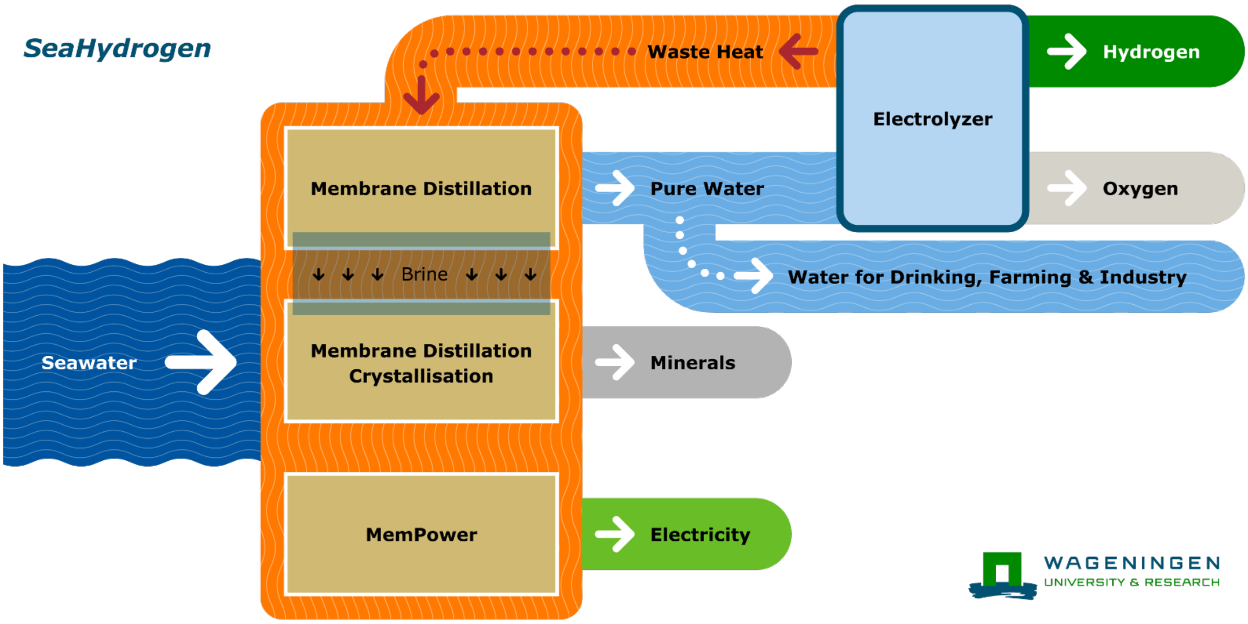


Figure 3 The proposed SeaHydrogen Nexus approach for hydrogen production from seawater.

In such a system the elements of hydrogen production are integrated with its surroundings, regarding the need and production of water (1), the use of waste heat (for 1, 2 and 3), the chance of valorizing compounds out of seawater brine (2) and the option to produce electricity (3) with water technology. The concept is based on 3 succesive generations of Membrane Distillation technologies: (conventional) Membrane Distillation, Membrane Distillation Crystallizaiton, and MemPower.

1) By using seawater and waste heat (1.6 GW, assuming an efficiency of 80% of the 8 GW electrolyser capacity) of the electrolyzer, based on rough calculations 20 till 35 million m^3 per year can be produced with Membrane Distillation (MD). MD is a technology which is not on the market on a large scale yet, but

already a long time proven technology. Its business case strongly depends the price of waste heat. In case of hydrogen production in an electrolyser, this business case is promising (ref). Producing pure water with RO would cost electricity, with MD we use the waste heat and produce demineralised water 'for free'.

2) By using brine (i.e. the concentrate of seawater) and waste heat the brine flow obtained in sub 1) can be further concentrated. With a new process, based on a patented technology, WUR will start research in 2024 to crystallize salts separately, so they can be valorized for different purposes.
3) In case less water is needed (e.g. in the winter period), more focus on another configuration, the Mempower electricity production. Based on a patent, WUR can develop a process where the heat can be converted to pressure and finally electricity in the most efficient way.

This business concept could be helpful in a lot of areas, national as well as international. In the next section each of the membrane distillation technologies will be described in more detail.

3.2 Components of the Nexus Approach

3.2.1 Membrane distillation for water production from seawater

One of the cornerstone technologies in the Nexus Approach is membrane distillation (MD) for water production from seawater. MD offers a unique solution to produce ultrapure water from seawater, which can serve as a feedstock for the electrolyzer, reducing dependence on drinking water resources. This component forms the foundation of the Nexus Approach by providing the essential raw material for hydrogen production.

Recently, it has been identified (ref1, ref2) that the production of hydrogen from seawater using a combination of membrane distillation and an electrolyser may be a breakthrough for commercial and large scale implementation of MD.

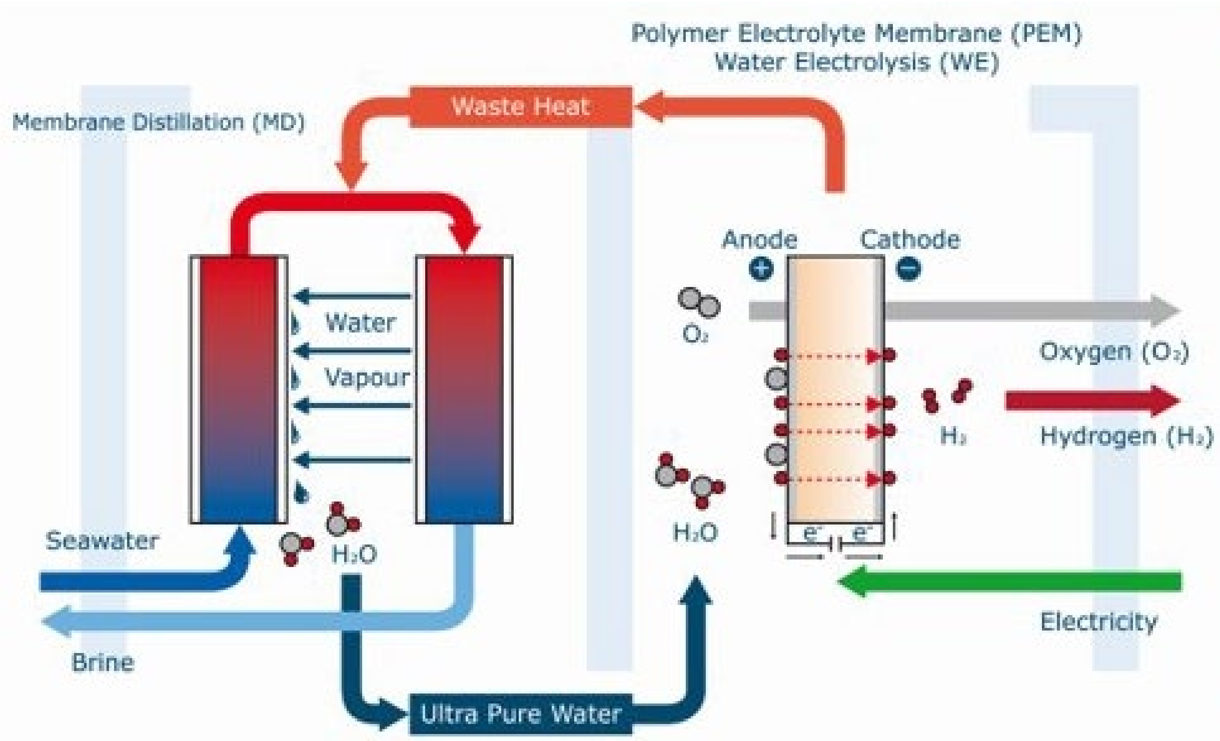


Figure 4 ***Membrane Distillation: the proposed SeaHydrogen Nexus approach for production of demineralised water from seawater utilizing the waste heat of the (Proton Exchange Membrane – Water Electrolyzer (PEMWE) hydrogen electrolyzer (ref). The orange box in Figure 5 refers to the positioning of this technology in the Nexus approach.***

An integrated MD-PEMWE system has been developed and realized for the proof of concept of "Seawater to Hydrogen", see Figure 4. This is the first ingredient of het Nexus approach as also is visualised in Figure 5. The membrane distillation as applied for this seawater desalination case is referred to as MD1.

At a rated stack power of 50 kW, the integrated system produced about 1 kg of hydrogen per hour, while producing nearly three times as much ultrapure water (UPW) as required for the PEMWE electrolyzer. The system has been successfully demonstrated "in the field" at a site (Texel, The Netherlands) with full exposure to a harsh maritime climate over a period of approximately 1,000 hours in the months of October and November of 2021 (ref).

3.2.2 Membrane distillation for water production and brine concentration from seawater brines

The Nexus Approach extends the utility of MD to not only produce fresh water but also concentrate brines generated from seawater desalination. This dual capability further enhances resource utilization and reduces waste, as concentrated brines can serve as cooling agents for the electrolyzer or be processed for valuable minerals.

The proposed process is visually represented in both Figure 5 and Figure 6, showcasing the operational range of various Nexus-relevant technologies based on the concentration factor of seawater as the intake source. The MD process is employed to dehydrate the seawater brine (referred to as MD2), aiming to attain a nearly saturated product (here: NaCl) solution. When coupled with the MD process for seawater (MD1), this combination efficiently removes approximately 90% of the water content from seawater.

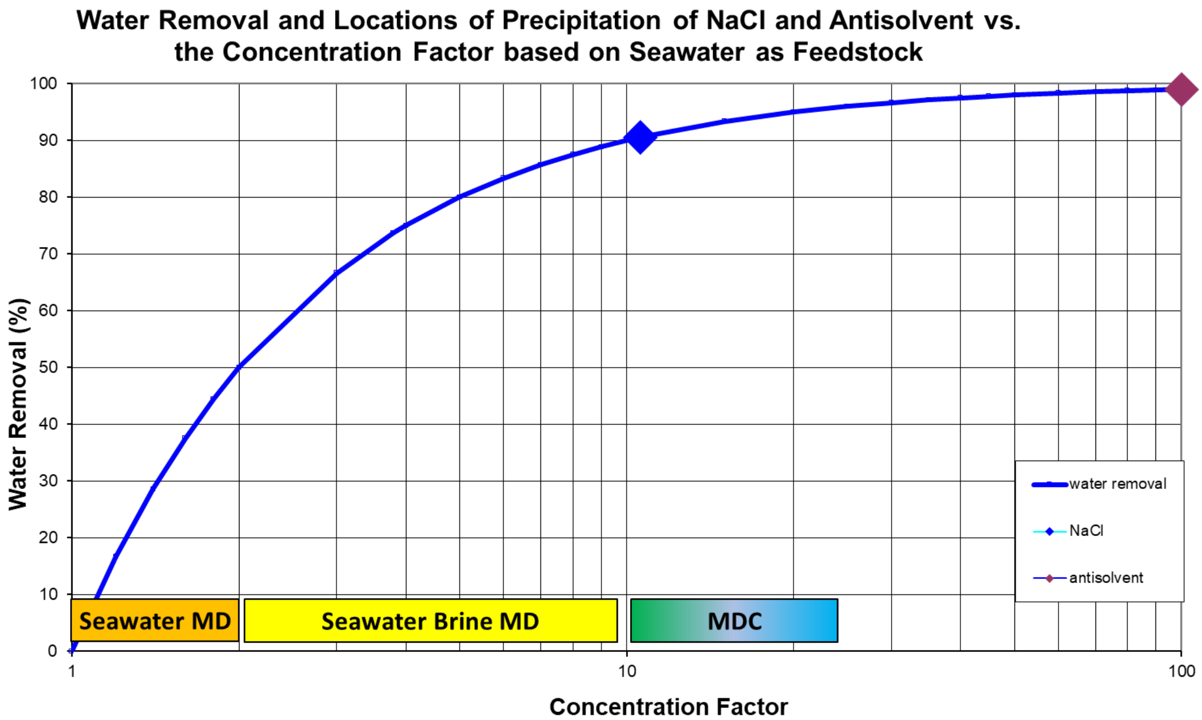


Figure 5 ***Membrane Distillation: the proposed SeaHydrogen Nexus approach for production of demineralised water from seawater (MD1, orange), and its brine (MD2, yellow) until the precipitation limit of NaCl from the waste heat of the hydrogen electrolyzer. Water removal and locations of precipitation of NaCl and antisolvent (here taken as $MgCl_2$) as function of the concentration factor for seawater are also shown (as discussed in section 3.2.3). The operation windows of seawater MD (discussed in section 3.2.1), Membrane Distillation (MD) for brine treatment (this section) and Membrane Distillation Crystallization (MDC, see section 3.2.3) are indicated.***

3.2.3 Membrane distillation crystallisation for minerals recovery from seawater brines

Seawater is a treasure trove of valuable minerals, and the Nexus Approach explores the potential of membrane distillation crystallization (MDC). By harnessing this technology, we can recover minerals from seawater brines, offering economic opportunities and reducing waste in the process. This technology, patented by WUR (EP 2671845 A1), offers the advantage of executing antisolvent crystallization to lower the solubility and the absolute load of the original salt for the next MD step.

In the MDC process an antisolvent (such as $MgCl_2$) is introduced to induce oversaturation in the brine. This triggers the precipitation of a significant portion of NaCl as solid crystals within the crystallizer. The resulting mother liquid retains at saturation levels of NaCl, but at strongly reduced concentrations. This lowered NaCl solubility is attributed to the salting-out effect caused by the antisolvent. This liquid, which is unsaturated in antisolvent and saturated in NaCl, is dewatered in a third MD process (MD3) to regenerate and reuse the antisolvent. The effect of fouling and precipitation of NaCl in this final MD process is relatively low due to the low NaCl-solubility. Furthermore, the absolute quantities of NaCl (measured in kilograms) are constrained due to the substantial removal achieved in the crystallizer phase.

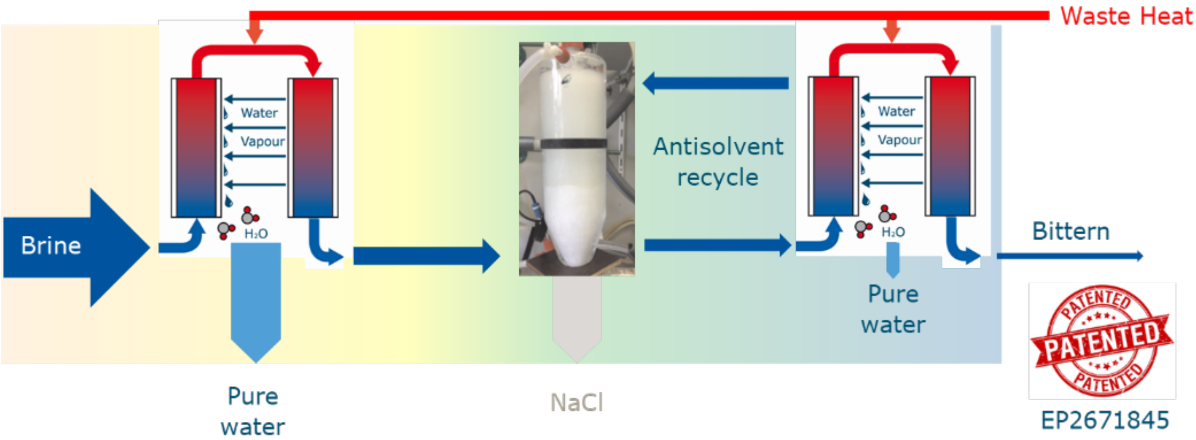


Figure 6 ***Membrane Distillation Crystallisation: the proposed SeaHydrogen Nexus approach for production of minerals and demineralised water from the waste heat of the hydrogen electrolyzer. Principle of product recovery (in this case NaCl) using MDC technology. The width of the arrows schematically illustrates the size of the water stream. The green/blue box in Figure 5 refers to the positioning of this technology. The left hand side of this figure refers to MD2 for brine treatment as discussed in section 3.2.2.***

The proposed steps in the sections 3.2.1 - 3.2.3 have some additional advantages:

- The possibility to use waste heat from the hydrogen electrolyzer for all three MD steps (MD1, MD2, and MD3)
- Corrosion-resistant polymer materials can be used for all three MD steps, avoiding expensive high-quality metals as needed in conventional processing
- High quality water is produced for all three MD steps, limiting emissions of brines, and allowing Minimum Liquid Discharge (MLD) (towards Zero Liquid Discharge, ZLD)
- Solid salt(s) can be recovered and valorized to allow further reuse of scarce materials

3.2.4 MemPower for electricity production from waste heat

Waste heat is a valuable resource often overlooked in traditional hydrogen production. The Nexus Approach also introduces the MemPower technology, a technology designed to convert excess waste heat into electricity. This not only enhances energy efficiency but also offers an additional revenue stream and resource optimization.

Identifying a means of converting thermal energy from a source at temperature below 100 °C, as is the case for hydrogen electorlyzer, has proven difficult. Thermoelectric devices are one of the better known technologies in this regard (ref).

WUR has developed the patented and awarded MemPower® technology to simultaneously produce power (electricity) and high quality water (e.g. drinking water) from an aqueous feedstock (e.g. seawater or its brine) using low grade heat (solar heat, waste heat, etc.). This membrane distillation process producing a pressurised distillate is schematically visualised in Figure 7.

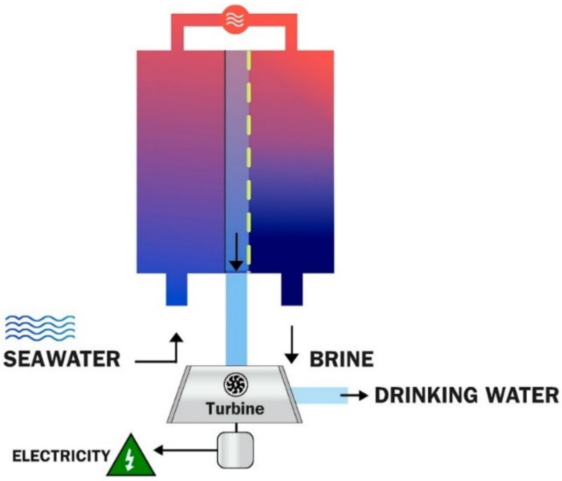


***Figure 7** Application of (open loupe) MemPower® for production of drinking water and electricity during desalination of seawater with low grade heat (waste/solar heat, etc.).*

By mixing up the drinking water and brine (from which additional electricity can produced using Reverse Electrodialysis RED or in Pressure Retarded Osmosis PRO) and recirculating it towards the membrane module, a Thermo-Osmotic Energy Convertor (TOEC) can be made using this MemPower® technology. This is visualized in Figure 8. In this system no water is produced but any aqueous feedstock can be used as working fluid (which recirculates, and is not consumed) in the TOEC.

With this closed-loop MemPower® Generator a highly efficient conversion of waste heat ((upto 60% of the Carnot efficience, ref)) of the hydrogen electrolyzer into electrical energy can be realised.

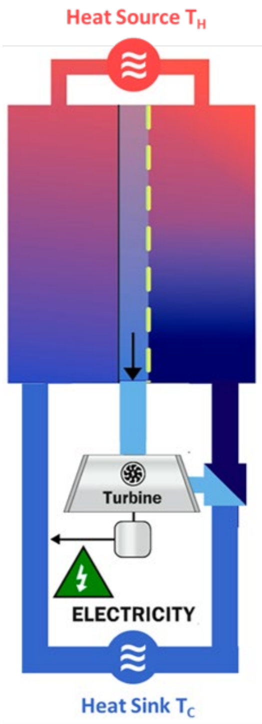


Figure 8 ***Closed-loup MemPower: the proposed SeaHydrogen Nexus approach for production of power (electricity) from waste heat of the hydrogen electrolyzer. This is the full-scale power generation variant of MemPower (without desalination) utilizing a vapour-gap membrane module a heat exchanger and a cooler. The system operates with a heat source (hydrogen electrolyser) at hot temperature T_H, and a heat sink at cold temperature T_C (seawater).***

4 Argumentation

In this section, we will present a sequence of key arguments that underpin the merits of the Nexus Approach for hydrogen production from seawater. These arguments encapsulate the core tenets of our position and provide a structured rationale for its adoption.

4.1 Sequential sections presenting the main arguments

4.1.1 Utilization of waste heat

The *SeaHydrogen* Nexus approach maximizes the utilization of waste heat generated during hydrogen electrolysis. This argument is grounded in the potential to enhance overall system efficiency by repurposing waste heat for various applications, such as distillate production from seawater and electricity generation.

4.1.2 Reduced drinking water dependence

By employing membrane distillation (MD) configurations, the *SeaHydrogen* Nexus approach aims to produce demineralized water from seawater, reducing dependence on traditional drinking water sources. The argument emphasizes the capacity to meet both hydrogen production needs and contribute to fresh water resources.

4.1.3 Resource optimization

SeaHydrogen's approach optimizes resource utilization by efficiently converting waste heat into valuable products. The argument emphasizes the ability to produce demineralized water, nearly NaCl-saturated seawater brine, solid NaCl and potentially also other salts, and electricity concurrently, contributing to resource diversity and sustainability.

4.1.4 Environmental benefits

The environmental benefits of the *SeaHydrogen* Nexus approach are highlighted through reduced dependence on traditional desalination methods, lower energy consumption, and potential solid salt production. This argument underscores the approach's alignment with sustainability goals and reduced ecological impact.

4.1.5 Economic opportunities

SeaHydrogen's approach opens economic opportunities by generating multiple valuable products. The argument emphasizes the potential for revenue generation through demineralized water, salt production, and electricity sales, making the hydrogen production process economically viable and sustainable.

4.1.6 Scalability and alignment with national goals

The scalability of the *SeaHydrogen* Nexus approach is a key argument, supporting the scalability of the hydrogen production process to achieve national energy and environmental objectives. This section emphasizes the alignment with national goals for increased hydrogen production, resource efficiency, and sustainability.

4.2 Supporting evidence for each argument

Based on the 2030 target of 8 GW hydrogen electrolyzer capacity several limiting use cases can be calculated using the *SeaHydrogen* Nexus approach, assuming full utilization of the generated waste heat, and comparing them with the current benchmark (Case 0: hydrogen from RO-seawater).

The total production capacity of an installed electrolyser power of 8 GW will be 174 ton/h hydrogen and 1387 ton/h oxygen assuming an average electrolyser efficiency of 80% (i.e. 20% production of heat). For each kg of hydrogen 9.6 kg of water is needed under ideal circumstances. When assuming a small excess of water of 5%, the total water consumption of the electrolyser is 1744 m^3/h.

The waste heat produced is about 1.6 GW with a typical temperature of 80 °C. To obtain insight in the potential of the produced waste heat a set of limiting cases (Case 1, 2 and 3) and a set of hybrid cases (Case 4 and 5) are defined and compared to the benchmark (Case 0).

These (limiting) cases and its main characteristis are:

- Case 1: Water
  - Goal: maximal utilisation of waste heat for distillate production from seawater
  - How: once through MD1 configuration for water production at < 20% recovery (no marine impact)
  - Result: production of both water for the electrolyser as well as excess water for other purposes
- Case 2: Water & Salt
  - Goal: maximal utilisation of waste heat for both distillate production from seawater and salt production
  - How: recyle MD(C) configuration with membrane distillation of seawater (MD1) and seawater brine (MD2) for water production at > 90% recovery, including solid salt production and recovery of the used antisolvent (MDC)
  - Result: production of both water for electrolyser as well as excess water for other purposes and additionaly production of salt (no brine discharge)
- Case 3: Electricity
  - Goal: maximal electricity production utilising all waste heat from the hydrogen electrolyser with closed-loup MemPower
  - How: water production for the electrolyser with seawater RO
  - Result: electricity production

In addition various hybrid cases can be defined. Two typical examples are:

- Case 4: Water & Electricity
  - Goal: utilising part of the waste heat for minimal water production from seawater to feed the electrolyser
  - How: once through MD1 configuration for water production at < 20% recovery (no marine impact). Residual waste heat is utilised for closed-loup MemPower
  - Result: production of water for the electrolyser (no excess water for other purposes) and electricity production
- Case 5: Water, Electricity & Salt
  - Goal: utilisating part of the waste heat for both distillate production from seawater and salt production
  - How: recyle MD(C) configuration with MD of seawater (MD1) and seawater brine (MD2) for water production at > 90% recovery, including solid salt production and recovery of the antisolvent (MDC)
  - Result: production of water for the electrolyser (no excess water for other purposes), additionally production of salt (no brine discharge) and electricity.

These cases are compared with the current situation as a reference:

- Case 0: Electrolyser + Seawater RO (benchmark using RO for water production)

The results of the analysis of the 5 cases and the benchmark case are summarized in Table 1 to show their potential. It must be noted that in practice a wide range of combinations of several cases can be made aiming at full utilization of the waste heat of the hydrogen electrolyzer depending on the target objectives and desired products (fresh water, salt and electricity).

		Case:	case 0	case 1	case 2	case 3	case 4	case 5
		purpose is production of:	Benchmark	water	salt + water	energy	water + energy	water + energy + salt
Electrolyzer	Installed power	[MWe]	8000	8000	8000	8000	8000	8000
	Waste heat produced	[MWth]	1600	1600	1600	1600	1600	1600
	RO energy input	[MWe]	9	0	0	9	0	0
MD 1	Water for H2	[m3/h]		1744	1744	0	1744	1744
	Excess Water	[m3/h]		5501	4008	0	0	0
	Seawater intake	[m3/h]		43472	6391	0	10464	1938
	Brine discharge	[m3/h]		36226	0	0	8720	0
	TDS brine	[g/l]		0	0	0	0	0
	Energy (waste heat) used for MD 1	[MWth]		1600	235	0	385	71
MD 2 + MDC	Salt Produced	[ton/h]		0	224	0	0	68
	Water Produced	[m3/h]		0	415	0	0	126
	Energy (waste heat) used for MD 2 + MDC	[MWth]		0	1365	0	0	414
MemPower	Energy Produced	[Mwe]				136	103	95
	Energy (waste heat) used for Mempower	[MWth]				1600	1215	1115
Summary	Total H2 production	[ton/h]	174	174	174	174	174	174
	Total O2 production	[ton/h]	1387	1387	1387	1387	1387	1387
	Total electricity use	[MWe]	8009	8000	8000	7873	7897	7905
		[kWh/kg H2]	45.9	45.9	45.9	45.1	45.3	45.3
	H2 produced with 8 GW (corrected)	[ton/h]	174.2	174.4	174.4	177.2	176.7	176.5
	Extra H2 produced compared to benchmark	[%]	0.0	0.1	0.1	1.7	1.4	1.3
	Total Waste heat use	[MWth]	0	1600	1600	1600	1600	1600
	Recidual waste heat at ~ 80°C (cooling need)	[MWth]	1600	0	0	0	0	0
	total water production	[m3/h]	1744	7245	6168	1744	1744	1870
	Excess water produced	[m3/h]	0	5501	4424	0	0	126
	Salt produced	[ton/h]	0	0	224	0	0	68
	Seawater intake	[m3/h]	3488	43472	6391	3488	10464	1938
	Brine discharge	[m3/h]	1744	36226	0	1744	8720	0
	TDS Brine	[g/l]	70	42	0	70	42	0
	additional cooling at ~30 °C (in case of MDC)	[MWth]			1600			1600

Table 1 SeaHydrogen results for several limiting cases (case 1 – 3) and hybrid cases (case 4-5) relative to the current situation (case 0: hydrogen from RO-seawater).

The produced waste heat of 1.6 GW can be exploited for production of:

- 7245 m^3/h of demineralized water from seawater (case 1)
- 6168 m^3/h of demineralized water from seawater and 224 ton/h of solid salt (case 2)
- 136 MW electricity (case 3)
- 1744 m^3/h of demineralized water from seawater and 103 MW electricity (case 4)
- 1744 m^3/h of demineralized water from seawater, 68 ton/h of solid salt and 95 MW electricity (case 5)

Note: The percentages and capacities mentioned above are calculated based on the specified cases and provide insights into the potential impact of the *SeaHydrogen* Nexus approach.

- In case 1 all waste heat is used to produce 7245 m^3/h of demineralised water.
  - 1744 m^3/h, 24% of the produced water can be used as feedstock for the hydrogen electrolyser.
  - 5501 m^3/h, 76% for other purposes such as drinking water. The latter capacity corresponds with ~4% of the drinking water use in The Netherlands in 2021 (ref).
- In case 2 all waste heat is used to produce 6168 m^3/h demineralised water and 224 ton/h of solid salt.
  - 1744 m^3/h, 28% of the produced water can be used as feedstock for the hydrogen electrolyser.
  - 4424 m^3/h, 72% for other purposes such as drinking water. The latter capacity corresponds with ~3% of the current drinking water use in The Netherlands (ref).
  - 224 ton/h of produced salt corresponds with ~30% of the annual produced amount by rock salt mining in The Netherlands (ref).
- In case 3 all waste heat is used to produce 136 MW electricity.
  - 136 MW corresponds with ~2% of the electricity consumption of the electrolyser.
  - It is needed to use 9 MW for RO (assuming 5 kWh/m^3 water) to produce the 1744 m^3/h demineralized water as feedwater for the electrolyzer.
  - The residual 127 MW electricity can be used to decrease the net electricity consumption to 7873 MW or it can be used to produce an additional amount of 3.0 ton/h of hydrogen (1.7% additional production).
- In case 4 part of the waste heat is used to produce 1744 m^3/h demineralized water as feedwater for the electrolyser and the rest is used to produce 103 MW electricity.
  - By production of 1744 m^3/h demineralized water, no additional RO is needed.

    - The 103 MW of electricity can be used to decrease the net electricity consumption to 7897 MW or it can be used to produce an additional amount of 2.5 ton/h of hydrogen (1.4% additional production).
- In case 5 part of the waste heat is used for the production of 1744 m^3/h demineralised water and 68 ton/h of solid salt and the rest is used to produce 95 MW electricity.
    - By production of 1744 m^3/h demineralized water, no additional RO is needed.
    - 68 ton/h of produced salt corresponds with ~9% of the annual produced amount by rock salt mining in The Netherlands (ref).
    - The 95 MW of electricity can be used to decrease the net electricity consumption to 7905 MW or it can be used to produce an additional amount of 2.3 ton/h of hydrogen (1.3% additional production).
- In case 0 the benchmark is shown.
    - It is needed to use 9 MW for RO (assuming 5 kWh/m^3 water) to produce the 1744 m^3/h demineralized water as feedwater for the electrolyzer.
    - The net electricity consumption is 8009 MW.

4.3 Counterarguments and refutations

While the *SeaHydrogen* Nexus approach presents a compelling case for hydrogen production from seawater, it is essential to acknowledge potential counterarguments and address them with appropriate refutations.

4.3.1 Concerns about energy efficiency

Counterargument: Critics may argue that the additional processes, such as membrane distillation and solid salt production, could potentially compromise the overall energy efficiency of the system.

Refutation: The *SeaHydrogen* Nexus approach has been designed to optimize energy efficiency by strategically utilizing waste heat. Detailed analyses and simulations demonstrate that the benefits derived from additional processes outweigh the potential energy losses, resulting in a net gain in efficiency.

4.3.2 Environmental impact of salt production

Counterargument: The production of solid salt may raise concerns about the environmental impact, particularly in terms of brine disposal and resource extraction.

Refutation: The *SeaHydrogen* Nexus approach considers the environmental impact comprehensively. By incorporating recycling configurations for membrane distillation and maximizing resource utilization, the approach aims to minimize environmental consequences associated with salt production and brine disposal.

4.3.3 Economic viability and cost considerations

Counterargument: Skeptics may question the economic viability of the *SeaHydrogen* Nexus approach, citing potential high capital and operational costs associated with implementing advanced processes.

Refutation: The economic analysis presented in Section 4.1.5 highlights the potential for revenue generation through the production of demineralized water, solid salt, and electricity. The approach strategically balances costs and benefits, ensuring long-term economic viability.

4.3.4 Practical implementation challenges

Counterargument: Critics might express concerns about the practical challenges associated with implementing the *SeaHydrogen* Nexus approach on a large scale, including technological barriers and infrastructure requirements.

Refutation: The scalability argument (Section 4.1.6) addresses the practicality of the approach, emphasizing its alignment with national goals. Ongoing advancements in technology and infrastructure development support the feasibility of large-scale implementation over time.

4.3.5 Competition with established desalination methods

Counterargument: Traditional desalination methods, such as reverse osmosis, are well-established and widely adopted. Critics may question the necessity of adopting a novel approach like *SeaHydrogen* Nexus.

Refutation: *SeaHydrogen* Nexus doesn't seek to replace established desalination methods but rather complements them. By maximizing waste heat utilization, it enhances the efficiency of hydrogen production while contributing to other valuable outputs, presenting a unique and advantageous proposition.

5 Substantiating the Position

5.1 Details on why our position is justified

The justification for the *SeaHydrogen* Nexus approach is grounded in a thorough analysis of its multiple advantages and innovative features:

Optimal Waste Heat Utilization: The core of the *SeaHydrogen* Nexus approach lies in the efficient utilization of waste heat generated during hydrogen production. This not only enhances overall system efficiency but also allows for the simultaneous production of valuable byproducts like demineralized water, nearly NaCl-saturated seawater brine, solid NaCl and potentially other salts, and electricity.

Resource Optimization: The approach optimizes the use of resources by strategically incorporating membrane distillation configurations for water production and salt recovery. This multi-product strategy not only maximizes the value extracted from the process but also contributes to resource diversity and sustainability.

Environmental Benefits: By reducing dependence on traditional desalination methods and lowering energy consumption, the *SeaHydrogen* Nexus approach aligns with environmental sustainability goals. The consideration of solid salt production and recycling configurations further showcases a commitment to minimizing environmental impact.

Economic Viability: The economic analysis presented in Section 4.1.5 demonstrates the potential for revenue generation through various products. The approach seeks a balance between costs and benefits, ensuring its long-term economic viability and contributing to economic opportunities in the hydrogen production sector.

Scalability and Alignment with National Goals: The scalability argument (Section 4.1.6) establishes the *SeaHydrogen* Nexus approach as aligning with national goals for increased hydrogen production, resource efficiency, and sustainability. This adaptability to national objectives further justifies its position in the broader context of energy and environmental policies.

5.2 References to relevant laws, regulations, research, or policies

The *SeaHydrogen* Nexus approach is substantiated by referencing relevant laws, regulations, research findings, and policies that support its alignment with global and national energy and environmental objectives. Some key references include:

International Energy Policies: Drawing on global initiatives and agreements related to clean energy and green hydrogen production, such as agreements under the Paris Agreement or international frameworks promoting sustainable energy development.

National Hydrogen Strategies: Citing and aligning with specific national hydrogen strategies and policies, showcasing how the *SeaHydrogen* Nexus approach contributes to achieving outlined goals.

Environmental Regulations: Referring to laws and regulations related to environmental sustainability and waste heat utilization to underline the approach's compliance with established standards. This also holds for integrated concentrate/brine management by valorisation.

Energy Efficiency Guidelines: Citing guidelines and research findings related to energy efficiency in hydrogen production and waste heat utilization, demonstrating how the *SeaHydrogen* Nexus approach adheres to and exceeds industry standards.

Water Management Policies: Establishing the approach's alignment with water management policies by referencing regulations governing desalination practices and water usage as well as showcasing new adaptation measures for climate change by supplying drinking water from sustainable sources. Contributing to promoting to safeguarding health issues such as water borne diseases.

By linking the *SeaHydrogen* Nexus approach to established laws, regulations, and research findings, the justification for its position is strengthened, providing a robust foundation for its adoption in the field of hydrogen production from seawater.

6 Call to Action

Our proposed Nexus Approach for hydrogen production from seawater is more than an idea; it's a blueprint for a sustainable and transformative future. To bring this vision to life, we need a concerted effort from various stakeholders and a clear roadmap for action, see Figure 9.

1. From Catalyst to Starting Point to Comprehensive Concept

The journey towards the realization of the Nexus Approach begins with catalysts who believe in its potential. We call upon those who can be catalysts to spark discussions, raise awareness, and initiate the transition. From these catalysts, we move to a starting point, a dedicated platform where experts, innovators, and decision-makers converge to explore the Nexus Approach's possibilities. Ultimately, our goal is the establishment of a comprehensive concept that paves the way for large-scale implementation.

2. From Implementation to Platform to Execution

Execution is the linchpin of any transformative idea. We urge governments, organizations, and individuals to move from discussions to real-world implementation. We propose the creation of a dedicated platform that facilitates collaboration, knowledge sharing, and resource allocation. This platform will serve as the driving force behind the execution of the Nexus Approach, turning a visionary concept into a practical reality.

Essential requirements to build the platform are:

a) Leadership in Building Integral Concept Support
Developing an integral concept necessitates strong leadership in garnering support from diverse stakeholders. We encourage those in influential positions to take the lead in building a robust network of support, ensuring that the Nexus Approach gains traction and buy-in from all sectors.

b) Subsidies for Comprehensive Concepts Instead of Fragmented Endeavors
Rather than pursuing fragmented approaches, we advocate for subsidies and funding opportunities that prioritize comprehensive concepts. This shift will not only accelerate progress but also prevent the dispersion of resources and efforts

c) Engagement with Industry Leaders
The private sector plays a pivotal role in the success of any innovative endeavor. We call for proactive engagement with industry leaders to ensure that the Nexus Approach aligns with their goals, needs, and capabilities. Collaboration with businesses is essential for a seamless transition.

The time for action is now. The Nexus Approach is not a distant vision but an attainable goal, and it hinges on the collective commitment of visionaries, implementers, and partners. Let us embark on this journey, leveraging our combined strength to revolutionize hydrogen production and usher in a more sustainable and efficient era.

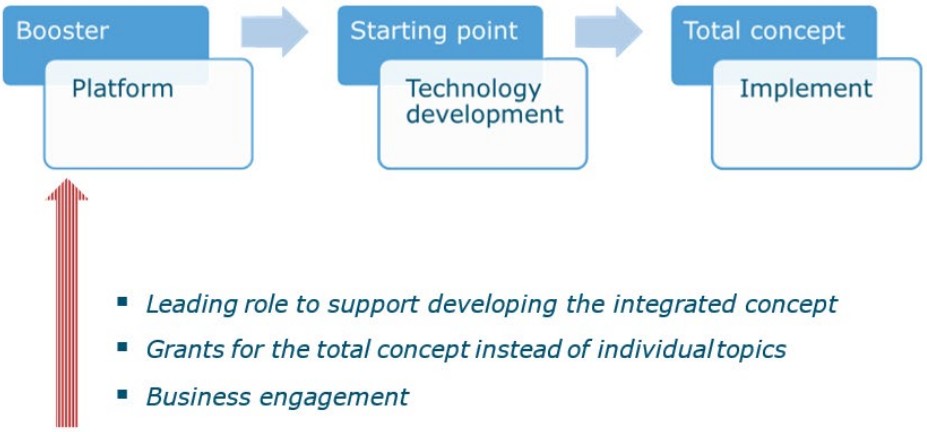


Figure 9 The proposed call to action for implementation of the SeaHydrogen Nexus approach.

7 Conclusions

7.1 Summary of main arguments

7.1.1 Utilization of waste heat

The *SeaHydrogen* Nexus Approach places a strong emphasis on maximizing the utilization of waste heat generated during hydrogen electrolysis. By repurposing this excess thermal energy for membrane distillation and electricity generation, the approach significantly enhances overall system efficiency. This not only addresses the challenge of waste heat underutilization but also contributes to the sustainability and resource efficiency of hydrogen production.

7.1.2 Reduced drinking water dependence

A key aspect of our position is the reduction in dependence on traditional drinking water sources. The use of membrane distillation configurations enables the *SeaHydrogen* Nexus Approach to produce demineralized water directly from seawater. This dual-purpose application not only fulfills the water requirements for hydrogen production but also mitigates competition for drinking water resources, particularly in regions facing water scarcity.

7.1.3 Resource optimization

SeaHydrogen's approach optimizes resource utilization by efficiently converting waste heat into valuable products. The integration of three generations of membrane distillation technologies allows for the simultaneous production of demineralized water, concentrated seawater brine, solid NaCl and other salts, and electricity. This multi-faceted resource optimization contributes to a more sustainable and diversified approach to hydrogen production.

7.1.4 Environmental benefits

The *SeaHydrogen* Nexus Approach offers significant environmental benefits by reducing dependence on traditional desalination methods, lowering energy consumption, and potentially producing solid salts. This environmentally conscious approach aligns with global sustainability goals, offering a cleaner and more ecologically responsible solution for hydrogen production from seawater.

7.1.5 Economic opportunities

By generating multiple valuable products, including demineralized water, salt, and electricity, the *SeaHydrogen* Nexus Approach creates economic opportunities. This approach is economically viable and sustainable, providing potential revenue streams and diversifying income sources. The integration of economic considerations into the hydrogen production process enhances its overall feasibility.

7.1.6 Scalability and alignment with national goals

The scalability of the *SeaHydrogen* Nexus Approach positions it as a key player in achieving national energy and environmental objectives. As nations, including the Netherlands, set ambitious targets for hydrogen production, this integrated concept offers a practical means to scale up production while promoting resource efficiency and sustainability. The approach aligns with the broader goals of transitioning to a hydrogen-based economy.

7.2 Recommendations

In essence, our position advocates for a paradigm shift in hydrogen production from seawater. The *SeaHydrogen* Nexus Approach, rooted in comprehensive resource utilization, waste heat management, and sustainability, provides a compelling solution to the challenges faced by traditional methods. By adopting this integrated concept, we believe that nations can contribute significantly to the global transition to cleaner energy sources, meet ambitious hydrogen production targets, and create a more resilient and sustainable future.

7.2.1 Adoption of the Nexus approach

In conclusion, we strongly recommend the adoption of the *SeaHydrogen* Nexus Approach as a transformative and sustainable solution for hydrogen production from seawater. This integrated concept addresses the shortcomings of traditional methods, promotes resource utilization, and fosters a more efficient, environmentally responsible, and resource-conscious hydrogen production landscape.

7.2.2 Further research and development

To enhance the practical implementation of the *SeaHydrogen* Nexus Approach, we advocate for further research and development. This includes exploring the business case for membrane distillation technologies, refining the MemPower technology for optimal electricity production, and conducting comprehensive studies on the economic and environmental implications of scaling up the proposed approach.

To explore the potential of nature to improve the quality of life

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