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E. Røstbø
(signatur forfatter)

K. Torgersen
(signatur forfatter)

Forfatter(e): Erlend Velken Røstbø og Kjetil Johan Torgersen

Fagansvarlig: Mohammad Mansouri

Veileder(e): Mohammad Mansouri og Peter Breuhaus

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Course coordinator: Mohammad Mansouri

Supervisor(s): Mohammad Mansouri and Peter Breuhaus

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Evaluation of synergetic effects of integrated recirculating aquaculture systems with water electrolysis units

Department of Mechanical and Structural Engineering and Materials Science

Authors: Erlend Velken Røstbø og Kjetil Johan Torgersen

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Preface

This master thesis was written in spring 2022 at the University of Stavanger in the department of mechanical and structural engineering and materials science, by two students. The thesis corresponds to 30 credits (ECTS) and is the finishing part of a master of science within mechanical engineering with the specialization focus in renewable energy. The thesis addresses production of hydrogen using electrolyzer units, where utilization of the two sub-products; Oxygen and energy in the form of heat, is of particular interest to be used in synergy with recirculating aquaculture systems (RAS).

We would like to take this opportunity to thank for the good guidance from the main supervisor, Mohammad Mansouri. Throughout the semester, Mohammad has been easily accessible, given us good input and had a motivational commitment, which has been important for our work, in addition to follow-up and good ideas and inputs from Peter Breuhaus, NORCE. A huge thank you to Greenstat ASA and specifically Oda Marie Ellefsen for providing us with this opportunity, and also Viking Aqua AS for giving us invaluable data, information and inputs. We also acknowledge the funding provided by the Future Energy Hub (FEH) project at the University of Stavanger for acquisition of the software tools for simulation studies performed for this work. Last but not least, we greatly appreciate inputs from Torbjørn Ellingsen (Moreld Apply AS), Arild Stapnes Johnsen and Klaudia Teresa Tolstow (both Dalane Energi AS) for information regarding the economical aspects of the thesis.

University of Stavanger, Norway

June 30th 2022

E. Røstbø .... K. Torgersen ....

Erlend Velken Røstbø   Kjetil Johan Torgersen

Abstract

Recirculating aquaculture systems (RAS) are developing rapidly as a pathway towards a more sustainable and efficient aquaculture industry. Such facilities allow for precise control of parameters involved in fish farming, such as oxygenation units for providing oxygen and replenish oxygen saturation levels in the recirculated water. In order to locally supply the oxygen demand to these facilities, water electrolysis technology may be a complementary solution of which oxygen and heat are secondary products, typically unutilized in conventional production units, in addition to the main product which is hydrogen.

To study the synergetic effects of combining RAS facilities for Atlantic salmon and water electrolysis systems, three pre-defined case studies of varying sizes have been established with regards to the technical feasibility, impact on the production cost of hydrogen, as well as sensitivity analyses of relevant economical variables. Simulation of the alkaline water electrolysis process is also carried out through Aspen Plus software, and the varying oxygen demand during the growth of Atlantic salmon is modeled for each case study presented in this report.

The three case studies show considerable economical benefits through scale-up of the combined facilities. A promising hydrogen production cost of 27.74 kr/kg H_2 was achieved for the largest facility (case 3), producing more than 50 tonnes of O_2 per day, where revenues from oxygen sales and district heating are included. A more detailed techno-economic analysis, optimization of the general concept, a study of including alternative energy sources such as wind and solar, as well as further work with the simulated process in Aspen Plus may be recommended for future studies of the established cases in this paper.

Sammendrag

Resirkulerande akvakultursystem (RAS) er i stadig utvikling som eit lovande alternativ for å oppnå ein meir bærekraftig og effektiv akvakulturnæring. RAS-anlegg gjer det mogleg å kontrollere viktige parametre i fiskeoppdrett, som til dømes oksygeneringseiningar for å tilføre oksygen og oppfylle metningsnivå i det resirkulerte vatnet. For å lokalt kunne dekke oksygenbehovet til desse anleggene, kan vatnelektrolyse fungere som ein komplementær løysning der oksygen og varme er sekundære produkt, som typisk ikkje er nytta i konvensjonelle produksjonseiningar, i tillegg til hovedproduktet som er hydrogen.

For å studere dei synergetiske effektane av å kombinere RAS-anlegg for atlantisk laks og vatnelektrolyse, er det etablert tre forhandsdefinerte casestudier av ulike dimensjonar med hensyn til teknisk gjennomførbarhet, innvirkning på produksjonskostnadene for hydrogen, samt sensitivitetsanalyser av relevante økonomiske parametere. Simulering av den alkaliske vatnelektrolyseprosessen er òg utført gjennom Aspen Plus-programvare, og det varierande oksygenbehovet gjennom vekstperioden til atlantisk laks er modellert for kvar case-studie.

Dei tre casestudiene kan konkluderast med at det er store økonomiske fordeler ved oppskalering av dei kombinerte anlegga. Ein lovande hydrogenproduksjonskostnad på 27,74 kr/kg H_2 er oppnådd for det største anlegget (case 3), som produserer i overkant av 50 tonn O_2 per dag, der inntekter fra oksygensal og fjernvarme er inkludert. Ein meir detaljert teknoøkonomisk analyse, optimalisering av det generelle konseptet, studie angåande inkludering av alternative energikjelder som vind- og solkraft, samt vidareutvikling av simuleringa i Aspen Plus er anbefalt som vidare arbeid med dei etablerte casene i dette prosjektet.

Nomenclature

Abbreviations

AEC	Alkaline electrolysis cell
AEMEC	Anion exchange membrane electrolysis cell
BoP	Balance of Plant
C	Carbon
CCS	Carbon capture and storage
Co	Cobalt
CS	Carbon steel
CAPEX	Capital expenditure
CEPCI	Chemical engineering plant cost index
CDMM	Crustaceans, diadromous fish, marine fish and miscellaneous species
DNA	Deoxyribonucleic acid, the hereditary material in almost all organisms
FC	Fuel cell
HTO	Hydrogen to oxygen, hydrogen breakthrough to anode of electrolyzer stack
ICE	Internal combustion engine
KOH	Potassium hydroxide
LCOH	Levelized cost of hydrogen
LH_2	Liquid hydrogen
LMA	Longterm market analysis
LSM	Lanthanum magnate
LO_x	Liquid oxygen
Mo	Molybdenum
Ni	Nickel
NOK	Norwegian kroner
NVE	Norwegian Water Resources and Energy Directorate
OPEX	Operational expenditure
Pd	Palladium
PEMEC	Proton exchange membrane electrolysis cell
PFSA	Perfluorosulfonic acid
PSA	Pressure swing adsorption
Pt	Platinum

Ru	Ruthenium
RAS	Recirculating aquaculture system
SDG	Sustainable development goal
SGR	Specific growth rate
SMR	Steam methane reforming
SOEC	Solid oxides electrolysis cell
SS	Stainless steel
UV	Ultraviolet light
YSZ	Yttria-stabilized zirconia
øre	Norwegian cents, 1 kr contains 100 øre

Symbols

A	kW	Capacity factor
A_{Cell}	m^2	Individual cell area
C	C	Coulomb, the SI derived unit of electric charge
C_A	kr	Local area cost
C_{BM}	$	Bare module cost
C_{EL_t}	kr	Cost of electricity in year t
C_F	dimensionless	Capacity factor
C_{OL}	kr	Cost of operating labour
C_P	$	Purchase cost for compressor at base conditions
C_{stor}	€/Nm^3	Cost of storage
C_t	kr	Fixed and variable operational and maintenance cost in year t
$C_{tot_{stor}}$	€/kr	Total cost of hydrogen and oxygen storage
C_x	$^{\circ}C^x$	Temperature loss constants related to gas purity
dg	days	Number of days interval
d_x	bar	Additional loss constants owing to pressurized operation
e^-		Electron
E_x	bar	Pressure loss constants related to gas purity
exp	2.71828...	Eulers number
F	$96,485C \cdot mol^{-1}$	Faraday constant
F_{BM}	Dimensionless	Bare module factor, considering material type
f_x	%	Faraday efficiency constants
$\Delta_r G$	$kJ \cdot mol^{-1}$	Molar Gibbs energy of water decomposition reaction
$\Delta_r H$	$kJ \cdot mol^{-1}$	Standard molar enthalpy of water decomposition reaction

i	$A \cdot m^{-2}$	Current density
I_t	kr	Investment cost in year t
j	%	Long-term inflation
k	dimensionless	Correction factor
$\dot{m}$	kg/s	Massflow
$m_{H_{2tot}}$	kg	Total production of hydrogen in year t
m_{O_2}	$mg \cdot kg^{-1} \cdot min^{-1}$	Specific oxygen consumption
MR	%	Total mortality rate
m_1	g	Starting body mass
m_2	g	Ending body mass
n	year	Lifetime
N_{cell}	quantity	Number of cells in cell stack
N_{el}	quantity	Number of electrons
N_{hour}	$hours \cdot year^{-1}$	Operating hours per year
N_{np}	quantity	Number of non-particulate processing steps
N_{OL}	quantity	Number of operators per shift
N_S	quantity	Number of processing steps involving handling of particulate-solids
N_w	weeks	Number of weeks interval
$n_{H_2,prod}$	mole	Number of hydrogen moles produced
$n_{H_2,th}$	mole	Theoretical amount of hydrogen moles that should be produced
p	bar	Operating pressure
$\overline{P}$	MW	Average electricity usage at top level
Q_1	quantity	Fish quantity at the start of the week
Q_2	quantity	Fish quantity at the start of the next week
r	%	Interest rate
R	kr/MW	Tariff rate consumption
R_{DH}	kr	Revenues from district heat
R_{O_2}	kr	Revenues from oxygen sales
R_r	%	Real rate of return
r_x	$°C^x$	Ohmic loss constants
s	V	Coefficient for overvoltage on electrodes
S_{Hw}	kJ/kg	Specific heat capacity for water
$\Delta_r S$	$J \cdot K^{-1} \cdot mol^{-1}$	Molar entropy of reaction
T	°C	Operating temperature
T_w	°C	Water temperature
t_x	V	Coefficient for overvoltage on electrodes
u	%	Marginal loss rate

U_{Cell}	V	Real cell potential
U_{Rev}	V	Reversible voltage
U_{Therm}	V	Thermoneutral voltage
$\dot{V}_{H_2}$	Nm^3	Daily production volume of hydrogen
$\dot{V}_{O_2}$	Nm^3	Daily production volume of oxygen
W	g	Body weight
W_F	dimensionless	Working factor
W_{stack}	W	Power input to cell stack
$\hat{\eta}$	V	Overpotential
$\hat{\eta}_{an}$	V	Anode overpotential
$\hat{\eta}_{cat}$	V	Cathode overpotential
$\hat{\eta}_{ohm}$	V	Ohmic overpotential
$\hat{\eta}_{conc}$	V	Concentration overpotential
η_F	%	Faraday efficiency

Important definitions

Currency convert	10.35 (NOK/EUR) as of June 14 2022 9:13 UTC +2 [1]
Currency convert	1.05 (EUR/USD) as of June 14 2022 9:13 UTC +2 [1]
Currency convert	9.90 (NOK/USD) as of June 14 2022 9:13 UTC +2 [1]
Electrolyte	Refers to the Potassium hydroxide (KOH) present as electrolyte in the alkaline electrolyzer stack.
Salmon	By salmon it is referred to Atlantic salmon (Salmo Salar), which is the salmon produced in Norway. This thesis refers to salmon as the general species. Besides, it is referred to as salmon when the weight is higher than 1 kg, as in contrast to smolt and post-smolt.
Smolt	Refers to salmon juveniles that have undergone smoltification and have adapted to life in seawater. This thesis refers to smolt as salmon with a weight between 5 g and 100 g.
Postsmolt	Refers to the first stage after the salmon have undergone smoltification. The size range of postsmolt is not clearly defined, but in this thesis postsmolt is refered to as salmon with a weight of about 100 g to 1 kg.

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Chapter 1

Introduction

As the future prospects of energy and food security in the world are ever-changing, a need for finding new and resilient solutions while maintaining the general development and basis of these industries become apparent. This thesis aims to bring forward a synergy study to dig deeper into combining solutions regarding these aspects, in particular land based aquaculture and electrolytic hydrogen production, which may be deemed important to meet the food and energy demands of the future.

1.1 Background information

According to United Nations (UN), the global population is expected to increase by 835 million people between 2019 and 2030 reaching a total of 8.5 billion, expanding the global food demand (including animal products and particularly fish) [2], [3]. In September 2015, the UN launched the "Agenda 2030" for sustainable development, which was to serve as a blueprint for global peace and prosperity. By adopting the "Agenda 2030", countries demonstrated determination to take bold and transformative steps to shift the world onto a more sustainable and resilient path [4].

Global aquaculture production has seen a large increase in the past two decades, with more than a tripling in production from 34 Mt in 1997 to 112 Mt in 2017. This involves freshwater fish, algae, mollusks, crustaceans, diadromous fish, marine fish, and miscellaneous species [5]. This growth can be seen in Figure 1.1.

Asia is the largest aquaculture producer that accounted for 92% of the live-weight volume of animals and seaweeds in 2017. China alone supplied 58% of the volume, and is thus by far the greatest contributor. Outside of Asia, the largest aquaculture producers are Norway and Chile, both supplying 1-2% of the global production, mainly from Atlantic salmon (Salmo salar) farming [5]. In order to shed light on the contemporary challenges

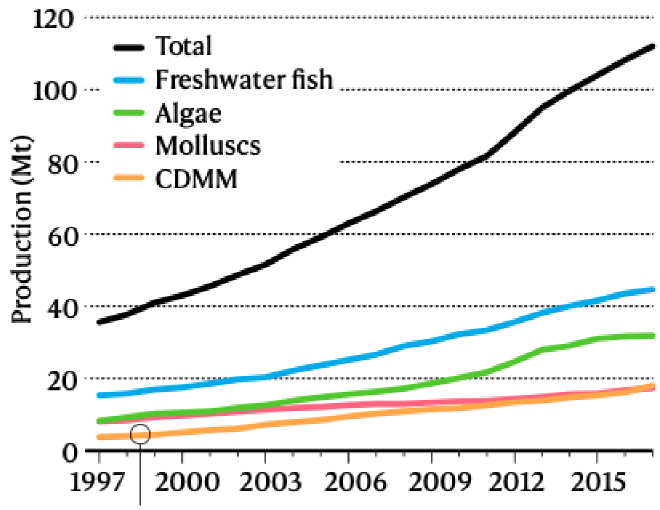


Figure 1.1: Growth of global live-weight aquaculture production, where CDMM includes crustaceans, diadromous fish, marine fish, and miscellaneous species [5]

of the world, the UN has presented 17 sustainable development goals (SDG) as shown in Figure 1.2. The goals represent pathways towards solving many of the challenges we are faced with in the world today and also partly mirrors the importance of the main task of this thesis; to study synergies between the production of pollution-free energy carriers, ie. hydrogen, and recirculating aquaculture systems (RAS) with next to zero impact on marine environments and minimal water consumption.

The task of the project has either a direct or indirect influence on many of the SDG´s. Among those that are directly influenced are goals 2, 6, 7, 9, 12, 13, and 14, where the impact is of such significance that the further development of the concept may contribute to a great degree towards these goals. Also, goals 1, 3, 8, 11, 15 and 17 are being contributed towards in a more indirect manner where certain ring effects may be apparent to provide supportive measures.

When it comes to producing hydrogen gas from electrolysis, the development of new and more efficient technology and incentives issued by both national and international governing bodies are worth mentioning. In 2020, the Norwegian government released a detailed hydrogen strategy plan towards 2030, "Regjeringens hydrogenstrategi" [6], to further bring a call to action with incentives regarding production, further processing, storage and distribution of electrolytic hydrogen in particular. The strategy involves plans for the maritime transportation sector for increased usage of fuels such as hydrogen and ammonia, where all types of vessels and propulsion systems such as fuel cells (FC) or internal combustion engines (ICE) are to be considered.

By combining the production of green hydrogen for the maritime industry and RAS facilities through the utilization of by-products, oxygen and heat, the overall efficiency of the electrolysis process may be greatly increased, which is one of the main challenges

Figure 1.2: The 17 Sustainable Development Goals as presented by the UN [8]

of electrolysis today. For conventional electrolyzer units, regardless of type, the oxygen produced is usually disregarded for further processing and utilization and is simply vented into open air downstream of the O_2 gas separation unit. In most cases, the cost-benefit of electrolytic oxygen with regards to storing, selling and transporting is not deemed profitable where other technologies are available [7]. However, in order to increase the product yield of the water electrolysis, storing and utilizing the locally produced oxygen is of particular interest for industries such as land based recirculating aquaculture where such a synergetic effect may be economically viable for all parts involved.

1.2 Objectives

The objective of this thesis is to evaluate the technical feasibility of an integrated recirculating aquaculture system (RAS) with water electrolysis units to provide the minimal necessary oxygen input. The main activities included is the establishment of the integrated concept (scaling between hydrogen production and oxygen demand based on pre-defined case studies), simulation (modeling) of the baseline concept, and thermodynamic analysis of the concept, as well as high-level economic analysis of the concept to study possible effects on hydrogen production costs.

The thesis seeks to answer the following questions:

- **Q1 - Technical feasibility:** what are the demands of an oxygenation unit in the RAS, O_2 storage and compression
- **Q2 - Demand modeling:** scaling between hydrogen production and oxygen demand based on fish species and RAS size for optimal utilization
- **Q3 - Cost analysis:** achievable cost impact on hydrogen, comparing different scenarios, sensitivity analysis

The questions are answered by providing a current and comparable analysis of green hydrogen production from electrolysis. To do this, comparable costs are required. The cost of hydrogen over the lifetime (Levelized Costs Of Hydrogen - LCOH) is the lowest long-term sales price hydrogen can have for the economic result of a particular hydrogen plant to be zero. It provides a unit cost in NOK/kg H_2 which provides a direct comparison of technologies, despite different production sizes and other project-specific prerequisites.

1.3 Methodology

The structure of the workflow to carry out this master thesis is given in Figure 1.3. The left box indicates the work performed before the first step, as well as before step 4. Literature reviews and system identifications are then used as a starting point for answering the research questions stated. The main workflow is indicated in the middle, while intermediate steps and outputs are shown to the right. Step 1, 2 and 3 are performed to answer the first objective about technical feasibility. This is based on an empirical approach and calculations. Step 3 and 4 includes the validation of electrolyzer size based on differing oxygen demands in order to answer the second objective about modeling demands. This validation is necessary in order to perform step 5 to answer the third objective about cost analysis.

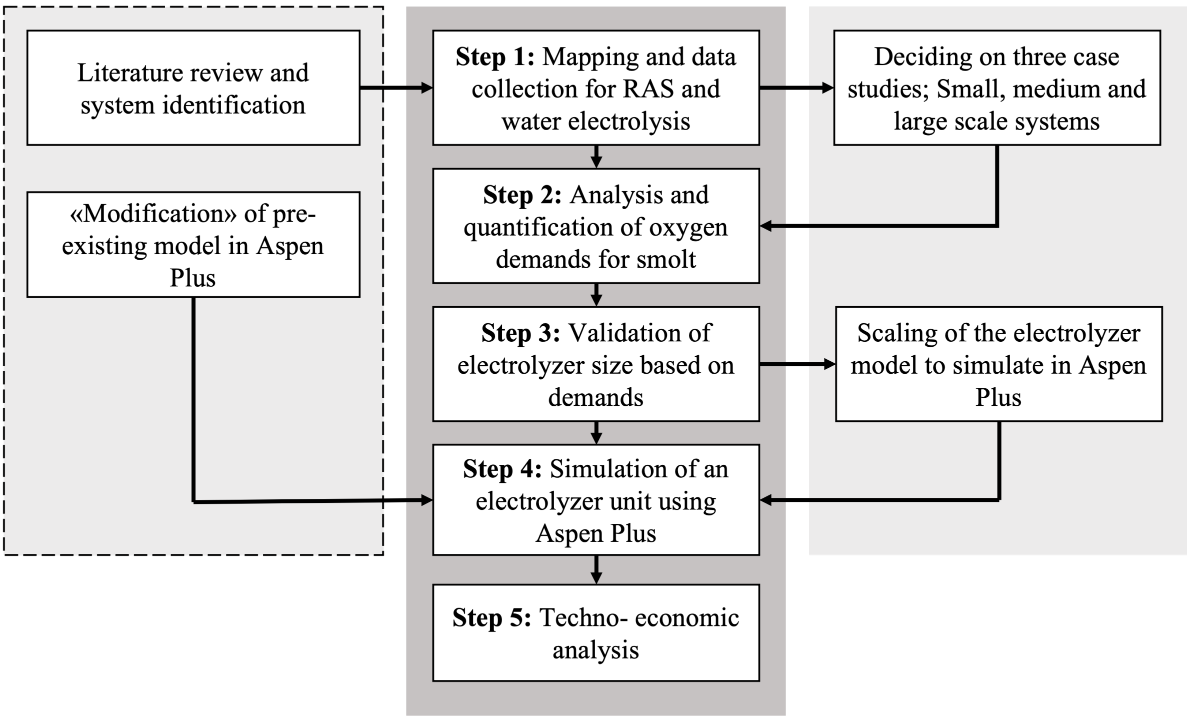


Figure 1.3: Workflow of this master thesis

The sources of information are based on the available literature (such as scientific articles), except for some techno-economic variables, which are either known (such as exchange rates) or verified using expert citations and interviews. All calculations made under their respective section are explained thoroughly. Three different case studies are represented, the last two being based on simulation of case 1: Small scale facility. Using Aspen Plus and Aspen Custom Modeler as a tool to simulate the production of oxygen and hydrogen, it is easy to scale up this scenario in order to fulfill cases 2 and 3.

The model relied upon is earlier work of Sanchéz et al. [9], [10], but scaled up in production outcome of hydrogen and oxygen. This is done by increasing power input to the cell stack as well as increasing the pre-defined parameters; cell number and cell number area. To maintain a stable simulation it is important to keep the temperature of the cell stack to $\sim$75°C. Aspen Plus gives the output as hydrogen and oxygen produced. The scaling is based on oxygen demand calculations.

1.4 Scope and limitations

The main focus of this thesis is to study the synergies between water electrolysis and recirculating aquaculture systems (RAS). The scope includes simulation of the electrolysis process through Aspen simulation software, scaling of process units with a basis in three different case studies, as well as specific techno-economic analyses and comparative studies of the defined cases.

The aim of the study is the establishment of the concept and to evaluate synergetic effects of integrating RAS facilities with water electrolysis units. Further performance optimization and work regarding improvement of the technical solutions and potential cost savings are disregarded and considered beyond scope of the project. However, the suggestions for further work presented in Chapter 6 provide suggestive measures and pathways on the way forward to achieve these goals.

Due to difficulties obtaining real data for the varying oxygen demand of different RAS facilities, a model was implemented to simulate these parameters. A mean value of the required oxygen demand of each of the defined cases was further utilized as the dimensioning factor for the water electrolysis units and the Balance of Plant (BoP).

1.5 Thesis outline

This thesis has been organized in 5 main parts; Chapter 2 Recirculating aquaculture systems and Chapter 3 electrolyzer technologies consists of theory based on a typical RAS and various water electrolyzer technologies. Chapter 4 Establishment of case study presents data and theory behind the techno-economic variables used for three different case studies, which are modeled and simulated using AspenTech software. Chapter 5 Results and discussion contains the solutions for the case studies which are then further discussed. Chapter 6 Conclusion contains the conclusion of the thesis with a section presenting suggestions for further work.

Chapter 2

Recirculating aquaculture systems

A recirculating aquaculture system, known as RAS, is a process made to farm fish or other aquatic organisms by reusing the water in the production. The process involves many technologies such as mechanical and biological filters, disinfection units, and oxygen (O_2) and carbon dioxide (CO_2) adjustment units. RAS can be used for many types of species such as; shrimps, clams, or fish, although fish farming is primarily used [11].

RAS is growing rapidly and can be deployed in huge farms generating thousands of tonnes of fish every year, or in small systems used for restocking or to save endangered species. The main reason for utilizing such a system is because of low environmental impacts, such as the use of less water from the environment compared to other technologies, e.g flow-through systems. RAS contributes to decreasing the eutrophication potential of the outlet water and eliminates potential disease transfer of wild stock. Because of a bio-secure culture environment, these systems can also help to limit the use of antibiotics and vaccines. Other benefits are also the possibility to re-use discharged nutrients in agriculture or produce biogas in an anaerobic digester [11], [12].

Re-circulation of the water can be carried out at different intensities depending on how much water is re-used. This has a direct correspondence with how much fish or stock is produced. Re-circulation also enables the farmer to control all the parameters in the production process. A simple block flow diagram for a typical RAS can be seen in Figure 2.1 [11].

2.1 Components

As aforementioned the RAS facility involves many different technologies and process units for aquaculture farming. The main components of the process will be given a more detailed explanation in this section.

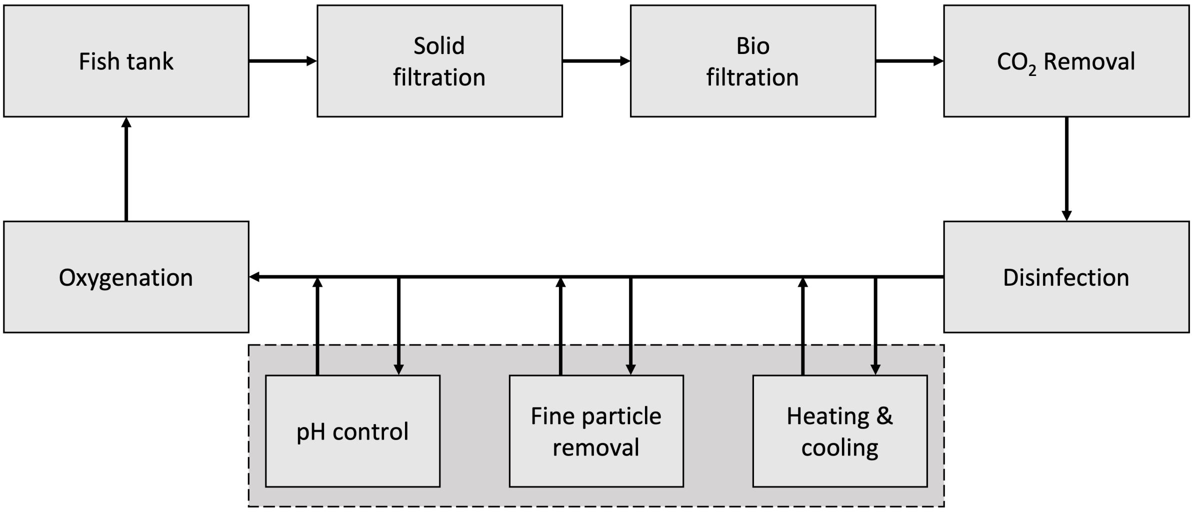


Figure 2.1: Simplified block flow diagram of a recirculating aquaculture system

2.1.1 Fish tank

Mainly there are three types of fish tanks being used with each one having a different design; Circular tank, D-ended raceway, and raceway type. Each tank design has its advantages and disadvantages. Different tank properties include; Self-cleaning effects, space utilization, oxygen control, regulation, and low residence time of particles. The different types of fish tanks being used can be seen in Figure 2.2 [11].

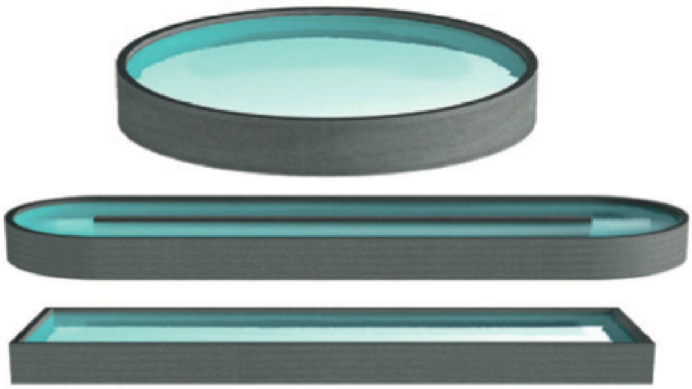


Figure 2.2: Circular, D-ended raceway and raceway type fish tank used in RAS [11]

2.1.2 Solide-filtration

To remove organic waste products, the most practical solution is to apply a mechanical filtration unit at the outlet of the fish tank. Mechanical filters can remove organic particles from the stream, improve conditions for nitrification and reduce the load on and provide a stabilizing effect on the bio-filter [11]. Almost all RAS facilities filter the outlet water by using a micro-screen fitted with a filter cloth, typically 40 to 100 microns. The drum-filter is the most commonly used type of micro-screen.

2.1.3 Bio-filtration

The finest particles and dissolved compounds such as phosphates and nitrogen (N_2) will pass through the mechanical filter, thus enabling the use of a bio-filter. Phosphate is an inert substance with no toxic effect, but nitrogen in the form of ammonia (NH_3) is toxic. This need to be transformed into the more harmless *nitrate* (NO_3), which happens in the bio-filter. This breakdown of organic matter in the filter is carried out by using bacteria. The bacteria oxidize the organic matter by consuming oxygen and producing carbon dioxide, ammonia, and sludge. Nitrifying bacteria first convert free ammonia into nitrite (NO_2^-) and then finally to nitrate. The efficiency of the bio-filter is primarily dependent on the pH of the system and the water temperature [11].

2.1.4 Carbon dioxide removal

If the concentration of CO_2 in the water is too high, it will cause a reduction of the pH in the water re-circulation system. The CO_2 in the water is produced by the fish when digesting the feed and from the biological activity of the bio-filter. Free N_2 is also present. The accumulation of CO_2 and N_2 will have detrimental effects on the growth and welfare of the fish. Hydrogen sulfide (H_2S) can also be produced, but under anaerobic conditions and especially in salt water systems. H_2S is extremely toxic to fish, and the fish will be killed if this is generated in the system.

The CO_2 is removed by aeration of the water by the use of degassing. This method is often referred to as stripping. Aeration is carried out by pumping air into the water, creating a turbulent environment between the air bubbles and the water. This drives out unwanted gases.

Another efficient method for removing gases is by using a *trickling filter* system, also called a *de-gasser*. In this process, the gases are stripped off by creating physical contact between the water and some plastic media stacked in a column. The water is flushed from the top, creating turbulence through the column, thus maximizing the contact [11].

2.1.5 Disinfection

Common disinfection treatment is by applying ultraviolet light (UV). This destroys the DNA in biological organisms such as pathogenic bacteria and one-celled organisms in aquaculture. It is an old treatment that has been in use for decades in the medical field and is ensured not to harm or impact the fish as the process is carried out outside of the fish tank. Bacteria grow very rapidly in organic matter, and it is thus best to use a disinfection unit combined with the filtration processes for removing the organic matter. The UV dose is often expressed in microWatt-seconds per cm^2 [$\mu W\,s/cm^2$]. The units are placed underwater for best efficiency [11].

2.1.6 Oxygenation

The aeration process described in Section 2.1.4 is adding oxygen to the water by the simple exchange between the gases in the water and the gases in the air, depending on the saturation level of oxygen in the water. The equilibrium of oxygen in water is 100% saturation. When the water is in the fish tanks, the oxygen is used by the fish, thus the levels of oxygen have been lowered from 100% down to approximately 70%. This percentage is further reduced in the bio-filter before the aeration brings the oxygen levels up to around 90% or 100% [11].

Having above 100% in the inlet water for the fish tank is often preferred to have sufficient oxygen available for a stable and high growth rate of fish. To have saturation levels above 100% requires the use of pure oxygen, which is mainly delivered in tanks in form of liquid oxygen [11].

Water with 200-300% saturation is called *super-saturated water*, and to achieve this there is a need for high-pressure oxygen cone systems or low-head oxygen systems. The principle is the same as the water and pure oxygen are mixed under pressure whereby the oxygen is forced into the water. The oxygen cone typically reaches pressures of about 1.4 bar using a pump. In an oxygen platform, the pressures are much lower, about 0.1 bar, and water is pumped through the box, which mixes the oxygen and water. The difference in these systems is that the oxygen cone solution uses a small part only of the circulating water for oxygen enrichment, and the platform is used for the main recirculation flow. Using pure oxygen as the oxygenation technique rather than simple aeration could yield up to five times more transfer rate [11], [12].

The process of oxygenation should be controlled with accurate measurements and the best way to do so is to use an oxygen probe which measures after the oxygenation system.

2.2 Fish species

A RAS facility can operate under a wide range of operational circumstances, where conditions such as temperature and oxygen saturation levels can be controlled with high precision. Due to this level of manipulation of the environmental conditions for the fish breed, new opportunities arise for culturing a wide array of underwater species regardless of the local climate.

2.2.1 Demands

Different species require different conditions for optimal growth and to reduce stress levels. The most common species being bred in both open and closed fish farm facilities in Norway are typically cold water species such as Atlantic salmon and Rainbow trout, although Atlantic cod is also a growing curiosity among industrial actors.

For closed facilities onshore, various tropical warm water species such as King prawn (Whiteleg shrimp) and Yellowtail kingfish have a growing interest in Norway due to exclusivity in markets by the likes of for example sushi restaurants. These species are traditionally bred in tropical climates, and the market in Norway has been sustained through import which in most cases includes large travel distances with additional costs, concerns with regards to fish welfare, product freshness, and emissions.

When it comes to oxygen consumption, warm water species in general demand more oxygen because of a higher metabolism rate. Also, warm waters tend to hold less oxygen compared to cold water, which again leads to a higher demand for oxygenation units in closed facilities to fulfill the optimal saturation levels in the inlet water for the fish tanks.

The focus of this study is the farming of Atlantic salmon in recirculating aquaculture systems, due to its popularity both in the Norwegian market as well as for export. Norwegian seafood company Mowi, previously known as Marine Harvest, predicts a growing global demand for Atlantic salmon and suggests the market for locally produced salmon to be a good fit for global macro trends [13].

2.2.2 Modelling the growth and oxygen demand of Atlantic salmon

To determine the different parameters governing the growth and oxygen demand, a model was implemented based on information for the specific growth rate (SGR) of Atlantic salmon from smolt to slaughter size (see Appendix C). Specific growth rate (SGR) is a percent measure for estimating the daily growth of a species, as given in Equation 2.1:

$$SGR(\%) = \left(\left(\frac{m_2}{m_1} \right)^{\frac{1}{dg}} - 1 \right) \times 100 \tag{2.1}$$

where m_1 is starting body mass, m_2 is ending body mass and dg is the number of days interval. If the SGR rates are known, Equation 2.1 may be rearranged to determine the periodic growth of Atlantic salmon through a general feed ration:

$$m_2 = m_1 \left(1 + \frac{SGR}{100} \right)^{dg} \tag{2.2}$$

Equation 2.2 is applied to the model, where the growth of any given quantity of salmon is determined weekly based on SGR tables for smolt and full-size salmon by Norwegian feed producer Skretting [14]. Due to variation in oxygen consumption with the live weight of the fish, demands may be expressed as a function of body mass, water temperature, growth rate, feeding rate, swimming velocity, and stress levels [15]. A simplified expression presented by Christiansen et al. giving the consumption as a function of water temperature and body mass was chosen for the model [16]:

$$m_{O_2} = 5.5W^{0.2} \times \exp^{0.7T_w} \tag{2.3}$$

where m_{O_2} is specific oxygen consumption (mg·kg^{-1}·min^{-1}), W is body weight (g) and T_w is water temperature (°C). Using a water temperature of 12°C which is common for salmon farming, weekly growth, and oxygen demand are calculated for all three cases presented in Chapter 4.

Mortality among the farmed fish is an undeniable occurrence for any facility. Mortality rates may become quite severe especially in open facilities offshore due to reduced fish welfare (stress), illnesses as well as environmental factors such as algal blooms [17]. One of the critical arguments in support of moving fish farms onshore is to reduce illnesses and hence mortality rates, which also affects wild species offshore due to shared environments. The mortality rates of open fish farms in Norway have increased drastically in recent years. In the cases presented in Chapter 4, total mortality rates are set to 24% for smolts (100 g), a relatively acute number for closed facilities, and 2% for post-smolt and slaughter size salmon up to 5 kg [18]. The mortality is calculated weekly through Equation 2.4:

$$Q_2 = Q_1\left(1 - \frac{MR}{N_w}\right) \tag{2.4}$$

where Q_1 is fish quantity at the start of the week, Q_2 is the fish quantity at the start of the next week, MR is the total mortality rate and N_w is the number of weeks interval.

Chapter 3

Electrolyzer technologies

In order to split water to produce pure hydrogen, electrolyzers are used. It is a well-established technology mostly used in the chemical industry. The principle is simple and allows different technological variations based on physical-chemical and electrochemical aspects [19]. The overall global reaction occurring in a water electrolysis system is the reforming of water (H_2O) into dihydrogen (H_2) and dioxygen (O_2) [20]:

$$H_2O(l) + \text{electrical energy} \rightarrow H_2(g) + \frac{1}{2}O_2(g) \tag{3.1}$$

Reaction 3.1 takes place in an electrochemical system which is composed of two electrodes; anode and cathode, where oxidation and reduction of water occur, respectively [20]. The reaction occurs under different conditions and environments which are all more explained in the following sections. The three main technologies used today, as well as a more experimental fourth one [19], [20], are classified into:

- Alkaline electrolysis cell (AEC)
- Proton exchange membrane electrolysis cell (PEMEC)
- Solid oxides electrolysis cell (SOEC)
- Anion exchange membrane electrolysis cell (AEMEC)

3.1 Theory

The standard molar enthalpy of water decomposition, $\Delta_r H$, is the energy that is required to split 1 mole of H_2O into 0.5 mole of O_2 and 1 mole of H_2. Parts of the total energy needed corresponds to the thermal energy necessary for the reaction to take place. Thus, increasing the thermal energy provided to the system can allow for a reduction in electrical energy required for the reaction of water splitting. The thermodynamic relation is given below in Equation 3.2, where $\Delta_r G$ is the molar Gibbs energy of water decomposition, and $\Delta_r S$ is the molar entropy [20]:

$$\Delta_r H = \Delta_r G - T\Delta_r S \tag{3.2}$$

Gibbs energy is the minimum electric energy and $T\Delta_r S$ is the minimum heat required for the reaction to take place. An external electric generator, either from the grid or renewable energy sources such as wind or solar will provide the electrical energy needed ($\Delta_r G$), and the heat energy ($T\Delta_r S$) will be provided by the working temperature conditions [20].

From equation 3.2 we can define two electrolysis voltages. One is the Gibbs energy, which is the thermodynamic voltage (U_{Rev}), also called *reversible voltage*. The second voltage is the enthalpic voltage (U_{Therm}), which is also called the *thermoneutral voltage* of the water decomposition reaction. This represents the global energy required for the reaction to occur. The two electrolysis voltages can be calculated from equation 3.3 and 3.4, where F is the Faraday constant (96,485 C mol^{-1}) and N_{el} is the number of electrons exchanged (N_{el}=2) [20].

$$U_{Rev} = \frac{\Delta_r G}{N_{el} F} \tag{3.3}$$

$$U_{Therm} = \frac{\Delta_r H}{N_{el} F} \tag{3.4}$$

In the cases for electrolysis under standard temperature ($T = 298K = 25°C$) and pressure ($P = 1\ bar = 10^5\ Pa$), water is under liquid phase and the products are under gaseous phases, which are often employed for alkaline and acidic electrolysis systems. The standard energy values can be defined as:

$$\Delta_r G^\circ = 237.22\text{kJ mol}^{-1} \rightarrow U_{Rev} = \frac{\Delta_r G^\circ}{2F} \approx 1.23V \tag{3.5}$$

$$\Delta_r H^\circ = 285.8\text{kJ mol}^{-1} \rightarrow U_{Therm} = \frac{\Delta_r H^\circ}{2F} \approx 1.48V \tag{3.6}$$

From equations 3.5 and 3.6, a supplementary voltage (U_{Ent}=0.25 V) can be defined. This is derived from the entropy $\Delta_r S$ (163.15 J mol^{-1} K^{-1}) change, i.e the heat demand for the reaction to occur, corresponding to the minimum overvoltage with respect to U_{Rev} to be applied to the electrolysis cell in order to start the reaction.

Its important to note that all the thermodynamic values ($\Delta_r G$, $\Delta_r H$, U_{Rev}, U_{Therm}) are dependent on temperature, and thus can change depending on the environment and conditions. It can then be noted that the standard cell voltage for Formula 3.1 is 1.23 V independently on the electrolysis system.

3.1.1 Alkaline electrolyzer cell (AEC)

These are the simplest and commercially most used types of electrolyzers. They have a simple cell stack and system design which makes them relatively easy to manufacture. The electrode area can be as high as 3 m^2 and use *potassium hydroxide* (KOH) in high concentrations (25-30%) as the electrolyte. Nickel (Ni) coated stainless-steel is used for electrodes and zirconium dioxide (ZrO_2) based diaphragms. Figure 3.1 illustrate a typical alkaline cell design [19]. KOH and water is permeating through the porous structure

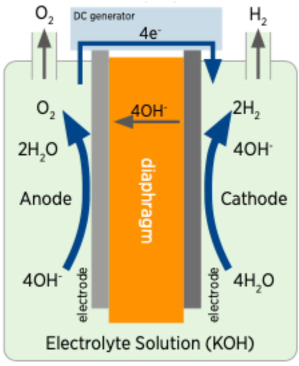


Figure 3.1: Alkaline electrolyzer cell [19]

of the diaphragm with hydroxyl ion (OH^-) as the ionic charge carrier. This provides functionality for the electrochemical reaction [19]. The reactions taking place are:

Anode:

$$4OH^- \leftrightarrow 2H_2O + O_2 + 4e^- \tag{3.7}$$

Cathode:

$$4H_2O + 4e^- \leftrightarrow 2H_2 + 4OH^- \tag{3.8}$$

The hydrogen and oxygen produced are mixed and dissolved in the electrolyte, which limits the lower power-operating range and the ability to operate at higher pressures. In order to prevent this, a thicker diaphragm is used, but in turn, this creates lower efficiencies as the current resistance increases. Lifetime of an alkaline electrolyzer may reach above 30 years. [19]

3.1.2 Proton exchange membrane electrolyzer cell (PEMEC)

These "electrolysis cells" use a thinner *perfluorosulfonic acid* (PFSA) membrane and more advanced electrodes which achieves higher efficiencies because of less resistance. The membrane is mechanically and chemically more robust, allowing for higher pressures. Because of this they can operate at up to 70 bar with the oxygen side at atmospheric pressures. Cell design can be seen in Figure 3.2. [19] The reactions taking place are:

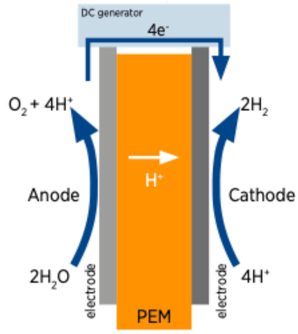


Figure 3.2: PEM electrolyzer cell [19]

Anode:

$$2H_2O \leftrightarrow O_2 + 4H^+ + 4e^- \tag{3.9}$$

Cathode:

$$4H^+ + 4e^- + \leftrightarrow 2H_2 \tag{3.10}$$

The acidic environment, oxygen evolution and high voltages create a very oxidative environment, which demands using materials that can withstand such conditions. This implements a need for titanium-based and noble metal catalysts to ensure a long-term stability of the cell; hence, increasing the cost of the PEM´s. PEM´s are very compact and have a simple system design, but are sensitive to mineral impurities in the water. Lifetime of large-scale PEM systems still have to be validated. [19]

3.1.3 Solid-oxide electrolyzer cell (SOEC)

These operate at a high temperature range of between 700-850°C, which allows for the use of relatively cheap nickel electrodes. Part of the energy needed for separation is provided through heat, where waste heat can be used, causing a decrease in electricity demand. Typical SOE cell can be seen in Figure 3.3. [19] The reactions taking place are:

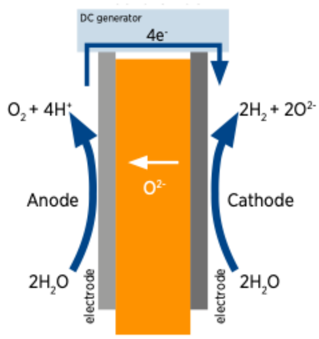


Figure 3.3: SOEC cell [19]

Anode:

$$2O^{2\text{-}} \leftrightarrow O_2 + 4e^{\text{-}} \tag{3.11}$$

Cathode:

$$2H_2O + 4e^{\text{-}} \leftrightarrow 2H_2 + 2O^{2\text{-}} \tag{3.12}$$

Solid-oxide electrolyzers are only in the laboratory stage and are thus only deployed at the kW-scale [19].

3.1.4 Anion exchange membrane electrolyzer cell (AEMEC)

These are the latest technology, and the potential lies in the combination of a less harsh environment than alkaline and the efficiency and simplicity of the PEM electrolyzer. It enables the use of titanium-free components as well as non-noble catalysts and can operate at high pressures as the PEM. Figure 3.4 illustrate the AEM cell [19]. The

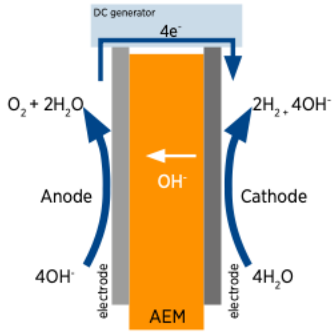


Figure 3.4: AEM cell [19]

reactions taking place are:

Anode:

$$4OH^{\text{-}} \leftrightarrow 2H_2O + O_2 + 4e^{\text{-}} \tag{3.13}$$

Cathode:

$$4H_2O + 4e^{\text{-}} \leftrightarrow 2H_2 + 4OH^{\text{-}} \tag{3.14}$$

The AEM membrane has mechanical stability and chemical problems leading to unstable lifetime profiles. Performance is not yet as good as the expected outcome because of low conductivity, slow catalyst kinetic and poor electrode architectures [19].

3.2 Products

For all the electrolysis technologies the products are the same; hydrogen, oxygen, and excess heat. All of the products can be utilized, either for on-site production purposes or for sale, and will be discussed further in this section.

3.2.1 Hydrogen

All technologies can provide an H_2 output purity of 99.99 percent. There are however minor differences in pressure range; 1-35 bar for AEC, 1-70 bar for PEMEC, 1-35 bar for AEMEC and 1-40 bar for SOEC [19], [21]. Hydrogen as an energy carrier can be used in new applications such as management of smart grids for more energy flexibility, hydrogen refueling stations for fuel cell powered vehicles or as chemical storage of renewable energies [22].

3.2.1.1 Storage

Hydrogen can be stored stand-alone both as a compressed gas, as well as in liquid form at cryogenic temperatures under the boiling point at 1 atmospheric pressure of -253°C, so-called liquid hydrogen (LH_2) [23]. The most common storage method is to compress the hydrogen in tanks or pressure vessels, although new pathways and opportunities for storage applications are under research such as underground storage in depleted oil and gas wells, aquifers, salt caverns or lined-hard rock caverns [24]. Currently, extensive research work is also being conducted to study the properties of storing hydrogen bound with different materials and compounds [25]. However, different hydrogen storage materials and underground storage are disregarded for the purposes presented in this project.

Compressed hydrogen in gas form may be stored under a wide range of service pressures, all dependent on the application use and convenience. Generally, due to the low volumetric density of hydrogen, high service pressures for the pressure vessels ranging from short-term storage solutions compressed to 200 bar in steel cylinders, to purpose built lightweight composite cylinders capable of handling upwards of 800 bar for long term storage and transport applications are available on the market today [23]. Due to the scope of this project, the hydrogen produced from the electrolyzer is assumed to be separated, dried, and compressed to 200 bar in a steel tank cylinder for further use.

3.2.1.2 Current markets

The major current uses for pure hydrogen are mainly for producing ammonia for fertilizers, food production, metallurgical uses, and treatment and in oil refining to be used for hydro-treating the crude oil in the refining steps in order to improve the hydrogen-to-carbon ratio in fuels, as well as other industries. In the coming years, the use of hydrogen in transportation might become the main applications. Several advancements in fuel cell technology, storage and transportation of hydrogen has been seen in recent years, creating a possible market for easier handling and sale of hydrogen as a product [22].

In Norway, DNV GL [26] has an estimation for a future market for national use of about 250,000 tonnes of H_2/year in 2030. Hydrogen used in the production of ammonia and methanol accounts for about 75% of this, and is mostly produced for and by Yara Herøya and Tjeldbergodden. The use of hydrogen for transport is expected to increase and the market potential is estimated to be upwards of 60,000 tonnes of H_2/year in 2030. New use in the industry represents a limited market given the expected cost-competitiveness of hydrogen towards 2030 [26]. Figure 3.5 gives estimation for different categories in kilotonnes and percentages. Maritime sector demands correspond to approximately ~18,000 tonnes H_2, which would be the preferred market for H_2 sales because of location purposes of the facility, which would realistically be close to the shore.

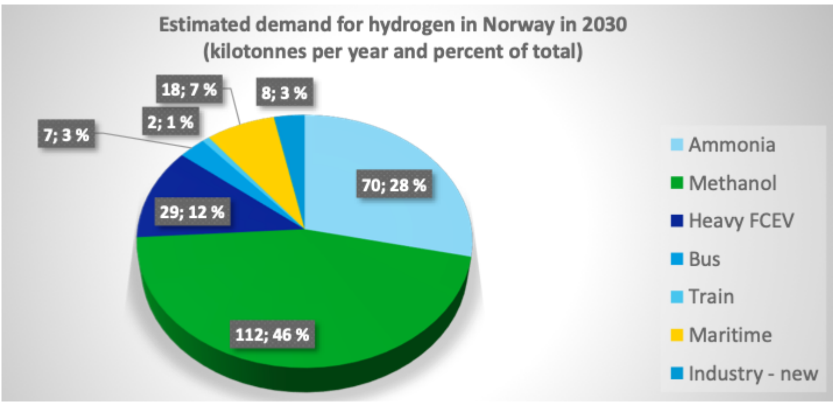


Figure 3.5: Estimated demands for hydrogen in 2030 by DNV GL [26]

3.2.2 Oxygen

For Alkaline water electrolysis, there are several manufacturers (such as NEL and Hydrogenics) which promises oxygen output purity of 99.5% [22]. The oxygen can be used in various industries, mainly these include; paper production, glass manufacturing, steel and metal industry, medical care industry, food, thermal gasification, oxy-fuel carbon capture systems (CCS) as well as fish farming and water oxygenation which is the scope of this paper [21].

To store the oxygen produced on the anode of the electrolyzer stack, some modifications are necessary towards the Balance of Plant (BoP). In a PEM unit, utilizing the oxygen may be beneficial in the case of running the stack in balanced mode, with equal operating pressures on both the anode and cathode side, which again allows for a thinner membrane due to a reduction in mechanical stress from pressure difference [19]. The benefits of a thin membrane includes a higher overall efficiency due to the lower internal cell resistance, as well as reduced gas permeation through the membrane contributing to an increase in production rate as well as higher purity levels of the hydrogen and oxygen leaving the stack.

Modifications to the BoP on the anode side may include an O_2 gas separator unit, a pressure swing adsorption unit (PSA) with a low-pressure compressor, a buffer tank and alternatively a high pressure, multi-stage booster compressor and filling ramp for long-term storage of oxygen in cylinder tanks [7], [27]. The oxygen is stored typically at a service pressure ranging from 100-300 bar, depending on use. Medical oxygen is usually stored in smaller cylinders pressurized at 150-200 bar and fed to the patient through a pressure regulator [28]. Similarly, industrial oxygen is filled into cylinders of different sizes with full service pressure ranging from 150-200 bar.

As with the storage and transport of hydrogen, liquefying the oxygen (LO_X) for the duty is in many cases considered a viable option, especially if the oxygen is purchased from a supplier and not generated on-site with an oxygen generator or through a PSA unit. The cryogenic temperatures for oxygen are under the boiling point of roughly 90 K (-183 °C) at atmospheric pressure, and an evaporator is needed in order to heat the cool, liquid oxygen into gaseous form after storage for further use [29].

The electrolytic oxygen delivered to the RAS facilities in the three cases presented in this report is compressed in a 2-stage compressor and temporarily stored in steel vessels at 200 bar. This is due to the importance of securing the oxygen supply to the oxygenation process within the RAS facility. A shortage of oxygen supplied to the facility may lead to catastrophic consequences, both with regards the mass mortality of fishes and also economically for the production.

3.2.3 Heat

The excess heat can be utilized in district heating, especially for PEMEC and AEC. The operating temperature of these systems is typically 70-90°C for AEC and 50-80°C for PEMEC. Current systems (2020) can provide heat for utilization at 50°C, which are expected to increase up to 70°C within 2024 according to manufacturers [21]. For Solid-oxide the recoverable heat will be fed into the system again to be used as input to the cells in order to decrease the energy demand for operation [21].

3.3 Comparison of technology

Water electrolysis is considered as a well-established technology where AEC has been in use industrially for decades, and PEMEC has been available commercially for many years now even though in limited sizes as compared to AEC. SOEC and its high temperature steam electrolysis can be considered as relatively new, with less development on a system level [30]. This also accounts for AEMEC technology which are considered to only be at the R&D stage. Both SOEC and AEMEC require more effort towards devel-

Table 3.1: Main characteristics of AEC, PEMEC, SOEC and AEMEC systems [19], [31]–[33]

Description	**AEC**	**PEMEC**	**SOEC**	**AEMEC**
Electrolyte	20-40% KOH	Membrane	YSZ	Polymer
Cathode	Ni-Mo alloys	Pt, Pt-Pd	Ni/YSZ	Pt, Pd, Co
Anode	Ni-Co alloys	RuO_2, IrO_2	LSM/YSZ	PtRu/C
Current density (A/cm^{-2})	0.2 - 0.4	0.6 - 2.0	0.3 - 2.0	0.2–2
Cell voltage (V)	1.8 - 2.4	1.8 - 2.2	0.7 - 1.5	1.4–2.0
Voltage efficiency ($\%_{HHV}$)	62 - 82	67 - 82	<110	-
Cell area (m^2)	<4	<0.3	<0.01	>0.03
Operating temp. (°C)	60 - 90	50 - 80	700 - 1000	40 - 60
Operating pressure (bar)	<30	<200	<25	<35
Prod. Rate ($m^3{}_{H2}/h$)	<760	<40	<40	-
Stack energy ($kWh_{el}/m^3{}_{H2}$)	4.2 - 5.9	4.2 - 5.5	>3.2	4.6–5.9
System energy ($kWh_{el}/m^3{}_{H2}$)	4.5 - 6.6	4.2 - 6.6	>3.7	5.1–6.2
Gas purity (%)	>99.5	99.99	99.9	>99.9
Lower dynamic range (%)	10 - 40	0 - 10	>30	>5
System response	Seconds	Milliseconds	Seconds	-
Cold-start time (min)	<60	<20	<60	<20
Stack lifetime (h)	60,000 - 90,000	20.000 - 60.000	<10,000	>5,000
Maturity	Mature	Commercial	Demo	R&D
Capital cost (€/kW_{el})	1000 - 1200	1860 - 2320	>2000	-

opment for a system integration. Table 3.1 compares the main characteristics in terms of cell materials, performances, capacity and cost of the different types of electrolysis technologies.

3.3.1 Advantages and Disadvantages

Considering that the AEM technology is only at the R&D stage and is highly unavailable, it will be left out of this and future sections for comparison. Thus, the main three technologies left will be further looked upon.

Alkaline electrolyzer [21]:

Advantages

- Long stack lifetime of more than 100,000h currently
- MW scale systems are already being deployed
- Has a low operating temperature, with quick start up for response in grid services making it suitable for use as a flexible technology
- Technology is very mature and can be adapted to both centralized and decentralized plants

Disadvantages

- Less flexibility under atmospheric operation
- The use of highly caustic electrolyte
- High membrane resistance (inefficiency)
- Leakage of KOH
- Low maximum operational current density, nominally operated around 0.6 A/cm^2

Proton exchange membrane [21]:

Advantages

- Smaller footprint
- Quick response times
- PEM modules has a low operating temperature, low noise, high power density
- Pressurized hydrogen can be produced for direct storage without compression; however, it is challenging due to mechanical instability for very high pressures
- Current densities >1.0 A/cm^2 can be used for operational systems leading to compact system sizes
- MW scale systems are already being deployed

Disadvantages

- Very sensitive to impurities, with a prerequisite of very pure water as input
- Lifetime of the system is still uncertain
- Catalyst used in electrode layers are expensive and scarce
- Cost efficient water treatment and drying the hydrogen at high pressure are still challenges to be addressed
- Modules are expensive due to catalysts and bipolar plates (oxide resistant elements)

Solid- oxide electrolyzer [21]:

Advantages

- Has high efficiency, high production rates
- Can be operated at high current densities at or above 0.8 A/cm^2
- Can be used to make synthesis gas from co-electrolysis of steam and CO_2. CO-electrolysis plants have been commercialized
- Can cope with transient variations due to quick response times
- Can be used reverse mode as a fuel cell for grid balancing

Disadvantages

- Are still in demonstration phase for large scale applications for hydrogen production and are not readily commercially available
- The stack components are susceptible to corrosion
- Current SoA lifetime is short compared to Alkaline and PEM

Tables 3.2 and 3.3 presents a list of manufacturers which can provide AEL and PEM production systems [30]. Please note that these lists are from 2015.

Table 3.2: Manufacturers of AEC and system characteristics [30], [34]

Manufacturer	**Country**	**Product name**	**Capacity range (Nm^3 h^{-1})**	**Pressure (bar)**	**Energy consumption (kWh Nm^{-3})**
IHT	CH	-	760	30	$\sim$ 4.6
NEL Hydrogen	Norway	A485 [34]	485	1	$\sim$ 4.5
Wasserelektrolyse	Germany	EV150	225	1	$\sim$ 5.3
Erredue s.r.l	Italy	G256	170	30	$\sim$ 5.3
Hydrogenics	Canada/EU	HyStat60	60	25	$\sim$ 5.2
Mc. Phy	France	-	60	10	$\sim$ 5.2
Teledyne Energy	United States	SLM1000	56	10	-

Table 3.3: Manufacturers of PEMEC and system characteristics [30]

Manu- facturer	**Country**	**Product name**	**Capacity range (Nm^3 h^{-1})**	**Pressure (bar)**	**Energy consumption (kWh Nm^{-3})**
Siemens	Germany	E60	60	30	$\sim$ 4.9
Areva H2Gen	France	E60	60	30	$\sim$ 4.9
Proton on-site	United States	Hogen C30	30	30	$\sim$ 5.8
ITM	United Kingdom	HPac 40	2.4	15	$\sim$ 4.8

NEL Hydrogen is a global dedicated hydrogen company. Their roots date back to 1927, and since then, have had a long history of development and continuous improvement of hydrogen technologies. Today, their solutions cover the entire value chain from hydrogen production technologies [35]. The company claims to have the world's most energy efficient electrolyzers, the A series, which features a cell stack power consumption between 3.8-4.5 kWh/Nm^3 of hydrogen gas produced, up to 2.2 MW per stack. The A series electrolyzers comes in varying sizes, from 50 Nm^3/h to 19,400 Nm^3/h [34].

Because of the availability and its local position in Norway, their AEL product range is chosen as the base for the case studies based on arguments presented in the aforementioned sections, mainly that:

- Technology is very mature and can be adapted to both centralized and decentralized plants
- MW scale systems are already being deployed
- Long stack lifetime of 100,000h currently

Three products from the A series is presented in Table 3.4.

Table 3.4: Specifications of AEL systems from NEL Hydrogen

Specifications	**A300**	**A1000**	**A4000**	**Unit**
Net Production Rate	300-485	600-970	2,400-3,880	Nm^3/h
Power Consumption stack	3.8-4.5	3.8-4.5	3.8-4.5	kWh/Nm^3
Delivery Pressure	1-200	1-200	1-200	barg
Purity	99.99 to 99.998	99.99 to 99.998	99.99 to 99.998	%

Chapter 4

Establishment of case studies

Based on comparisons made in chapter 3, AEL is the chosen type of technology to be used in three different case studies. It is simulated using Aspen Plus with a pre-defined model based on the original paper of Sánchez et al. [9], as well as an example retrieved from the website of AspenTech under *"Hydrogen Sustainability Applications"* [36], which is based upon the same model. In this chapter, three case studies are represented, each with different dimensions of input/output flows and techno-economic evaluations.

4.1 Process description

A simplified flowsheet of the system without cooling flow can be seen in Figure 4.1. A detailed flow diagram with the cooling flow included is presented in Appendix A. H_2 and O_2 are generated at a steady state from the cell stack (STACK). The rate of production is mainly determined by the operating pressure and temperature, as well as the power input. The cell stack is modeled with a fixed circulation of KOH and operates adiabatically (with a minor specified heat loss to the surroundings). KOH is added as a component to model the heat capacity more accurately. Explicit electrolyte chemistry is not modeled. The anode and cathode operate with equal pressures such that the electrolyte is balanced 50/50. H_2 and O_2 are removed at the cathode and anode, respectively. The gases are separated in a flash column (H2-SEP and O2-SEP) and the electrolyte recirculates through two intercoolers (IC-R1 and IC-R2). The coolers are specified for a fixed cooling flow outlet temperature of 62°C. The circulating cooling flow as seen in **Appendix A** is split 50/50 between the two coolers, and the flow is adjusted to meet a specified stack temperature. The fan (FAN) is modeled with a COOLER block and its power demand are not computed.

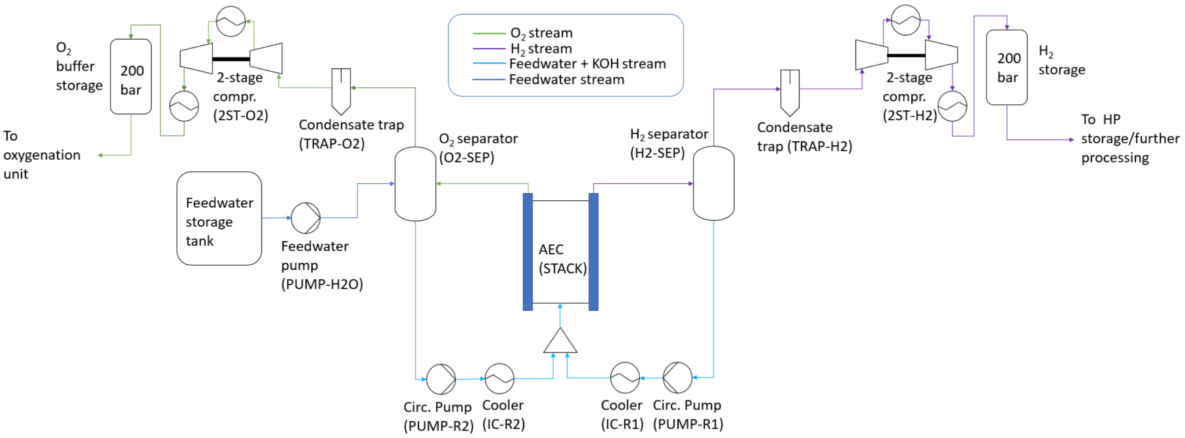


Figure 4.1: Simplified process flow diagram for the simulation setup in Aspen Plus, cooling flow excluded

4.2 Model description

The cell stack is not modeled using actual physics, but with empirical correlations that predict the electrochemical behavior under different operating conditions such as temperature (T) and pressure (p). The equations for the cell stack allow for determining the polarization curve, gas purity, and Faraday efficiency as a function of the current. These equations were developed by the previous work of Sánchez et al. [10] and are based upon Ulleberg´s [37] model developed in 2003, which is one of the most widely used models to describe the electrochemical response of an electrolyzer.

The polarization curve analyzes the different over- potentials that occur during the electrolysis of water to determine the cell potential (U_{cell}) according to the current density [9]. For the reaction to occur, the minimum voltage is required, (U_{rev}), which was briefly explained in section 3.1. Nevertheless, the cell voltage (U_{cell}) is always higher than (U_{rev}) because of the appearance of a series of overpotentials due to kinetic and resistive effects. So, the real cell voltage (U_{cell}) can be defined as the sum of reversible voltage and each of these overpotentials ($\hat{\eta}$), activation overvoltages ($\hat{\eta}_{cat}$,$\hat{\eta}_{an}$), ohmic overpotentials ($\hat{\eta}_{ohm}$) and concentration overpotentials ($\hat{\eta}_{conc}$) [9], as shown in equation 4.1:

$$U_{cell} = U_{rev} + (\hat{\eta}_{cat} + \hat{\eta}_{an} + \hat{\eta}_{ohm} + \hat{\eta}_{conc}) \tag{4.1}$$

Equation 4.1 can be expressed as equation 4.2 by introducing different constants arrived from previous works [10].

$$U_{cell} = U_{rev} + \big((r_1 + d_1) + r_2 \cdot T + d_2 \cdot p\big) \cdot i + s \cdot log\left[\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right) i + 1\right] \tag{4.2}$$

Where r_1, r_2, d_1, d_2, t_1, t_2, t_3 are polarization curve coefficients given in Table 4.1, T is operating temperature, p is operating pressure and i is the current density. The Faraday efficiency, η_F, describes the effectiveness of the process, and by comparing the moles of H_2 produced, $n_{H_2,prod}$, and the theoretical moles that should be produced during the same time, $n_{H_2,th}$, the formula is defined in Equation 4.3 [9].

$$\eta_F = \frac{n_{H_2,prod}}{n_{H_2,th}} \tag{4.3}$$

As in Equation 4.2, the Faraday´s efficiency can also be modelled using empirical correlations. For a given temperature and using 4 parameters (f_{11}, f_{12}, f_{21} and f_{22}) [[9], [37]], we end up with equation 4.4:

$$\eta_F = \left(\frac{i^2}{f_{11} + f_{12} \cdot T + i^2} \right) \cdot \left(f_{21} + f_{22} \cdot T \right) \tag{4.4}$$

In Equation 4.5 a model for the hydrogen breakthrough, HTO, which is the mole fraction of H_2 in O_2 product at the anode (dry basis), has been made. This is based on results of previous works [[10], [38]] and considers the influence of temperature and pressure on the purity of the gases [36]:

$$\begin{aligned} HTO = & \left[C_1 + C_2\,T + C_3\,T^2 + \left(C_4 + C_5\,T + C_6\,T^2 \right) \cdot exp \left(\frac{C_7 + C_8\,T + C_9\,T^2}{i} \right) \right] \\ & + \left[E_1 + E_2\,p + E_3\,p^2 + \left(E_4 + E_5\,p + E_6\,p^2 \right) \cdot exp \left(\frac{E_7 + E_8\,p + E_9\,p^2}{i} \right) \right] \end{aligned} \tag{4.5}$$

All coefficients and parameters of Equation 4.5 has been calculated through a non-linear regression using MATLAB with input from actual data from their pilot-scale hydrolysis unit. This is previous works of Sánchez et al. [9], [10]. Temperature, T, operating pressure, p, and current density, i, are variable parameters, and all other terms appearing are constant. Equations 4.2-4.5 defines the core of the cell stack used in Aspen Plus for the simulation and is created using the Aspen Custom Modeler software. The current density, i, is not directly specified in the simulation, but rather the power input, W_{stack}, is fixed by an input stream. By applying Equation 4.6, it is however possible to obtain the current density [36].

$$W_{stack} = U_{cell} \cdot N_{cell} \cdot i \cdot A_{cell} \tag{4.6}$$

where U_{cell} is the cell voltage, N_{cell} is the number of cells and A_{cell} is their individual area [36]. Table 4.1 gives the coefficients considered in equations 4.2-4.5.

Table 4.1: Constants used in the electrochemical model of the AEC in Aspen [9]

Model	Coefficient	Value	Unit
Polarization curve	r_1	4.45153×10^{-5}	Ω m^2
	r_2	6.88874×10^{-9}	Ω m^2 °C^{-1}
	d_1	-3.12996×10^{-6}	Ω m^2
	d_2	4.47137×10^{-7}	Ω m^2 bar^{-1}
	s	0.33824	V
	t_1	-0.01539	m^2 A^{-1}
	t_2	2.00181	m^2 °C A^{-1}
	t_3	15.24178	m^2 °C^2 A^{-1}
Faraday efficiency	f_{11}	478645.74	A^2 m^{-4}
	f_{12}	-2953.15	A^2 m^{-4} °C^{-1}
	f_{21}	1.03960	-
	f_{22}	-0.00104	°C^{-1}
Gas purity (H_2 in O_2)	C_1	0.09901	-
	C_2	-0.00207	°C^{-1}
	C_3	1.31064×10^{-5}	°C^{-2}
	C_4	-0.08483	-
	C_5	0.00179	°C^{-1}
	C_6	-1.13390×10^{-5}	°C^{-2}
	C_7	1481.45	A m^{-2}
	C_8	-23.60345	A m^{-2} °C^{-1}
	C_9	-0.25774	A m^{-2} °C^{-2}
	E_1	3.71417	-
	E_2	-0.93063	bar^{-1}
	E_3	0.05817	bar^{-2}
	E_4	-3.72068	-
	E_5	0.93219	bar^{-1}
	E_6	-0.05826	bar^{-2}
	E_7	-18.38215	A m^{-2}
	E_8	5.87316	A m^{-2} bar^{-1}
	E_9	-0.46425	A m^{-2} bar^{-2}

4.3 Techno-economic analysis

Input costs for the H_2 and O_2 production process are determined by analyzing factors involved in the design of the whole system. The cost parameters are divided into different categories shown below [39]:

- **Investment cost:** The single time investment which includes electrolyzer cost, construction and design
- **Variable operating and maintenance cost:** This includes cost of de-ionised water, KOH, material and all costs related to operating the system
- **Electricity cost:** Includes the cost of the electricity demand of the system

In this case, the H_2 production is greatly influenced by the electrolyzer capital cost as well as the electricity cost during operation. The operating hours of the facility will to a great extent impact the cost of H_2 costs [39]. Figure 4.2 gives a brief illustration of how the costs and revenues are diversified.

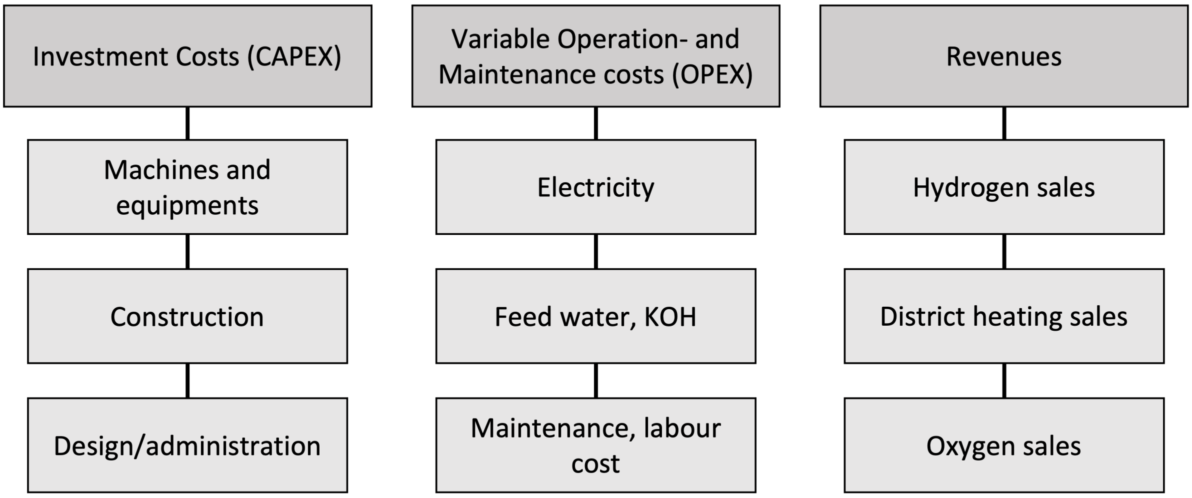


Figure 4.2: Techno-economic parameters

The required rate of return for the project can be calculated by using a set rate and using the current inflation. However, in this thesis, the rate of return is collected from Enova´s 2022 profitability analyses [40], under *other power production*, from which they found it to be **6.1**%. Adjusting for a tax rate of 22% [41], the real rate of return can be calculated as follows:

$$R_r = 6.1\% \cdot (1 - 0.22) \approx 4.8\% \tag{4.7}$$

Thus, the real rate of return to be used in the case studies is set to **4.8**%.

4.3.1 Investment cost

It is assumed that the investment costs for the projects consists of three parameters; design, the actual construction and electrolyzer costs, and installation of the facility. The land cost would be a preferred cost to include but is not accounted for because of unavailable data as well as difficult to predict placement. According to NVE [42], the distribution of investment costs in the energy sector can be sorted as follows in Table 4.2:

Table 4.2: Distribution of investment costs for thermal technologies without electricity production [42]

Component	Share of investment cost
Machines and equipment	65%
Construction costs	20%
Design / administration	15%

To arrive at a satisfactory price estimate for the investment cost associated with the electrolyzer, various literature studies are used that provide data for this. Average price in €/kW has been used as this was the most used currency, adjusted for into NOK, and is seen as a summary in table 4.3.

Table 4.3: Economic data for AEL

Studies	**Year**	**€/kW**	**kr/kW**
Danish Energy Agency [21]	2021	∼€750	7,762.5
IRENA [19]	2020	∼€714[1]	7,425[1]
J. Brauns et al. [43]	2020	∼€1,150	∼11,903
J. Proost [44]	2019	∼€1,150	∼10,868
A. Buttler et al. [45]	2018	∼€1,150	∼11,903
NVE [46]	2017	∼€1,100	∼11,385
Average		∼€985	**∼10,200**

Thus, **10,200 kr/kW** are used as the base investment costs for the electrolyzers. This is also confirmed as a realistic price to be used through meetings with technology users [47]. It is assumed that the prices in Table 4.3 are from ∼2020, as most studies are from 2018 through 2021. The costs in the three case studies have been adjusted using a calculated inflation factor. The inflation factor is calculated by Equation 4.8, using the long-term inflation, and that there are two years between the reference year (2020) and the start year (2022):

$$(1+j)^{start\ year - ref.year} \tag{4.8}$$

where j is the long-term inflation given by *Statistics Norway* [48]. This gives an inflation factor as follows:

$$(1+5.4\%)^2 \approx 1.11\% \tag{4.9}$$

Any cost reductions from the reference year to the start year are not taken into account in the case studies. For re-investment costs[2], on the other hand, technology development and cost reductions achieved were taken into account. Components that are replaced are mainly the cell stack, but also compressors, pumps, and other parts that are exposed to a lot of wear and tear. Technology development is taking place as a result of the increasing installation of electrolysis systems globally. At the same time, ever-larger plants are being installed that reduce capital costs and provide economies of scale [42]. To estimate what the cost is for re-investing in electrolyzers in the future, literature assessments of future costs were used. This can be seen as a summary in Table 4.4:

[1]Adjusted from $750

[2]Only stack replacement is included in the re-investment costs

Table 4.4: Forecasted prices for AEL in 2030

Studies	€/kW	kr/kW
O. Schmidt et al. [49]	€635	6,572
Danish Energy Agency [21]	€570	5,900
A. Buttler et al. [45]	€580	6,003
J. Proost [44]	~€850	8,800
Average	**~€660**	**~6,800**

The average price estimate for AEL in 2030 is summarized as **~6,800 kr/kW**. The operating hours are set rather conservatively to 90 000 hours. This is due to different claims by manufacturers where state-of-the-art electrolyzer units are reported to last over 100 000 hours [19], [21]. The re-investment comes after approximately 11 years as shown in Equation 4.10:

$$\frac{Operating\ hours}{Hours\ per\ year \cdot C_F} = \frac{90,000}{8760 \cdot 0.9} \approx 11\ years \tag{4.10}$$

where C_F is the capacity factor set to 0.9, which simply represents the fraction of time that the facility is on-line and operating at the design capacity. Typical values of C_F for continuous chemical processes are in the range of 0.92-0.98 [50]. Well-managed plants typically shut down for one/two weeks per year for scheduled maintenance, giving a C_F of 0.96/0.98. In this thesis, it is chosen to use a value of 0.9 for conservative measures.

Using 11 years as stack-replacement time, the yearly reduction in investment costs can be calculated:

$$\frac{((985 \cdot 1.11\%) - 660)\ €/kW}{11\ years} \approx 39\ €/kW \approx 404\ kr/kW^3 \tag{4.11}$$

4.3.1.1 Compressors

From R. Turton et al. [50], it is possible to calculate a given *bare module* cost for the compressors for the storage facility, using the following Equation:

$$C_{BM} = C_P \cdot F_{BM} \tag{4.12}$$

Where C_{BM} is the bare module cost, C_P is the purchased cost for the base conditions and F_{BM} is a bare module factor representing the materials used. F_{BM} is a factor found in the appendix of the book, using carbon steel (CS) as the material type for the oxygen output, and stainless steel (SS) for the hydrogen output side, this was found to be 2.7 and 5.7, respectively. C_P is calculated as follows:

$$log_{10}C_P = 2.2897 + 1.3604 \cdot log_{10}(A) - 0.1027 \cdot (log_{10}(A))^2 \tag{4.13}$$

[3] Yields a yearly reduction of 3.95% and will be used further in the case studies.

Where A is a capacity factor, in this case, it represents the amount of kW duty for the compressors. It is important to note that the cost values are from 2001 and has to be adjusted accordingly. This can be done by using the *Chemical Engineering Plant Cost Index* (CEPSI). In 2001 this index was 394 [50], [51], and as of February 2022 has increased to 806.3 [51].

4.3.1.2 Storage

Storage prices for compressed hydrogen vary with the type of storage vessel and pressure range. In this thesis, it is assumed to be hydrogen at 200 bar, and the chosen material type is steel tanks. Steel tanks are cheaper than carbon fiber/composite materials, but in return provide lower pressure ranges. Steel tanks can be made larger, and is highly available and cost-effective in terms of maintenance. Van Leeuwen and Mulder [52], found that high-pressure steel tanks vary in cost between 20-100 €/Nm^3 across the literature, with extremes at 195 €/Nm^3 and 490 €/Nm^3. This thesis assumes a cost of 60 €/Nm^3 for case 1, 40 €/Nm^3 for case 2 and 20 €/Nm^3 for case 3. Squadrito et al. [27] formulated a mathematical expression for calculating the total storage cost:

$$C_{tot_{stor}} = 3 \cdot C_{stor} \cdot (\dot{V}_{H2} + \dot{V}_{O2}) \tag{4.14}$$

Where C_{stor} is the storage cost in €/Nm^3, 3 represents the amount of days of storage capacity. which is assumed to be a sufficient amount. $\dot{V}$ is daily volumes of hydrogen and oxygen produced in Nm^3.

4.3.2 Variable operating and maintenance cost

The variable operating and maintenance costs included are the price of electricity including grid rent and tax fees, cost of maintenance and the cost of labor. The associated costs are detailed in the sections below.

4.3.2.1 Electricity price model

To determine a set electricity price, its important to first understand the factors defining it. The electricity net cost has three main factors which drive the total price [53]:

- **Electricity cost:** The electricity price is the cost of the actual electricity used. It will always have an average price, but it is calculated based on what is spent every hour throughout the month and what the price has been for the individual hour - unless there is a fixed price agreement. Electricity is an item that can be ordered from the electricity suppliers anywhere in the country.

- **Grid rent cost:** The electricity must be transported to the system. It is the grid companies that operate and maintain the electricity grid through which the electricity is transported. Grid rent covers the cost of having the electricity transported to the facility.

- **Taxes and fees:** About half of what is paid in grid rent is taxes and fees to the state. The largest fee is VAT for electricity consumption.

4.3.2.2 Electricity cost

It is difficult to predict the exact future cost of electricity, as there are many factors affecting this. The current uncertain political situation taking place in Eastern Europe affects gas prices to a large extent and leads to unusually high electricity prices for Norway, and other parts of Europe. The situation is extremely abnormal, and it will thus be very difficult to decide on long-term costs based on this. Therefore this thesis relates to previous publications from 2021 [[54], [55]] to determine a potential correct price for the next 20 years (project period). Table 4.5 gives the prices in weeks 17 and 16 from 2022, as well as past years to make a quick comparison of how much the current instability causes on electricity prices [56]. One can see

Table 4.5: Weekly price in øre/kWh for different areas in Norway [56]

Area in Norway	Week 17, 2022	Week 16, 2022	Week 17, 2021	Week 17, 2020
East	253.1	205.1	71.3	11.4
South-West	252.6	205.1	71.1	11.4
Mid	38.1	68.8	67.8	11.5
North	18.4	16.8	53.1	9.2
West	253,0	207.3	71.3	11.4
Average[4]	186.4	189.2	64.5	33.6

that already in 2021 that the price had almost doubled on average from the same week in 2020. This only goes to show that currently, we are in a time of major changes in the energy system in Europe. Only in 2020-2021 have there been changes that are likely to have an impact on the power system and power prices for the long term. EU has decided to raise its emission targets for 2030 and put forward proposals for changes in regulations to achieve this. This has already contributed to raising the CO_2 price significantly and has had a clear effect on power prices in Norway over the past year [54].

Norges Vassdrags- og Energidirektorat (NVE) analysis [54] points to the fact that we can expect higher power prices in Norway in the future than we have seen historically. This is partly because the exchange capacity between the Nordic countries and Europe is increasing and that we expect a persistently high CO_2 price in the years ahead. Power prices will increase towards 2030-35, but will fall in the longer term as renewable production in Europe increases. This fall in the longer term can be seen in Figure 4.3.

[4] The method for calculating variable price contracts is the average of contracts offered in more than ten network areas [56]

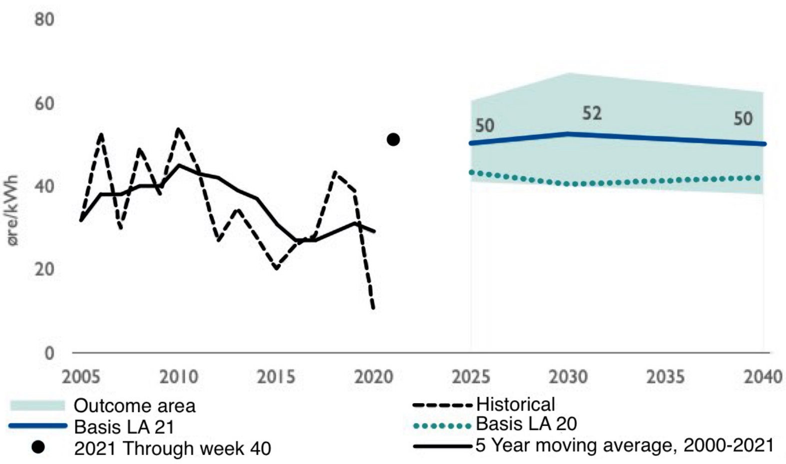


Figure 4.3: Price estimate model for future electricity price done by NVE [54]

In Figure 4.3, NVE has summed up historical, annual average power prices in Norway (black dotted line) and weighted average Norwegian power price from 2025 to 2040 basic scenario in their 2021 long-term- market analysis (LMA 21, blue solid line), and 2020 year's LMA (Green dotted line). The outcome space around the base course (blue shaded field) is given by lower and higher fuel and CO_2 prices. All prices are measured in 2021 kroner. Statnett [55] has given their LMA from 2020 in Figure 4.4.

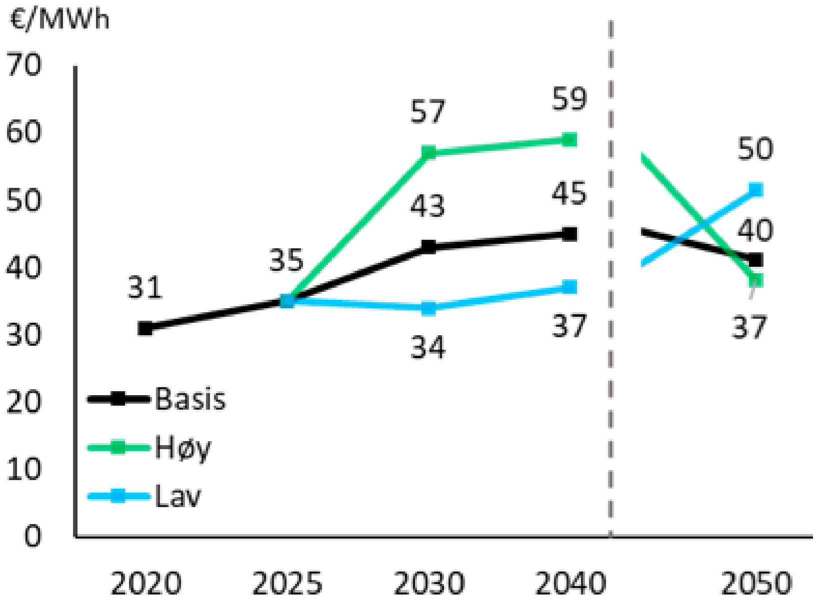


Figure 4.4: Price estimate model for future electricity price done by Statnett [55]

The green line in Figure 4.4 gives the high estimate for Statnett´s LMA 20, the blue line gives the low estimate and the black line gives the basis. The prices are listed in EUR/MWh, which is approximately the same as øre/kWh used in Figure 4.3. Both NVE´s and Statnett´s estimates for the long-term market analysis indicate that the price will descend around 2035-2040.

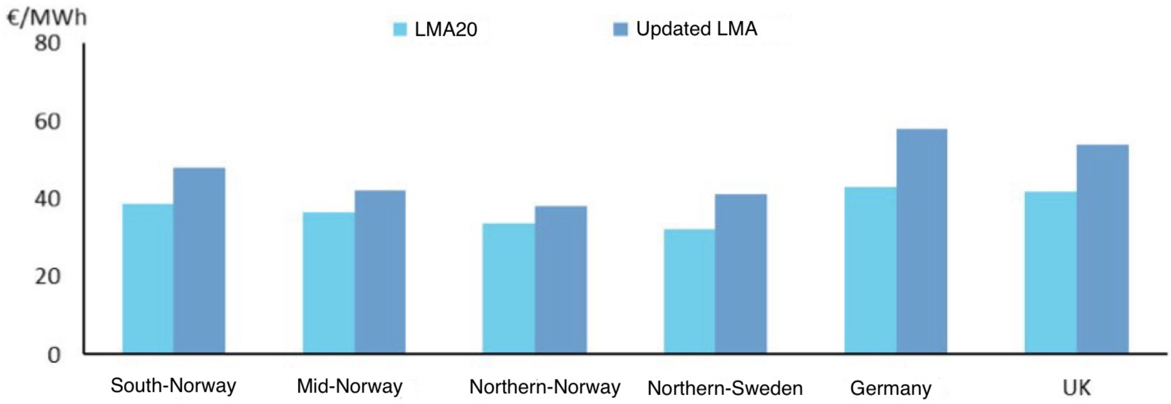


Figure 4.5: Simulated annual average prices in 2030 by Statnett [55]

Figure 4.5 indicates that the prices are differing from north to south in Norway in 2030. How long the price difference between north and south lasts will depend on several factors. In LMA20, Statnett expected that the difference in average price would be evened out towards 2040 as a result of more consumption in the north and grid reinforcements in the north-south of the Nordic region. As the price differences are even higher in their updated LMA from 2021, the price signals also become stronger. In the south, the signals will provide stronger incentives for more power production, while in the north, the incentives for establishing more consumption will increase. At the same time, the current political opposition limits the possibilities for wind power on land in Norway, while bottom-fixed offshore wind is not yet profitable with the price of power alone. Development of power production in Norway is therefore also a political issue [55].

The equalization of price differences can still take place earlier than in LMA20, but this will then primarily be driven by consumption development in the north, combined with grid reinforcements. This especially applies to consumption development in northern Sweden, where, among other things, there are enormous plans related to the steel industry [55].

4.3.2.3 Grid cost

Generally, industrial players above 15 MW in capacity and 100 GWh per year in consumption have their own industrial tariff in the transmission network in Norway. Agder Energi Nett, for example, has chosen to practice the same model in its distribution network. If the customer meets these requirements, the customer qualifies for a tariff reduction of 50%. Grid rent cost consists of two elements, a *fixed link* (power link) and a *variable link* (energy). The fixed link can be calculated as follows [57]:

$$\text{Fixed Link} = \overline{P} \cdot k \cdot (R - 50\%) \tag{4.15}$$

Where $\overline{P}$ is average usage at top load in MW and R is tariff rate consumption in NOK/MW. k is a correction factor that is calculated for each connection point in the transmission network. The calculated k-factor for the point is used when adjusting the settlement basis for all consumption in the connection point, regardless of the type of consumption (large consumption or ordinary consumption). This factor is set to 0.6 [57]. The variable link can be calculated as:

$$\text{Variable Link} = C_A \cdot u \cdot \overline{P} \cdot N_{hour} \tag{4.16}$$

Where C_A is local area price in NOK/MWh from Agder Energi Nett, u is marginal loss rate and N_{hour} is operating hours per year. The net grid rent cost can then be found using equation 4.17:

$$\text{Grid Rent cost} = \frac{\text{Fixed Link} + \text{Variable Link}}{\overline{P} \cdot N_{hour}} \tag{4.17}$$

Values in Table 4.6 are given by Statnett [57] and Agder Energi Nett, obtained from an industry expert [58].

Table 4.6: Constants used in the grid rent cost calculation [57]

Equation	**Coefficient**	**Value**	**Unit**
Fixed link	$\overline{P}$	AEC size	MW
	k	0.6	Unitless
	R	414 000	NOK/MW
Variable Link	C_A	570	NOK/MWh
	u	3.5	%
	N_{hour}	7884	h

4.3.2.4 Taxes and fees

In the last of the crisis packages presented to Stortinget in May 2020, the Norwegian government announced a strengthened focus on hydrogen-related research and technology development as a measure to meet these challenges. For pure hydrogen to become a competitive energy carrier, production costs have to be reduced. For hydrogen from water electrolysis, this means reducing the costs for the electrolysis plant itself, but also developing plants and systems that more efficiently convert electricity into hydrogen. Through the Research Council of Norway, Innovation Norway, and Enova, the public sector contributes to the development and demonstration of more energy- and cost-effective methods for the production of pure hydrogen. Power delivered for use in the electrolysis of water is currently exempt from the consumption tax [6]. The ordinary VAT of 25% is thus the only fee to pay on the power consumption, as well as the grid rent cost.

4.3.2.5 Maintenance cost

Estimation of maintenance cost includes the general maintenance of the electrolyzer facility as well as costs regarding the operational aspects, such as the purchase of feed water, KOH, cooling water, and other fixed charges. Maintenance cost is calculated as a percentage of CAPEX and is set to 5% for case 1, 4% for case 2, and 3% for case 3 based on assumptions made by Greensight AS for their hydrogen electrolysis case studies (3-5% of CAPEX) [59]. The percentages are again based yearly where they are deemed to be constant for the entire production period, and the percentage reduction from cases 1-3 is assumed due to the cost benefits of scale.

4.3.2.6 Labor cost

The cost of operating labor can be calculated using Equation 4.18 from R. Turton et al. [50, p. 241-242]:

$$C_{OL} = N_{OL} \cdot W_F \cdot \ yearly\ salary \tag{4.18}$$

where N_{OL} is the number of operators per shift and W_F is a working factor. To find N_{OL}, the following Equation is used:

$$N_{OL} = (6.29 + 31.7 \cdot (N_S)^2 + 0.23 \cdot N_{np})^{0.5} \tag{4.19}$$

where N_S is the number of processing steps involving the handling of particulate solids (transport, distribution, particulate size control, and removal). N_{np} involves the number of non-particulate processing steps, this includes heating and cooling, compression, and reaction. Pumps and vessels (such as separators) are not included. N_{np} is found from Figure 4.1, counting the number of coolers, compressors, and reactors, not taking into account the cooling loop. The AEL is assumed to be a reactor, in this case, thus N_{np} is equal to 4. Number of processing steps involving particulate solids is 0, giving a N_{OL} of:

$$N_{OL} = (6.29 + 0.23 \cdot 4)^{0.5} \approx 2.69 \tag{4.20}$$

The working factor W_F is taking into account how many weeks a single operator works per year and how many shifts are available in a year. It is assumed that a worker have 6 weeks off in a year including vacation and sick leave. The working factor is calculated as follows:

$$W_F = \frac{365\ days/year \cdot 3\ shifts/day}{46\ weeks/year \cdot 7\ shifts/week} \approx 3.4 \tag{4.21}$$

This means that 3.4 operators are hired for each operator needed in the plant at any time. Multiplying these numbers and rounding up to the nearest integer yields 10 operators, not including support or any supervisory staff. According to Statistics Norway [60], process- and machine operators have a monthly salary of ~42,690 kr (in 2021), giving a yearly salary of 512,280 kr, not including benefits and additions. This gives a cost of operating labor per year as:

$$C_{OL} = 10 \cdot 512,280\ kr = 5,122,800\ kr/year \tag{4.22}$$

4.3.3 Revenues

The revenues come from three different sources of income; hydrogen, oxygen, and district heating sales. A more detailed look at the current markets for the three products is presented in this subsection.

4.3.3.1 Hydrogen sales

While the sales price of hydrogen in industry or for re-electrification is determined by the price of natural gas [46], the use of hydrogen in the transport sector allows for a significantly higher sales price. the price depends on the willingness of the end-user to pay for a low-emission fuel, compared to the price for fossil fuels. In Norway, the price for hydrogen as a fuel for the transport sector is currently at 8.99 kr/hg hydrogen [[61], [62]], which corresponds to 72 kr/kg hydrogen plus VAT. This price is artificially set to be approximately equal to the price of petrol and diesel [46]. While the maritime sector would be the preferred market for this thesis, as stated in Section 3.2.1.2, the actual hydrogen sales price will be set as the levelized cost of hydrogen plus the margin for a given return (rate of return). More information regarding levelized cost of hydrogen is given in Section 4.3.4.

4.3.3.2 Oxygen sales

To make the supply of oxygen from water electrolysis an economically preferable choice for industrial players within land-based aquaculture, the sales price of electrolytic oxygen has to be competitive with conventional industrial oxygen production alternatives as discussed in Section 3.2.2. Generally, the price of industrial oxygen per unit mass is dependent on the scale and demand of the end-user. Large scale facilities usually benefit from a lower oxygen price per unit mass which may be as much as halved from smaller facilities. In Norway, prices are in the range of 2-4 kr/kg O_2 [[46], [59], [63]], depending on the size of the facility. For the case studies in this thesis, a sales price of 2 kr/kg O_2 is assumed in the budget accounts, although for the sensitivity analyses the oxygen price is varied to study the cost impact on the produced hydrogen and other key values.

4.3.3.3 District heating sales

Excess heat can be sold as thermal energy to the district heating system of the nearby local industries, and commercial and residential buildings. A district heating sales price can be calculated using the bulletins below [64]. It is worth mentioning that the district heat price is under the energy law [65], which states that: *"The price for district heating shall not exceed the price for electric heating in the relevant supply area"*. However, NVE is currently working on a new law, which is to be more specific towards the pricing, making it more favorable for the customers. This thesis uses the current energy law as an assumption.

- **Fixed link:** A monthly payment (depending on the company).
- **Power link:** The highest hourly value in the period. This is the maximum consumption and is used as a basis for calculating the power link. It is an expression of how much capacity must be reserved so that the customer will get enough heat in the coldest hour. In this thesis, the price is determined by the local network company and is expressed per kW.

- **Energy link:** The number of kWh available for sale during the period. The price is the sum of the spot price with the surcharge/electricity certificate and the energy link from the local grid company.

Thus, the following equation is considered to calculate the revenues of selling excess heat, in this thesis:

$$R_{DH} = \text{Fixed link} + \text{Energy link} + \text{Power link} \tag{4.23}$$

The price will be calculated at a monthly rate, then multiplied by 12 to get a yearly price to be used in the project lifetime of 20 years. Using data obtained from Lyse AS [66], Table 4.7 gives prices and values for business customers. Prices for private consumers are different (a bit higher).

Table 4.7: Monthly prices for business customers, from Lyse AS [66]

Price plan	**Fixed link**	**Energy link**	**Power link**
Business	31.7 kr	42.2 øre/kWh	Monthly electricity price (spot)
Business Plus	699 kr	37.2 øre/kWh	Monthly electricity price (spot)

The final price can be calculated using Equation 4.23 and Table 4.7 as follows:

$$R_{DH} = \text{Fixed link} + (\text{Energy link} + \text{Power link}) \cdot \text{Available heat} \tag{4.24}$$

The amount of available heat has been estimated based on available literature by using the average percentage value of input energy into the electrolyzer stack. An average percentage of ∼21.4% of the input energy as shown in Table 4.8 was found, and will be used to further calculate the potential revenues made from heat recovery. The amount of district heat available for sale is split into a summer and winter fraction, where a considerable reduction (factor 0.05) in demand is assumed for sales during the summer period.

Table 4.8: Percentage of input energy to the electrolyzer available as recoverable heat

Studies	**Percentage**
Rambøll/Embassy of Denmark [67]	17 - 22%
A technology user [47]	∼20%
Sánchez et al [9]	∼24%
F. Hepperger [68]	20%
A. Ottoson [69]	∼24%
Average	**∼21.4%**

4.3.4 Levelized cost of hydrogen

The levelized cost of hydrogen (LCOH) represents the lowest H_2 sales price (per unit of mass of H_2 produced) that would be required to recover different costs, such as those of investment, operating and maintenance costs of the producing plant over the assumed lifetime. It provides a unit cost in NOK/kgH_2 that provides a direct comparison of different production sizes and other project-specific prerequisites. LCOH is calculated by summing the total costs over the life of a plant, and dividing it by the total production over the life, as shown in Equation 4.25 [39], [42]:

$$LCOH = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime } H_2 \text{ Production}} = \frac{\sum_{t=1}^{n} \frac{I_t + C_t + C_{EL_t}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{m_{H_{2tot}}}{(1+r)^t}} \tag{4.25}$$

where I_t is the investment costs, C_t is the fixed and variable operational and maintenance costs in year t, C_{EL_t} is the cost of electricity in year t, $m_{H_{2tot}}$ is the total production of H_2 in year t, n is the lifetime and r is the interest rate. The weakness of calculating the LCOH using Equation 4.25 is that the expression does not take into consideration that costs change during the lifetime of the project, i.e using a constant electricity price based on current markets [70].

4.3.5 Production costs

Production costs refer to the total cost of producing a quantity of a product, in this case hydrogen. This cost is also represented in kr/kg H_2, as it is with LCOH, and can be calculated using Equation 4.26.

$$\begin{aligned} C_{PC} &= \frac{\text{Total Lifetime Costs} - \text{Revenues}}{\text{Total Lifetime } H_2 \text{ Production}} \\ &= \frac{\sum_{t=1}^{n}(I_t + C_t + C_{EL_t}) - \sum_{t=1}^{n}(R_{O_{2t}} + R_{DH_t})}{\sum_{t=1}^{n} m_{H_{2tot}}} \end{aligned} \tag{4.26}$$

Where $R_{O_{2t}}$ is the revenue of oxygen sales in year t, and R_{DH_t} is the revenues of district heating sales in year t. This cost is somewhat lower than LCOH, utilizing the revenues in the project period to bring the total cost of hydrogen production down.

4.3.6 Cost estimates

According to R. Turton et al. [50], there are five cost estimate classifications that are generally accepted and most likely to be encountered in the process industries; class 1 (detailed estimate), class 2 (definitive estimate), class 3 (preliminary estimate), class 4 (study estimate) and class 5 (order-of-magnitude estimate). This thesis considers class 4 (study estimate) as the cost estimating classification, and the accuracy range and the approximate cost are given in Table 4.9. to use the information in Table 4.9, it is necessary to know the accuracy of a class 1 estimate. A class 1 estimate (detailed estimate) is typically $+6\%$ to -4% accurate. This means that by doing such an estimate, the true cost of building the plant would likely be in the range of 6% higher than and 4% lower than the estimated price.

For a class 4 estimate, the accuracy range is between 3 and 12 times that of the class 1 estimate. Thus, we end up with 4 ranges of price estimates, which can be calculated as follows:

Table 4.9: Classification of cost estimate, originally from [71], but given in [50]

Class of estimate	**Level of project definition (as % of complete definition)**	**Typical purpose of estimate**	**Expected accuracy range (plus/minus range relative to best index of 1)**	**Preparation effort (relative to lowest cost index of 1)**
Class 5	0% to 2%	Screening or feasibility	4 to 20	1
Class 4	1% to 15%	Concept study	3 to 12	2 to 4
Class 3	10% to 40%	Budget authorization or control	2 to 6	3 to 10
Class 2	30% to 70%	Control or bid/tender	1 to 3	5 to 20
Class 1	50% to 100%	Check estimate or bid/tender	1	10 to 100

Lowest Expected Cost Range:

$$\begin{aligned} \text{High value for actual plant cost: } (\text{CAPEX}) \cdot [1 + (0.06) \cdot (3)] \\ \text{Low value for actual plant cost: } (\text{CAPEX}) \cdot [1 - (0.04) \cdot (3)] \end{aligned} \tag{4.27}$$

Highest Expected Cost Range:

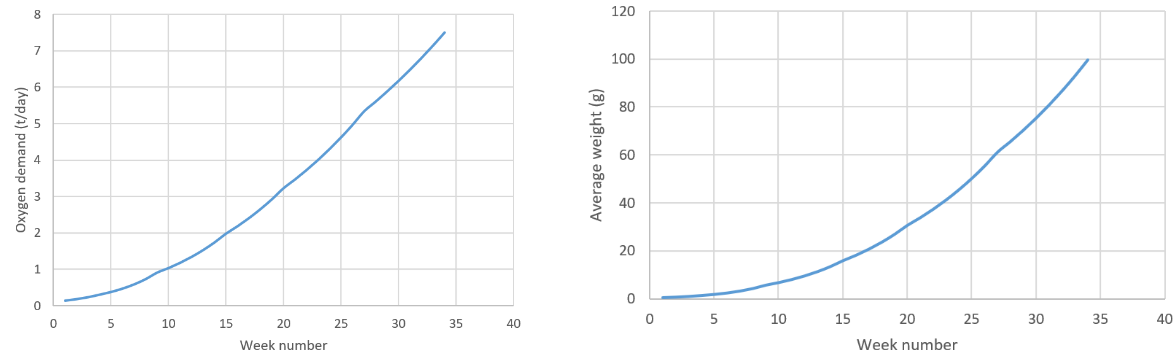
$$\begin{aligned} \text{High value for actual plant cost: } (\text{CAPEX}) \cdot [1 + (0.06) \cdot (12)] \\ \text{Low value for actual plant cost: } (\text{CAPEX}) \cdot [1 - (0.04) \cdot (12)] \end{aligned} \tag{4.28}$$

4.4 Case studies

In this section the aforementioned case studies will be presented in detail. Case 1 represents a small scale RAS facility for smolt production, case 2 is a post smolt production facility, whereas case 3 is a large full size RAS producing both a large quantity of post-smolt as well as full size salmon. The cases are determined due to different demands for oxygen, which again may provide insight into the economies of scale of combining RAS facilities with electrolysis units.

4.4.1 Case 1: Small scale facility

For the smallest case, it is intended to use an AEL unit in the order of 1 MW to produce enough oxygen for a small RAS facility producing small smolts of approx. 100 g. The oxygen demand was modeled applying the fish growth parameters explained in Section 2.2 and using



(a) Total oxygen demand per week for the growth of smolt in case 1

(b) Average body weight per week for the growth of smolt in case 1

Figure 4.6: Graphical presentations of oxygen demand and growth in case 1

Equation 2.3, where a correlation between the O_2 demand and average weight of the salmon smolt is observed, referring to Figures 4.6a and 4.6b. A quantity of 13,000,000 salmon roes are hatched and grown to a smolt size of 100 g. The production period is 34 weeks, and by then the quantity has been reduced significantly to 10,290,099 smolts, following the mortality rate formula presented in Equation 2.4, and assumed mortality rates for smolt production [18]. The total biomass at the end of the period is roughly 1,000 tonnes. It is a common practice by fish farmers to even out the distribution of salmon release through the year. For example, a fish farm may divide the quantity of salmon fry into four major releases throughout the year. This is carried out to even out the production, oxygen demand, feed demand and other factors that is necessary to ensure cost efficiency and even out production rates. For the growth model presented in this report, the seasonal release of salmon fry is disregarded, as it is beyond the scope of the project. The main interest is to gain insight into average oxygen demands for various RAS facilities as a means to scale the electrolyzers for optimizing oxygen yield.

The facility requires a daily average of approximately 3 tonnes of purified oxygen to supply the demands of smolt production. The A300 unit from NEL has the potential to produce oxygen in the range of 2.5 up towards in excess of 5 tonnes a day, where oxygen production surplus may be compressed and stored to ensure operational security.

Electrolyzer stack

Important economical parameters for this unit is presented in Table 4.10, where investment costs are calculated according to Table 4.2 and 4.3. The stack replacement cost has been set to ~26% of the AEL cost, according to the IRENA report [19], from where they state that capital costs estimate for large stacks (> 1 MW) is approximately €250/kW[1]. Using the estimated average cost from Table 4.3, this relation is found to be 26%. Cost for new cell stacks at the time of investments is calculated in Equation

[3] IRENA report uses \$270, which is approximately ~€250 as of June 3rd, 9:13 UTC +2 [1]

4.29 and 4.30:

$$€985,000 \cdot 0.26 = €256,100 \approx 2,650,635\ kr \tag{4.29}$$

First reinvestments for stack replacements happens in 2033, and cost is calculated with the aid of using the percentage reduction in prices:

$$€256,100 \cdot (1 - 0.0395)^{11} \approx €164,392 \approx 1,701,457\ kr \tag{4.30}$$

During the project lifetime of 20 years, there will only be one reinvestment in terms of new cell stack.

Compressors and storage

To find the cost for the two compressors (at the oxygen output and hydrogen output), Equations 4.12 and 4.13 are to be used. From the Aspen Plus simulation, we have a compressor duty at the oxygen side of ~12 kW. Using this as the capacity factor, we get:

$$\begin{aligned} log_{10}C_P &= 2.2897 + 1.3604 \cdot log_{10}(12) - 0.1027 \cdot (log_{10}(12))^2 \\ log_{10}C_P &= 3.638 \\ C_P &= 10^{3.638} = \$4,345 \end{aligned} \tag{4.31}$$

Inserting Equation 4.31 into Equation 4.12, and using F_{BM}=2.7, we get:

$$\begin{aligned} C_{BM} &= \$4,345 \cdot 2.7 \\ &= \$11,731 \end{aligned} \tag{4.32}$$

Using the CEPCI for February 2022, this price is adjusted as follows:

$$\$11,731 \cdot \frac{806.3}{394} \approx \$24,007 \approx 237,670\ kr \tag{4.33}$$

The compressor for the hydrogen storage system is calculated the same way, using a material bare module factor, F_{BM}=5.7 (stainless steel), and with a duty of ~23 kW. Adjusting this price as well, using the CEPCI, we end up with ~ \$104,447 (1,034,025 kr). This price can be verified by comparing it to NVE´s report [46], from where they have a slightly higher price at ~ \$136,000 (1,350,000 kr), but includes storage. Storage cost is calculated from Equation 4.14:

$$\begin{aligned} C_{tot_{stor}} &= 3 \cdot C_{stor} \cdot (\dot{V}_{H2} + \dot{V}_{O2}) \\ &= 3\ days \cdot 60\ €/Nm^3 \cdot (5063\ Nm^3 + 2531\ Nm^3) \\ &= €1,366,920 \approx 14,147,622\ kr \end{aligned} \tag{4.34}$$

Total costs for two compressors with 3 days of storage capacity, are thus found to be:

$$\sim 15,419,317\ kr \tag{4.35}$$

Revenues

The available amount of heat for sale as district heating was found in Table 4.8 to be ~21.4% of installed input energy. For this case, the amount of district heat available for sale is calculated as follows:

$$\begin{aligned} 24 \cdot \frac{365}{2} \cdot 0.9 \cdot 214 = 843,588\ kWh \text{ (6 month winter demand)} \\ 24 \cdot \frac{365}{2} \cdot 0.9 \cdot 214 \cdot 0.05 = 42,179.4\ kWh \text{ (6 month summer demand)} \end{aligned} \tag{4.36}$$

This results in a total demand of ~885,767 kWh per year, which is equivalent to ~73,814 kWh per month, below the 150,000 kWh limit for business plus plan according to Table 4.8. Thus, this gives a yearly revenue as follows:

$$\begin{aligned} R_{DH} &= 3170 \text{ øre} \cdot 12\ months + (42.2 \text{ øre/kWh} + 60 \text{ øre/kWh}) \cdot 885,767 \text{ kWh} \\ &\approx 905,635\ kr/year \end{aligned} \tag{4.37}$$

The hydrogen sales price is determined based on LCOH without funds from Enova. The revenue on a yearly basis for this case is thus:

$$R_{H_2} = 105.29\ kr/kgH_2 \cdot 149,796\ kg/year \approx 15,771,485\ kr/year \tag{4.38}$$

Collected values

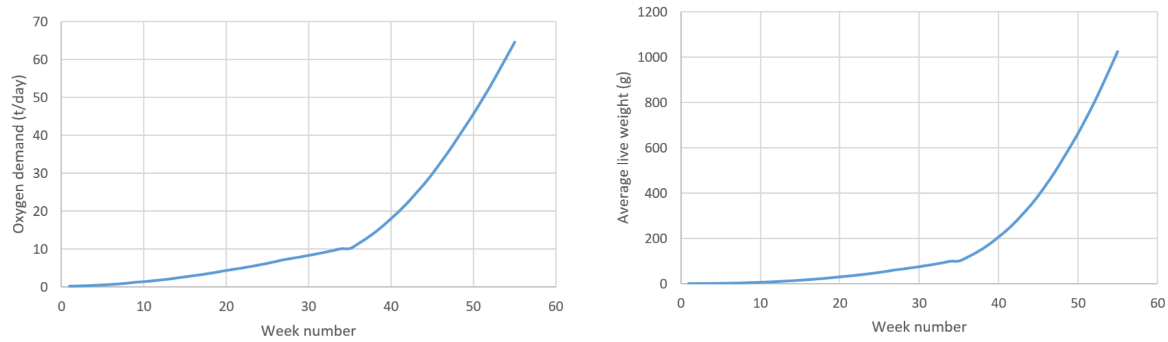
Collected values are presented in table 4.10, these are then transferred to Microsoft Excel, see **Appendix D**.

Table 4.10: Mean values of techno-economic data for a 1 MW AEL unit

Description	**Parameter**	**Value**	**Unit**
Revenues	Electrolyzer size	1	MW
	Stack lifetime	90,000	hours
	Real rate of retun	4.8	%
	District heating sales	905,635	kr/year
	Hydrogen sales	15,771,485	kr/year
OPEX	Maintenance cost	5	% of Capex [59]
	Electricity cost	81.44	øre/kWh
	labor cost	5,122,800	kr
CAPEX	Electrolyzer and equipment	10,194,750	kr
	Stack replacement cost	1,701,457	kr in 2033
	Construction costs	3,136,836	kr
	Design/administration	2,352,627	kr
	Compressors and storage	15,419,317	kr
Total investment cost		**32,804,988**	**kr**

4.4.2 Case 2: Medium scale facility

For this case, it is intended to use an AEL unit in the order of 5 MW to produce enough oxygen for a medium sized RAS. The facility grows post smolt to a size of approx. 1 kg before transferring to seawater. The oxygen demand and mean weight is presented in Figures 4.7a and 4.7b, where similarly to Case 1 a direct correlation between the two may be noticed. As with Case 1, it is assumed an even distribution of periodic release throughout the year, although only the total quantity and demands are shown here.



(a) Total oxygen demand per week for the growth of smolt in case 2

(b) Average body weight per week for the growth of smolt in case 2

Figure 4.7: Graphical presentations of oxygen demand and growth in case 2

The facility starts the production period with a quantity of 17,500,000 salmon roes hatched and grown to 1 kg, and the quantity is reduced to 13,747,886 at the end, which equates to a total biomass estimation of 14,000 tonnes. The average oxygen demand throughout the production period is roughly 15 tonnes a day, which is used as the dimensioning factor for the electrolyzer unit.

The economical details of the unit are carried out in Table 4.11, where the stack produces oxygen in the range of 10-16 tonne/day, depending on load and demand.

Electrolyzer stack

Cost for new cell stacks at the time of investments is calculated in Equation 4.39 and 4.40:

$$€4,925,000 \cdot 0.26 = €1,280,500 \tag{4.39}$$

First re-investments for stack replacements happens in 2033, and cost is calculated with the aid of using the percentage reduction in prices:

$$€1,280,500 \cdot (1 - 0.0395)^{11} \approx €821,960 \approx 8,507,286\ kr \tag{4.40}$$

During the project lifetime of 20 years there will only be one reinvestment in terms of new cell stack.

Compressors and storage

From the Aspen Plus simulation we had a compressor duty at the oxygen side of ∼12 kW and ∼23 kW at the hydrogen side, for case 1. In this case, 5 times more production of hydrogen and oxygen is assumed, thus increasing the compressor duties, accordingly. This yield compressor costs as follows:

$$\begin{aligned} log_{10}C_P &= 2.2897 + 1.3604 \cdot log_{10}(60) - 0.1027 \cdot (log_{10}(60))^2 \\ log_{10}C_P &= 4.383 \\ C_P &= 10^{4.383} = \$24,154 \end{aligned} \tag{4.41}$$

Using $F_{BM} = 2.7$ (carbon steel), we get:

$$\begin{aligned} C_{BM} &= \$24,154 \cdot 2.7 \\ &= \$65,215 \end{aligned} \tag{4.42}$$

Using the CEPCI for February 2022, this price is adjusted as follows:

$$\$65,215 \cdot \frac{806.3}{394} \approx \$133,459 \approx 1,381,300\ kr \tag{4.43}$$

The compressor for the hydrogen storage system is calculated the same way, using a material bare module factor, $F_{BM} = 5.7$ (stainless steel) and with a duty of ∼115 kW. Adjusting this price as well, using the CEPCI, we end up with ∼ \$528,293 (5,230,100 kr). Storage cost is calculated from Equation 4.14, using a cost of storage for steel tanks as 40 €/Nm^3:

$$\begin{aligned} C_{tot_{stor}} &= 3 \cdot C_{stor} \cdot (\dot{V}_{H2} + \dot{V}_{O2}) \\ &= 3\ days \cdot 40\ €/Nm^3 \cdot (25,315\ Nm^3 + 12,657\ Nm^3) \\ &= €4,556,640 \approx 47,161,224\ kr \end{aligned} \tag{4.44}$$

Total costs for two compressors with 3 days of storage capacity, are thus found to be:

$$\sim 53,772,624\ kr \tag{4.45}$$

Revenues

The available amount of heat for sale as district heating was found to be ∼21.4% of installed input energy. According to this percentage, case specifications is calculated as follows:

$$
\begin{aligned}
24 \cdot \frac{365}{2} \cdot 0.9 \cdot 1070 &= 4,217,940 \; kWh \text{ (6 month winter demand)} \\
24 \cdot \frac{365}{2} \cdot 0.9 \cdot 1070 \cdot 0.05 &= 210,897 \; kWh \text{ (6 month summer demand)}
\end{aligned}
\tag{4.46}
$$

This results in a total demand of ∼4,428,837 kWh per year, which is equivalent to ∼369,070 kWh per month, well above the 150,000 kWh limit for business plus plan according to Table 4.8. Thus, this gives a yearly revenue as follows:

$$
\begin{aligned}
R_{DH} &= 69,900 \text{ øre} \cdot 12 \; months + (37.2 \text{ øre/kWh} + 60 \text{ øre/kWh}) \cdot 4,428,837 \text{ kWh} \\
&\approx 4,313,218 \; kr/year
\end{aligned}
\tag{4.47}
$$

The hydrogen sales price is determined based on LCOH without funds from Enova. The revenue on a yearly basis for this case is thus:

$$
R_{H_2} = 72.13 \; kr/kgH_2 \cdot 747,977 \; kg/year \approx 53,953,058 \; kr/year \tag{4.48}
$$

Collected values

Collected values are presented in table 4.11, these are then transferred to Microsoft Excel, see **Appendix D**.

Table 4.11: Mean values of economic data for a 5 MW AEL unit

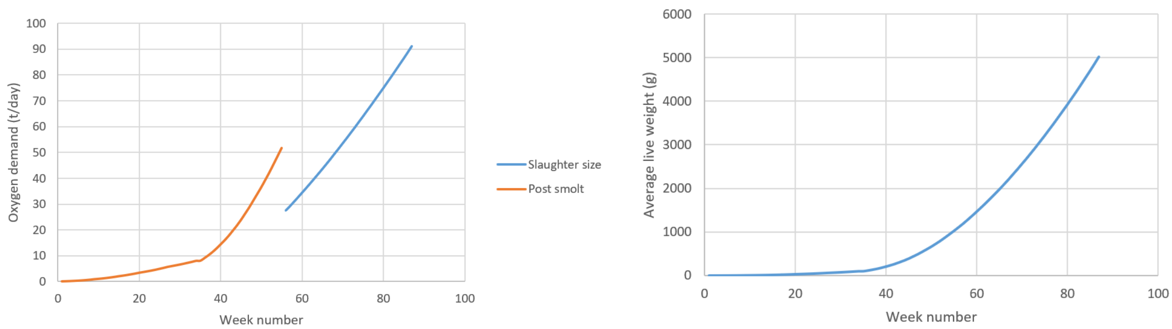
Description	**Parameter**	**Value**	**Unit**
Revenues	Electrolyzer size	5	MW
	Stack lifetime	90,000	hours
	Real rate of return	4.8	%
	District heating sales	4,313,218	kr/year
	Hydrogen sales	53,953,058	kr/year
OPEX	Maintenance cost	4	% of Capex [59]
	Electricity cost	81.44	øre/kWh
	Labor cost	5,122,800	kr/year
CAPEX	Electrolyzer and equipment	50,973,750	kr
	Stack replacement cost	8,507,286	kr in 2033
	Construction costs	15,684,235	kr
	Design/administration	11,763,179	kr
	Compressors and storage	53,772,624	kr
Total investment cost		**140,701,074**	**kr**

4.4.3 Case 3: Large scale facility

The final case addresses a large RAS facility split between post smolt production in addition to producing full size salmon of roughly 5 kg. The case is heavily inspired by Viking Aqua's planned 33,000 tonne RAS facility in Skipavika, Norway [72].

The facility considered in this case study produces roughly 5,600 tonnes of post smolt and 27,400 tonnes of full size salmon weighing in at approximately 5 kg. A total estimate of 14,000,000 salmon roes make up the demand for the scale of the facility, where 5,454,275 post smolt and 5,466,609 full size salmon are produced, applying the same parameters to the growth model as have been conducted in the previous cases.

A RAS setup of the scale and extent of the case presented here requires a substantial amount of oxygen supplied throughout the production period. The oxygen demand and average body weight may be seen represented in Figures 4.8a and 4.8b, where the discontinuity observed in Figure 4.8a is due to the export of post smolt from the facility. Based on discussions with representatives at Viking Aqua, the daily oxygen demand for such a facility is in the range of 50 tonne/day [73].



(a) Total oxygen demand per week for the growth of smolt in case 3

(b) Average body weight per week for the growth of smolt in case 3

Figure 4.8: Graphical presentations of oxygen demand and growth in case 3

Electrolyzer stack

Figure 4.9 gives the estimated total price, not including the compressor and storage.

Figure 4.9: Price estimation for total cost in case 3

Yellow line represents costs obtained from an industry expert [58]. The triangles are real costs associated with 1, 5 and 15 MW system, but are not to date. The grey line represents the cost found earlier in this thesis, 985 €/kW. As this is a linear price estimate, it overshoots a lot when it comes to scaling of large systems (>10 MW). The red line with the yellow squares, located at 1 MW and 5 MW, are the price estimates for the two earlier cases. These two estimates are confirmed to be realistic by a technology user [47], thus the trend of the red graph can be confirmed to behave realistically according to old data (yellow line) and the two earlier cases. From this it can already be decided that the price has to follow the trend of the yellow line, only a bit lower. Using the earlier linear price (grey line), the data obtained from an expert, as well as the blue line, from which the estimates was found by Parra and Patel [74] for very large systems, a new price estimate can be found. The blue line is a bit low in pricing the two earlier cases, as well as a realistic case 3 price, thus this is set to be the minimum value. The grey line is set to be the maximum value, and we know that the yellow is real, but a bit high due to old data. Taking these average prices at 15 MW, the last square in the red line can be found. This price is confirmed using the Danish Energy Agency report [21] (green line), from which they estimate an almost equal total price at 15 MW. This total price estimate are thus found to be:

$$\sim €10,040,000 \approx 103,914,000\ kr \tag{4.49}$$

Cost for new cell stacks at the time of investment is calculated in Equation 4.50 and 4.51:

$$€10,040,000 \cdot 0.65 \cdot 0.26 = €1,696,760 \tag{4.50}$$

First re-investments for stack replacement happens in 2033, and cost is calculated with the aid of using the percentage reduction in prices:

$$€1,696,760 \cdot (1 - 0.0395)^{11} \approx €1,089,159 \approx 11,272,795\ kr \tag{4.51}$$

There will only be one re-investment in terms of a new cell stack in this case study as well.

Compressors and storage

In this case, it is assumed 15 times more production of hydrogen and oxygen, thus increasing the compressor duties accordingly to ~180 kW and ~345 kW, respectively. These values yield compressor costs as follows, using the same steps as in case 1 and 2 with carbon steel for the oxygen compressor and stainless steel for the hydrogen compressor:

$$\begin{aligned} \text{Oxygen compressor} &= \$377,886 \approx 3,741,077\ kr \\ \text{Hydrogen compressor} &= \$1,402,409 \approx 13,883,849\ kr \end{aligned} \tag{4.52}$$

Storage cost is calculated from Equation 4.14, using a cost of storage for steel tanks as 20 €/Nm^3:

$$\begin{aligned} C_{tot_{stor}} &= 3 \cdot C_{stor} \cdot (\dot{V}_{H2} + \dot{V}_{O2}) \\ &= 3\ days \cdot 20\ €/Nm^3 \cdot (75,945\ Nm^3 + 37,972\ Nm^3) \\ &= €6,835,020 \approx 70,742,457\ kr \end{aligned} \tag{4.53}$$

Total costs for two compressors with 3 days of storage capacity, are thus found to be:

$$\sim 88,367,383\ kr \tag{4.54}$$

Revenues

The available amount of heat for sale as district heating was found to be ~21.4% of installed input energy. The amount of district heat available for sale according to this particular case and specifications, is calculated as follows:

$$\begin{aligned} 24 \cdot \frac{365}{2} \cdot 0.9 \cdot 3210 &= 12,653,820\ kWh \text{ (6 month winter demand)} \\ 24 \cdot \frac{365}{2} \cdot 0.9 \cdot 3210 \cdot 0.05 &= 632,691\ kWh \text{ (6 month summer demand)} \end{aligned} \tag{4.55}$$

This results in a total demand of ~13,286,511 kWh per year, which is equivalent to ~1,107,209 kWh per month, well above the 150,000 kWh limit for business plus plan according to Table 4.8. Thus, this gives a yearly revenue as follows:

$$\begin{aligned} R_{DH} &= 69,900 \text{ øre} \cdot 12\ months + (37.2 \text{ øre/kWh} + 60 \text{ øre/kWh}) \cdot 13,286,511 \text{ kWh} \\ &\approx 12,922,877\ kr/year \end{aligned} \tag{4.56}$$

The hydrogen sales price is determined based on LCOH without funds from Enova. The revenue on a yearly basis for this case is thus:

$$R_{H_2} = 54.04\ kr/kgH_2 \cdot 2,243,931\ kg/year \approx 121,198,821\ kr/year \tag{4.57}$$

Collected values

Collected values are presented in table 4.12, these are then transferred to Microsoft Excel, see **Appendix D**. The share and breakdown of costs is given in Figure 4.10 for easy presentation purposes.

Table 4.12: Mean values of economic data for a 15 MW AEL unit

Description	Parameter	Value	Unit
Revenues	Electrolyzer size	15	MW
	Stack lifetime	90,000	hours
	Real rate of return	4.8	%
	District heating sales	12,922,877	kr/year
	Hydrogen sales	121,256,696	kr/year
OPEX	Maintenance cost	3	% of Capex [59]
	Electricity cost	79.46	øre/kWh
	Labor cost	5,122,800	kr
CAPEX	Electrolyzer and equipment	67,544,100	kr
	Stack replacement cost	11,272,795	kr in 2033
	Construction costs	20,782,800	kr
	Design/administration	15,587,100	kr
	Compressors and storage	88,367,383	kr
Total investment cost		**203,554,178**	**kr**

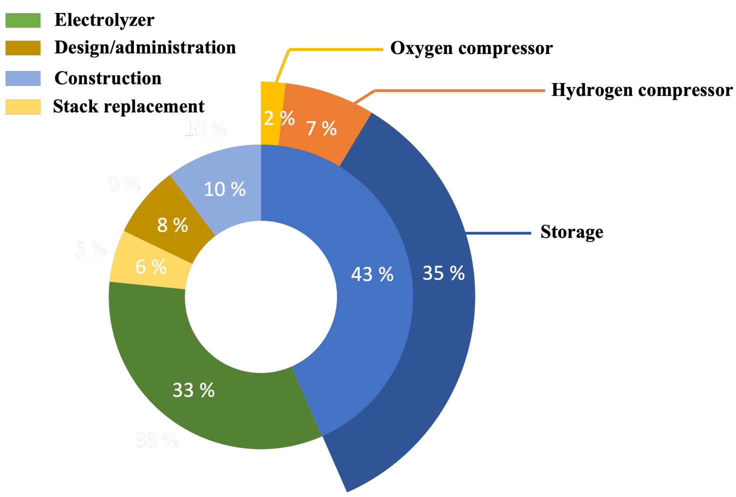


Figure 4.10: Share and breakdown of investment costs in case 3

Chapter 5

Results and discussion

5.1 Levelized cost of hydrogen

The lowest costs of hydrogen in kr/kg are given in Table 5.1 for each case. The values are calculated according to Equation 4.25. The costs are presented with Enova support, without support as well as with- and without compressor and storage.

Table 5.1: Levelized costs of hydrogen produced from the cases with and without Enova support, presented in NOK/kg

	Without compressor & storage		**With compressor & storage**	
	No support	Support	No support	Support
Case 1	96.27	92.55	105.29	97.51
Case 2	65.56	61.84	72.13	65.45
Case 3	37.36	**35.72**	40.86	37.64

The lowest cost achieved is 35.72 kr/kg H_2. This is without the investment cost of compressor and storage, and with Enova support of 45% of the initial investment cost. DNV [26] considers a price between ~23 and ~43 kr/kg to be realistic in Norway. Keeping this in mind, one can see that case 1 and 2 gets too expensive, but the cost is decreasing as the systems get larger in size. According to that same DNV [26] report, the cost of using another process, in this case, steam methane reforming (SMR), they found that a realistic price is between ~9.5 and ~15.3 kr/kg H_2, including carbon capture and storage (CCS). SMR, even with CCS, gives the cheapest production cost, but the hydrogen produced is blue hydrogen, which is not considered as clean as green hydrogen [75]. If the average production costs using SMR-CCS and PEM, with numbers from DNV, are compared to this report with the lowest production cost achieved, we see in Table 5.2 the percentage size for how much case 3 compares to other technologies.

Table 5.2: Comparing the best scenario of case 3, with numbers from DNV [26]. Please note that this report is from 2019, and their numbers are from 2017

Technology	**kr/kg H_2**	**Difference in %**
Case 3 AEL	35.72	~7.6%
DNV PEM	~41.5	-16.2%
DNV SMR-CCS	~12.4	~34.7%

We have in Table 5.2, that the best scenario in case 3, 35.72 kr/kg H_2, is compared to the AEL cost from DNV, which is found to be an average of ~33 kr/kg H_2, as well as their PEM and SMR-CCS analysis. PEM was found to have an average cost which is ~16.2% higher than case 3 AEL, and SMR-CCS was found to be ~34.7% cheaper than case 3 AEL. Case 3 shows that it is well within expected costs, and deviates approximately by 7.6%, considering DNV´s AEL analysis in Norway. Costs are expected to be lower if the system has its own electricity production systems, as this power is exempt from grid rent costs [26]. These may include own hydropower plants or wind power plants.

5.2 Production costs

Using oxygen and heat as yearly sales, it is possible to attain lower production costs for hydrogen in kr/kg H_2. For all cases, it was assumed that the oxygen was sold at 2 kr/kg. This price is verified by an industry expert [58] and NVE [[46], [63]], which all states that 2 kr/kg for high volumes and 4 kr/kg for low volumes can be expected.

Table 5.3: Production costs of hydrogen, with and without Enova support presented in NOK/kg

	Without compressor & storage		**With compressor & storage**	
	No support	Support	No support	Support
Case 1	71.35	68.99	77.06	72.14
Case 2	40.90	38.54	45.06	40.83
Case 3	27.57	**26.52**	29.79	27.74

Using the best scenario from Table 5.3, case 3 with Enova support and with no compressor and storage, costs get as low as 26.52 kr/kg H_2. This is well within expected costs, and is ~24.4% cheaper than the average cost given by DNV [26].

5.3 Net present value

Table 5.4 gives the net present value for each case, as well as the calculated internal rate of return, with and without Enova support. The calculations are done in Microsoft

Excel, and the spreadsheet for each case can be viewed in **Appendix D**.

Table 5.4: Net present value and internal rate of return for the cases with and without Enova support, presented in NOK

	Without support		**With support**	
	NPV	Internal rate of return	NPV	Internal rate of return
Case 1	11,480,082	8.61%	26,242,327	18.74%
Case 2	54,675,569	9.00%	117,991,052	19.34%
Case 3	163,814,050	13.00%	255,413,430	25.62%

5.4 Cost estimates

Estimates for all three cases are given in Table 5.5, where both the lowest and highest expected cost range was calculated according to Equations 4.27-4.28.

Table 5.5: Low and high cost estimates in NOK

	Lowest expected cost range		**Highest expected cost range**	
	Low value	High value	Low value	High value
Case 1	28,868,389	38,709,885	17,058,593	56,424,579
Case 2	123,816,945	166,027,267	73,164,558	242,005,847
Case 3	179,127,676	240,193,930	105,848,172	350,113,186

The actual expected range would depend on the level of project definition and effort. If the effort and definition of the project are at the higher end, then the expected cost range should be in the first two columns of Table 5.5. If the effort and definition are at the low end, then the expected cost range should be in the last two columns of Table 5.5. In this report it is presumed that the effort and definition are at the higher end, thus, the *lowest expected cost range* is the most realistic costs associated with case 1, 2 and 3, given in NOK.

5.5 Sensitivity analysis

Sensitivity analysis of case 3 was done as this is the most interesting case to look at in terms of Viking Aqua´s goals. Figure 5.1 gives the production costs of hydrogen in kr/kg based on an electricity price ranging from 10 øre/kWh up to 100 øre/kWh, as well as a difference in oxygen sales price from 0.5 kr/kg up to 5 kr/kg. The color is ranging from red (high-range) to green (low-range) and yellow (mid-range). Keep in mind that these electricity prices are total, thus including grid rent fees and taxes. NVE [76] estimated

	Electricity price [øre/kWh]																			
Oxygen price [kr/kg]	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
0,5	11,71	14,71	17,71	20,71	23,70	26,70	29,70	32,70	35,69	38,69	41,69	44,69	47,69	50,68	53,68	56,68	59,68	62,67	65,67
1,0	7,74	10,74	13,74	16,74	19,73	22,73	25,73	28,73	31,73	34,72	37,72	40,72	43,72	46,72	49,71	52,71	55,71	58,71	61,70
1,5	3,78	6,77	9,77	12,77	15,77	18,76	21,76	24,76	27,76	30,76	33,75	36,75	39,75	42,75	45,75	48,74	51,74	54,74	57,74
2,0	-0,19	2,81	5,80	8,80	11,80	14,80	17,79	20,79	23,79	26,79	29,79	32,78	35,78	38,78	41,78	44,77	47,77	50,77	53,77
2,5	-4,16	-1,16	1,83	4,83	7,83	10,83	13,83	16,82	19,82	22,82	25,82	28,82	31,81	34,81	37,81	40,81	43,80	46,80	49,80
3,0	-8,13	-5,13	-2,13	0,86	3,86	6,86	9,86	12,86	15,85	18,85	21,85	24,85	27,85	30,84	33,84	36,84	39,84	42,83	45,83
3,5	-12,10	-9,10	-6,10	-3,10	-0,11	2,89	5,89	8,89	11,89	14,88	17,88	20,88	23,88	26,87	29,87	32,87	35,87	38,87	41,86
4,0	-16,07	-13,07	-10,07	-7,07	-4,07	-1,08	1,92	4,92	7,92	10,92	13,91	16,91	19,91	22,91	25,90	28,90	31,90	34,90	37,90
4,5	-20,03	-17,04	-14,04	-11,04	-8,04	-5,04	-2,05	0,95	3,95	6,95	9,95	12,94	15,94	18,94	21,94	24,93	27,93	30,93	33,93
5,0	-24,00	-21,00	-18,01	-15,01	-12,01	-9,01	-6,01	-3,02	-0,02	2,98	5,98	8,97	11,97	14,97	17,97	20,97	23,96	26,96	29,96

Figure 5.1: Production cost for case 3 with different costs and sale prices. These values are for the entire project, including Enova support of 45%

	Hydrogen price [kr/kg]											
Oxygen price [kr/kg]	45	50	55	60	65	70	75	80	85	90	95	100
0,5	20	162	304	446	589	731	873	1 015	1 157	1 300	1 442	1 584
1,0	132	275	417	559	701	844	986	1 128	1 270	1 412	1 555	1 697
1,5	245	388	530	672	814	956	1 099	1 241	1 383	1 525	1 668	1 810
2,0	358	500	643	785	927	1 069	1 212	1 354	1 496	1 638	1 780	1 923
2,5	471	613	756	898	1 040	1 182	1 324	1 467	1 609	1 751	1 893	2 036
3,0	584	726	868	1 011	1 153	1 295	1 437	1 580	1 722	1 864	2 006	2 148
3,5	697	839	981	1 124	1 266	1 408	1 550	1 692	1 835	1 977	2 119	2 261
4,0	810	952	1 094	1 236	1 379	1 521	1 663	1 805	1 948	2 090	2 232	2 374
4,5	923	1 065	1 207	1 349	1 491	1 634	1 776	1 918	2 060	2 203	2 345	2 487
5,0	1 035	1 178	1 320	1 462	1 604	1 747	1 889	2 031	2 173	2 315	2 458	2 600

Figure 5.2: NPV in million NOK for different hydrogen and oxygen sale prices for case 3. These values are for the entire project, excluding Enova support of 45%

that an electricity price downwards of 26 øre/kW can be achieved in areas with good wind resources for a wind turbine. Using this as well as an oxygen sales price of 2 kr/kg, we can see from Figure 5.1 that a production cost could go as low as ~8.80 kr/kg H_2. From Figure 5.2 the NPV of case 3 in million NOK for different sale prices of hydrogen and oxygen are given. In this analysis the same amount of district heat is kept constant, as in the original case study of case 3. If we consider the artificial price of hydrogen at 72 kr/kg H_2, covered in Section 4.3.3.1, and still keep the same oxygen sale price of 2 kr/kg O_2, the NPV of the total project will be approximately 1.12 billion NOK. The corresponding internal rate of return of the NPV values in Figure 5.2 can be seen in Figure 5.3.

	Hydrogen price [kr/kg]											
Oxygen price [kr/kg]	45	50	55	60	65	70	75	80	85	90	95	100
0,5	5,90 %	12,91 %	19,07 %	24,89 %	30,55 %	36,13 %	41,68 %	47,21 %	52,73 %	58,25 %	63,76 %	69,28 %
1,0	11,56 %	17,84 %	23,71 %	29,39 %	34,98 %	40,54 %	46,07 %	51,59 %	57,11 %	62,63 %	68,14 %	73,65 %
1,5	16,59 %	22,51 %	28,22 %	33,83 %	39,39 %	44,93 %	50,45 %	55,97 %	61,49 %	67,00 %	72,51 %	78,03 %
2,0	21,32 %	27,06 %	32,68 %	38,25 %	43,79 %	49,32 %	54,83 %	60,35 %	65,86 %	71,38 %	76,89 %	82,40 %
2,5	25,88 %	31,53 %	37,10 %	42,65 %	48,18 %	53,70 %	59,21 %	64,73 %	70,24 %	75,75 %	81,26 %	86,78 %
3,0	30,37 %	35,96 %	41,50 %	47,04 %	52,56 %	58,07 %	63,59 %	69,10 %	74,61 %	80,13 %	85,64 %	91,15 %
3,5	34,81 %	40,36 %	45,89 %	51,42 %	56,94 %	62,45 %	67,96 %	73,48 %	78,99 %	84,50 %	90,01 %	95,53 %
4,0	39,22 %	44,75 %	50,28 %	55,80 %	61,31 %	66,83 %	72,34 %	77,85 %	83,36 %	88,88 %	94,39 %	99,90 %
4,5	43,61 %	49,14 %	54,66 %	60,17 %	65,69 %	71,20 %	76,71 %	82,23 %	87,74 %	93,25 %	98,76 %	104,27 %
5,0	48,00 %	53,52 %	59,04 %	64,55 %	70,06 %	75,58 %	81,09 %	86,60 %	92,11 %	97,62 %	103,14 %	108,65 %

Figure 5.3: Internal rate of return for case 3 with different hydrogen and oxygen sale prices. These rates are for the entire project, excluding Enova support of 45%

5.6 Energy analysis

All three cases have available excess energy, which in this project has been regarded as a possible revenue in terms of district heat. Keeping the correct water temperature in the RAS is an important feature for the well-being of the fish. Several fish species have different preferences in terms of temperature, thus utilizing a possible way to use the available excess energy. A common temperature for salmon farming is 12°C, neglecting heavy usage of heat transfer to warm up the water. The Norwegian sea-waters had an average of ~10.9°C [77] at 25th of June 2022. Just to give a prospect on the scale of case 3, a quick calculation can be made to find if the available energy is enough in order to maintain a stable temperature of 12°C. From interview with Trond Ove Høie [73] it was stated that Viking Aqua´s RAS is going to have 400,000 m^3/h of circulating water. This corresponds to 111,111.1 kg/s, assuming a density of 1000 kg/m^3. Using a specific heat capacity for water at 4.18 kJ/kg, raising the temperature only 1.1 degrees, from 10.9°C to 12°C, the energy required can be calculated as follows:

$$
\begin{aligned}
Q &= \dot{m} \cdot S_{Hw} \cdot \Delta T \\
&= 111,111.1 \cdot 4.18 \cdot (12 - 10.9) \\
&\approx 510,888\ kW \\
&\approx 4,027,840,992\ kWh/year
\end{aligned}
\tag{5.1}
$$

A massive 159 times greater energy demand than what is available annually by the 15 MW AEL unit in terms of heat if 1.1 degrees celsius was a fixed assumed difference in temperature.

5.7 Uncertainties

Here we will discuss some of the uncertainties encountered in the case studies. These range from the simulation model itself, where different errors in design and modeling of the system may have issues according to a realistic point of view, to the techno-economic analysis. Several points in the analysis are assumed values which may not represent a realistic case.

5.7.1 Simulation model

- **Model parameters**
  The model parameters of which were described in detail in Section 4.2, may be less suitable for upscaled simulation setups such as 1 MW input to the stack. The parameters are verified through lab tests of the performance of a 15 kW electrolyzer stack, and it is therefore uncertain if the accuracy is indeed impacted for the 1

MW simulation setup.

- **Heat loss factor**
  The heat loss factor is a set value which represents the heat loss to the surroundings. In the model it is preset to 0.1 (10%), but when up-scaling to 1 MW, it was initially increased in order to hold a temperature in the cell stack to 75°C. However, this in turn negatively affected the production rates and hence the efficiency of the custom stack model, and it was determined to keep the original preset of 0.1.

- **Oxygen demand**
  From Figures 4.6a, 4.7a and 4.8a one can note that the oxygen demand is not constant. This is due to the growth of the fish where an increased body weight results in more consumed oxygen. In the case studies, the oxygen demand has been at a constant value of which is the average demand throughout the year. In reality, the production of oxygen should be less in the beginning of the year and then slightly ramping it up towards the end of the year. From the figures, the demand through the year is increasing exponentially. A certain amount of stored oxygen should of course be taken into consideration to supply when the growing demand is larger, and when maintenance and shutdowns are due.

5.7.2 Techno-economic analysis

- **Electrolyzer price**
  The chosen price has been estimated by calculating an average sum of pre-existing values and data stated from different studies and literature. These may not be representative in terms of "deal packages" one can get from manufacturers, where other machines and equipment (compressors, storage etc.) may be included. The price is also listed in "price/kW" for easy scaling purposes. The problem with this is that scaling from e.g 1 MW to 2 MW doesn't necessarily give a double amount in costs, as the electrolyzer system in itself doesn't have to be double in size in terms of construction, site preparations as well as machines and equipment.

- **Compressor and storage**
  The oxygen compressor cost is calculated using a material factor representing carbon steel, while high austenitic stainless steel is assumed to be used both for the compression unit and storage on the hydrogen side. This is due to hydrogen embrittlement, which can occur with carbon steel [78]. In reality, the industry often use a diaphragm compressor for hydrogen. This proved to be difficult to find accurate prices for in terms of size and capacity, and thus, stainless steel was the chosen material type. The storage cost are also assumed to be in the order of

60/40/20 €/Nm^3 with case 1/2/3, respectively. This is mainly argumented for by using the economies of scale principle, where often larger systems and units will provide cheaper cost per unit. This might not be realistic in terms of the true cost of storage, where probably hydrogen storage would have a higher price than oxygen.

- **Electricity price**
  The thesis uses the LMA from NVE [54] and Statkraft [57]. Both analyzes give roughly the same electricity price in the long run, approx. 40-50 øre/kWh. However, for conservative measures, this thesis uses 60 øre/kWh as an annual expense. This price is very unpredictable, and as mentioned in previous sections, it is difficult to say specifically what this will be on an annual basis. Fluctuations will occur weekly, monthly or by political means or news, which should or can be taken into account. By using the sensitivity analysis, it makes it possible to look at the electricity price with the oxygen sales price, in order to more easily see the costs for produced hydrogen in NOK/kg H_2

- **District heating prices** The calculations exclude cost of infrastructure for district heating and heat recovery. This has to be considered when doing a more realistic case analysis. Also the price is assumed to be constant in winter and summer, while in reality the price will follow the electricity price to a large extent.

- **Land cost**
  Has not been accounted for. This is due to difficulty of getting real numbers for these associated costs. Normally, land cost is a large sum in the investment costs for the calculation of CAPEX in a project period, but because the thesis is mainly focusing on existing RAS, we assumed that the land area has already been acquired.

- **Labor cost**
  Is included in the OPEX, and although accounted for in terms of real data from Statistics Norway, will not be realistic in the long run. Labor cost is something that is negotiated annually by means of collective agreements. This is therefore something that can change from year to year during the project period, and will thus never truly be accurate in the long run. This is also true for any additions including in the salary, such as shift allowance for instance. The labor cost is also chosen to be the same for each case, when in reality this may not be true.

- **Inflation**
  The inflation factor is a set value from which is calculated using the long-term inflation. The long-term inflation is given by Statistics Norway, but is an ever changing variable renewed by a monthly basis. This is difficult and will not be

accurate to account for in a long-term scenario.

- **End of project period**
  Usually there is either a cost related to the demolition of the plant at the end of the project period (as a % of CAPEX), or earnings in terms of selling the equipment and land. This is something to consider at the last year of the project period, but is not accounted for in this analysis.

- **Maintenance costs**
  Due to the alkaline environment flowing through the AEL stacks, degradation related to corrosion of anode and cathode material and general wear over time may influence maintenance costs. In this report the costs are assumed as a fixed % of CAPEX per year, and therefore added costs due to stack degradation is disregarded. Yearly use of KOH as well as feed water is also included in the fixed % of CAPEX per year, rather than being calculated based on the real yearly amount. The feed water is assumed to be clean de-ionized water, which in itself have a cost to produce/buy, with its own system and process.

- **Cost estimates**
  The main reasons why capital cost estimates may be underestimated, comes from failure to include all of the equipment needed in the process. Typically, as a design progresses, the need for additional equipment is uncovered, and the estimate accuracy improves. In our estimates, additional equipment other than those mentioned in the overall thesis is not covered, which of course will contribute to estimation errors.

Chapter 6

Conclusion

Throughout the thesis, we have performed theoretical modeling of alkaline water electrolysis, using simulation tools, to achieve the production capacities needed for three different RAS sizes; small, medium and, large. The purpose was to determine the demands of the oxygenation units along with a given fish species and the number of quantity of fish in the system, as well as achievable cost impacts on hydrogen, including a sensitivity analysis and comparing different scenarios in a techno-economic sense.

The results show that it is preferred to invest in a large-scale 15 MW alkaline electrolysis system, if Enova support and all assumptions is provided. This will yield in an internal rate of return of 25.62%, with a net present value of approximately 255,413,430 NOK if considering a sales price of the hydrogen using the calculated LCOH. The total cost estimated for realizing such a project have an expected cost range between 179,127,676 kr and 240,193,930 kr. The lowest production cost of hydrogen was found to be 26.52 kr/kg H_2, excluding the investment cost of the compressor and storage system, and with an oxygen sales price of 2 kr/kg O_2 and revenues from district heating.

Three general questions were presented in Section 1.2 to be answered in the thesis. Regarding the technical feasibility of the system, a solution has been proposed with the inclusion of compression and storage units to act as a buffer and security for the supply of oxygen to the oxygenation units. Furthermore, the oxygen demand has been modeled both with regards to the oxygen consumption of Atlantic salmon and the production rates of alkaline electrolyzers. Last, but not least, the acquired data from modeling has been used further to perform a detailed cost analysis for each of the cases to study achievable cost impact on hydrogen, scenario comparisons and sensitivity analyses of relevant economical variables.

6.1 Important findings

This thesis indicates that it is possible to achieve a reasonable production cost for hydrogen which is within real estimates using economies of scale in synergistic processes with RAS. A scale-up of the combined facilities proves to be economically beneficial for both parties involved where a lower production cost of hydrogen is achieved, which again may influence the price of oxygen sold to the adjacent RAS facility.

6.2 Further work

Current research and quality of estimates would benefit greatly from further research. Enlisted below are bulletins that provide more detail on key points as a suggestion for improving this thesis further.

6.2.1 Model improvements

- **Cooling water loop**
  Due to a model limitation in mass flow (1000 kg/h) for the cooling water loop, upscaling the electrolyzer stack model from the original 10 kW stack is difficult. This limitation leads to higher operating temperatures leaving the stack for the 1 MW model (as seen in Appendix A), and bigger problems might occur during further scale-up. A solution is to increase the heat loss factor from the stack itself, which may be altered in the model, although this ultimately affects the production rates and efficiency of the process. Other alternatives include increasing the outlet temperature of cooling fluid leaving IC-R1 and IC-R2, and likewise decreasing the inlet temperature to increase the heat transfer from the electrolyte stream to the cooling stream. Again by altering these parameters, logic must be applied to make sure the temperatures stay within the range of what may be deemed realistic for a cooling loop and for the equipment as well.

- **Electrolyte**
  As stated in chapter 4, section 4.1, KOH is added as a component in order to model the *heat capacity* more accurately, and *explicit electrolyte chemistry* is not modeled. This can have impact on the model. The reason why KOH is utilized is due to its special properties in that it has a large specific conductivity. From the Aspen Physical Property System [79], they state that:

  > *In electrolyte solutions a larger variety of interactions and phenomena exist than in non-electrolyte solutions. Besides physical and chemical molecule interactions, ionic reactions and interactions occur (molecule-ion and ion-ion). Electrolyte activity coefficient models (NRTL, Pitzer)*

are therefore more complicated than non-electrolyte activity coefficient models. Electrolytes dissociate so a few components can form many species in a solution. This causes a multitude of interactions, some of which are strong.

This is difficult to model accurately, but should be considered to ensure a more realistic case.

As shown in Figure 6.1, one can see how different mass fractions can affect specific conductivity [43]. The fact that 35% wt is used can affect the model in the form of lower efficiencies, compared with a somewhat lower (25-27% wt) fraction (which is used by NEL [34]). Implementing an electrolyte package in Aspen will probably improve the results in the model.

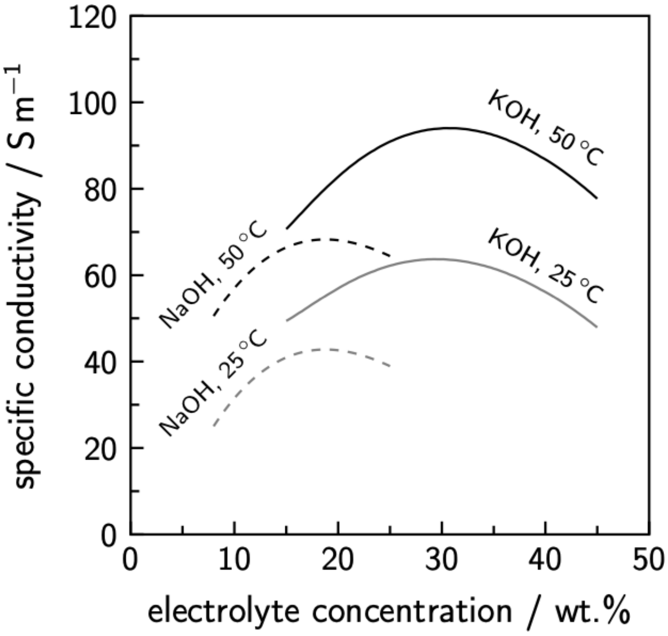


Figure 6.1: Specific electrolyte conductivity as a function of the concentration of potassium hydroxide (KOH) [43]

6.2.2 Techno-economic analysis

- **Equipment cost**
  Equipment such as pumps, vessels, heat-exchangers etc. has not been calculated separately in terms of costs as it probably should. The unit price should be calculated according to operating pressures, temperatures, as well as the type of material. Whether it is a stainless steel alloy or carbon steel can cause a large impact on the bare module costs. This should thus be accounted for in further work of a similar system in order to get a more accurate capital expenditure of the system with its components.

- **Variation in H_2 price and electricity**
  The hydrogen price will most likely vary in the same way and possibly as much as the electricity price, according to technology user [47]. It would therefore be interesting to investigate how flexible production could have been used, where the price of electricity or the price of hydrogen (set against each other) determines the capacity and production of the electrolyzer and the system. An optimized operation according to what is required of oxygen in the RAS in a daily or weekly timeframe. If one also takes into account the cooling of hydrogen to approx. minus 253°C, to be more accessible for the maritime sector, and uses financial hedging [80] as a security measure for future spot prices, the project could be even more sustainable, flexible and economical.

6.2.3 Other variables

- **Energy utilization with other fish species**
  It would be interesting to check in more detail how much of the excess energy realistically could be used. Salmon have a relatively low comfort temperature of around 12°C, but for example Yellowtail kingfish (Seriola lalandi) have a slightly higher comfort temperature. Orellana et al. [81] did an experiment where they kept this type of fish alive in a RAS for 488 days. In addition to other important parameters (pH, mineral level, oxygenation etc.), keeping a higher temperature was central. Here, the average temperature was 22.6°C $\pm$ 1.4°C, with the lowest value at 15.1°C and the highest at 28.3°C, represented by winter and summer time, respectively. Thus, a proposal for further work regarding a more detailed look into how large a RAS could realistically be when keeping these temperatures just by using the excess energy, is given. Other proposed aquaculture species may include Western king prawns (Penaeus latisulcatus) or Green seaweed (Ulva lactuca), which was experimented upon by Khoi and Fotedar [82], where the temperature was kept steady between 24°C and 25°C.

- **Local energy production and environmental aspects**
  The possibilities of local energy production and environmental aspects should be investigated. Examples may include solar photovoltaic´s on the roof of the RAS facility, local windpower- onshore or offshore, or nearby biogas reactors utilizing the waste products from the fish in order to produce natural gas and hydrogen. These may act as a backup fuel for a gas turbine, or as a locally produced fuel for local transport. The CO_2 from the biogas reactor may be used in a greenhouse for vegetable production [83]. These examples just goes to show how far this concept can be stretched, minimizing the environmental impacts as well as working as an example of circular economy in practice.

References

[1] Valutakalkulator, *Den norske Bank*, Accessed: June 14 2022. (2022), [Online]. Available: https://www.dnb.no/markets/valuta-og-renter/valutakalkulator.

[2] United Nations, "World Population Prospects 2019," p. 37, 2019, United Nations, Department of Economic and Social Affairs, Population Division, ISBN:978-92-1-148316-1. [Online]. Available: https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf.

[3] ——, "Global Population Growth and Sustainable Development," p. 22, 2021, United Nations, Department of Economic and Social Affairs, Population Division, ISBN:978-92-1- 005246-7. [Online]. Available: https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undesa_pd_2022_global_population_growth.pdf.

[4] Food and Agriculture Organization of the United Nations (FAO), "The state of world fisheries and aquaculture 2020," 2020, Sustainability in action. Rome., ISSN: 2410-5902. DOI: https://doi.org/10.4060/ca9229en. [Online]. Available: https://www.fao.org/3/ca9229en/ca9229en.pdf.

[5] R. L. Naylor, R. W. Hardy, A. H. Buschmann, *et al.*, "A 20-year retrospective review of global aquaculture," *Nature*, vol. 591, pp. 551–563, 2021, Published online: 24 March 2021. DOI: https://doi.org/10.1038/s41586-021-03308-6. [Online]. Available: https://www.nature.com/articles/s41586-021-03308-6.pdf.

[6] Regjeringen. "Regjeringens hydrogenstrategi: På vei mot lavutslippssamfunnet." Olje- og energidepartementet og Klima- og miljødepartementet, Accessed: 8 May 2022. (2020), [Online]. Available: https://www.regjeringen.no/contentassets/40026db2148e41eda8e3792d259efb6b/y-0127b.pdf.

[7] J. Kim, M. Qi, M. Kim, J. Lee, I. Lee, and I. Moon, "Biogas reforming integrated with PEM electrolysis via oxygen storage process for green hydrogen production: From design to robust optimization," *Energy Conversion and Management*, vol. 251, p. 115 021, 2022, ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2021.115021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0196890421011973.

[8] "Sustainable Development Goals." The United Nations Association of Norway, Accessed 05 June 2022. (2022), [Online]. Available: https://www.fn.no/om-oss/una-norway.

[9] M. Sánchez, E. Amores, D. Abad, L. Rodriguéz, and C. Clemente-Jul, "Aspen plus model of an alkaline electrolysis system for hydrogen production," *International Journal of Hydrogen Energy*, vol. 45, pp. 3916–3929, 2020, ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2019.12.027. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319919345276.

[10] M. Sánchez, E. Amores, L. Rodríguez, and C. Clemente-Jul, "Semi-empirical model and experimental validation for the performance evaluation of a 15 kw alkaline water electrolyzer," *International Journal of Hydrogen Energy*, vol. 43, no. 45, pp. 20 332–20 345, 2018, ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2018.09.029. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319918328751.

[11] J. Bregnballe, *A Guide to Recirculation Aquaculture*. the Food, Agriculture Organization of the United Nations (FAO), and EUROFISH International Organisation, 2015.

[12] M. Badiolaa, O. Basurkoa, R. Piedrahitab, P. Hundleyc, and D. Mendiolaa, "Energy use in recirculating aquaculture systems (ras): A review," *Aquacultural Engineering*, vol. 81, pp. 57–70, 2018. DOI: https://doi.org/10.1016/j.aquaeng.2018.03.003.

[13] Mowi. "Salmon farming: Industry handbook." Salmon Demand, pp. 18-23. (2020), [Online]. Available: https://mowi.com/it/wp-content/uploads/sites/16/2020/06/Mowi-Salmon-Farming-Industry-Handbook-2020.pdf.

[14] Skretting. "Skretting guidelines: Fôr." SGR tables for Atlantic salmon, pp. 75-76 (In Norwegian). (2012), [Online]. Available: https://www.skrettingguidelines.com/readimage.aspx?pubid=cd8a45bd-0e6e-409c-a2ee-1da2b7d19b06.

[15] H. Thorarensen and A. P. Farrell, "The biological requirements for post-smolt atlantic salmon in closed-containment systems," *Aquaculture*, vol. 312, no. 1, pp. 1–14, 2011, ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2010.11.043. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0044848610008161.

[16] E. J. J.S. Christiansen M. Jobling, *Oksygen og vannbehov. Nye reviderte tabeller*. Nor. Fiskeoppdrett, 1990, 15(10), pp. 28-29 (In Norwegian).

[17] V. H. S. Oliveira, K. R. Dean, L. Qviller, C. Kirkeby, and B. B. Jensen, "Factors associated with baseline mortality in norwegian atlantic salmon farming," *Scientific Reports*, no. 11, 2021. DOI: https://doi.org/10.1038/s41598-021-93874-6.

[18] Ø. Hilmarsen, E. A. Holte, H. Brendeløkken, R. Høyli, and E. S. Hognes. "Konsekvensanalyse av landbasert oppdrett av laks – matfisk og post-smolt." SINTEF Ocean, (In Norwegian). (2018), [Online]. Available: https://www.sintef.no/publikasjoner/publikasjon/1613480/.

[19] E. Taibi, H. Bianco, R. Miranda, and M. Carmo, *Green Hydrogen Cost Reduction*. IRENA, 2020, ISBN: 978-92-9260-295-6.

[20] T. A. Christophe Coutanceau Stève Baranton, *Hydrogen Electrochemical Production*. Academic Press, 2018, ISBN: 978-0-12-811250-2. DOI: https://doi.org/10.1016/B978-0-12-811250-2.00003-0. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128112502000030.

[21] Danish Energy Agency and Energinet. "Technology data: Renewable fuels." Version number: 0007. (2017), [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf.

[22] J. F. R.M. Navarro R. Guil, *Compendium of Hydrogen Energy: Hydrogen Production and Purification*. Woodhead Publishing, 2015, ISBN: 9781782423614. DOI: https://doi.org/10.1016/B978-1-78242-361-4.00002-9. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9781782423614000029.

[23] O. Faye, J. Szpunar, and U. Eduok, "A critical review on the current technologies for the generation, storage, and transportation of hydrogen," *International Journal of Hydrogen Energy*, vol. 47, no. 29, pp. 13 771–13 802, 2022, ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2022.02.112. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319922007261.

[24] S. R. Thiyagarajan, H. Emadi, A. Hussain, P. Patange, and M. Watson, "A comprehensive review of the mechanisms and efficiency of underground hydrogen storage," *Journal of Energy Storage*, vol. 51, p. 104 490, 2022, ISSN: 2352-152X. DOI: https://doi.org/10.1016/j.est.2022.104490. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X22005114.

[25] Y. Kojima, "Hydrogen storage materials for hydrogen and energy carriers," *International Journal of Hydrogen Energy*, vol. 44, no. 33, pp. 18 179–18 192, 2019, ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2019.05.119. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319919319755.

[26] DNV GL, "Produksjon og bruk av hydrogen i norge: Synteserapport om produksjon og bruk av hydrogen i norge," no. 2019-0039, 2019, Klima- og miljødepartementet og Olje- og energidepartementet. [Online]. Available: https://www.regjeringen.no/contentassets/0762c0682ad04e6abd66a9555e7468df/hydrogen-i-norge---synteserapport.pdf.

[27] G. Squadrito, A. Nicita, and G. Maggio, "A size-dependent financial evaluation of green hydrogen-oxygen co-production," *Renewable Energy*, vol. 163, pp. 2165–2177, 2021, ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2020.10.115. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148120316815.

[28] G. Maggio, G. Squadrito, and A. Nicita, "Hydrogen and medical oxygen by renewable energy based electrolysis: A green and economically viable route," *Applied Energy*, vol. 306, p. 117 993, 2022, ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2021.117993. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261921012964.

[29] B. Nitin, P. Sandilya, and G. Chakraborty, "Revisiting the dewar design for liquid oxygen storage in fuel cell energy systems," *International Communications in Heat and Mass Transfer*, vol. 134, p. 105 975, 2022, ISSN: 0735-1933. DOI: https://doi.org/10.1016/j.icheatmasstransfer.2022.105975. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0735193322000975.

[30] A. Godula-Jopek and D. Stolten, *Hydrogen Production: By electrolysis*. John Wiley & Sons, Incorporated, 2015, ISBN: 9783527676521. [Online]. Available: https://ebookcentral-proquest-com.ezproxy.uis.no/lib/uisbib/detail.action?docID=1956440.

[31] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, "Future cost and performance of water electrolysis: An expert elicitation study," *International Journal of Hydrogen Energy*, vol. 42, pp. 30 470–30 492, 2017, ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2017.10.045. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319917339435.

[32] C. Santoro, A. Lavacchi, P. Mustarelli, *et al.*, "What is next in anion-exchange membrane water electrolyzers? bottlenecks, benefits, and future," *European Chemical Societes Publishing*, 2022. DOI: doi.org/10.1002/cssc.202200027. [Online]. Available: https://chemistry-europe-onlinelibrary-wiley-com.ezproxy.uis.no/doi/pdfdirect/10.1002/cssc.202200027.

[33] J. C. Douglin, R. K. Singh, S. Haj-Bsoul, *et al.*, "A high-temperature anion-exchange membrane fuel cell with a critical raw material-free cathode," *Chemical Engineering Journal Advances*, vol. 8, 2021, ISSN: 2666-8211. DOI: https://doi.org/10.1016/j.ceja.2021.100153. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2666821121000697.

[34] NEL Hydrogen. "Atmospheric alkaline electrolyser." The A- series. Accessed: 12 May 2022. (2022), [Online]. Available: https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/.

[35] ——, "About nel." Accessed: 12 May 2022. (2022), [Online]. Available: https://nelhydrogen.com/about/.

[36] AspenTech, *Integrated Custom Model of Alkaline Electrolysis System for H2 Production*. Aspen Technology, 2021.

[37] Ø. Ulleberg, "Modeling of advanced alkaline electrolyzers: A system simulation approach," *International Journal of Hydrogen Energy*, vol. 28, pp. 21–33, 2003, ISSN: 0360-3199. DOI: https://doi.org/10.1016/S0360-3199(02)00033-2. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319902000332.

[38] W. Hug, H. Bussmann, and A. Brinner, "Intermittent operation and operation modeling of an alkaline electrolyzer," *International Journal of Hydrogen Energy*, vol. 18, no. 12, pp. 973–977, 1993, ISSN: 0360-3199. DOI: https://doi.org/10.1016/0360-3199(93)90078-O. [Online]. Available: https://www.sciencedirect.com/science/article/pii/036031999390078O.

[39] R. Y. Kannah, S. Kavitha, Preethi, *et al.*, "Techno-economic assessment of various hydrogen production methods – a review," *Bioresource Technology*, vol. 319, 2021, ISSN: 0960-8524. DOI: https://doi.org/10.1016/j.biortech.2020.124175. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960852420314498.

[40] "Normalavkastning i lønnsomhetsberegninger." Accessed 09 June 2022. (2022), [Online]. Available: https://www.enova.no/om-enova/drift/normalavkastning/.

[41] "Skattesatser 2022." Tax rates, deductions and amount limits in 2021 and 2022, Accessed 09 June 2022. (2022), [Online]. Available: https://www.regjeringen.no/no/tema/okonomi-og-budsjett/skatter-og-avgifter/skattesatser-2022/id2873852/.

[42] M. Sidelnikova, D. E. Weir, L. H. Groth, *et al.*, "Kostnader i energisektoren: Kraft, varme og effektivisering," no. 2/2015, 2015, *Norges vassdrags- og energidirektorat*, ISSN: 1501-2832. [Online]. Available: https://publikasjoner.nve.no/rapport/2015/rapport2015_02a.pdf.

[43] J. Brauns and T. Turek, "Alkaline water electrolysis powered by renewable energy: A review," *Processes*, vol. 248, no. 8(2), 2020, Institute of Chemical and Electrochemical Process Engineering, Clausthal University of Technology. DOI: https://doi.org/10.3390/pr8020248.

[44] J. Proost, "State-of-the art capex data for water electrolysers, and their impact on renewable hydrogen price settings," *International Journal of Hydrogen Energy*, vol. 44, no. 9, pp. 4406–4413, 2018, ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2018.07.164. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319918324157.

[45] A. Buttler and H. Spliethoff, "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review," *Renewable and Sustainable Energy Reviews*, vol. 82, no. 3, pp. 2440–2454, 2018, ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2017.09.003`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S136403211731242X`.

[46] K. Sundseth, S. Møller-Holst, and K. Midthun, "Hydrogenproduksjon ved småkraftverk," no. 73-2017, 2017, Delprosjekt 2: Flerbruk av hydrogen, oksygen og varme ved Smolten settefiskanlegg, *Norges Vassdrags- og Energidirektorat*, ISSN: 1501-2832.

[47] A. S. Johnsen, personal communication, IT responsible for Dalane Energi, Jun. 3, 2022.

[48] Konsumprisindeksen, *Statistics Norway*, Accessed: 24 May 2022. (2022), [Online]. Available: `https://www.ssb.no/priser-og-prisindekser/konsumpriser/statistikk/konsumprisindeksen`.

[49] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, "Future cost and performance of water electrolysis: An expert elicitation study," *International Journal of Hydrogen Energy*, vol. 42, no. 52, pp. 30 470–30 492, 2017, ISSN: 0360-3199. DOI: `https://doi.org/10.1016/j.ijhydene.2017.10.045`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0360319917339435`.

[50] R. Turton, J. A. Shaeiwitz, D. Bhattacharyya, and W. B. Whiting, *Analysis, Synthesis, and Design of Chemical Processes*. Pearson Education, Inc., 2018, Fifth Edition, ISBN-13: 978-0-13-417740-3.

[51] "Chemical engineering plant cost index (cepci)." Accessed 09 June 2022. (2022), [Online]. Available: `https://www.toweringskills.com/financial-analysis/cost-indices/#chemical-engineering-plant-cost-index-cepci`.

[52] C. van Leeuwen and M. Mulder, "Power-to-gas in electricity markets dominated by renewables," *Applied Energy*, vol. 232, pp. 258–272, 2018, ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2018.09.217`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0306261918315319`.

[53] Lyse AS. "Hva består strømregningen av?" Accessed: 1 May 2022. (2022), [Online]. Available: `https://www.lyse.no/strom/stromregningen`.

[54] H. Birkelund, F. Arnesen, J. Hole, *et al.*, "Langsiktig kraftmarkedsanalyse 2021 – 2040: Forsterket klimapolitikk påvirker kraftprisene," *Norges vassdrags- og energidirektorat*, vol. 250, no. 29/2021, 2021, ISSN: 1501-2832. [Online]. Available: `https://publikasjoner.nve.no/rapport/2021/rapport2021_29.pdf`.

[55] Statnett. "Langsiktig markedsanalyse 2020-2050: Oppdatering våren 2021." Accessed: 7 May 2022. (2021), [Online]. Available: `https://www.statnett.no/`

globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/lma/2021-06-30-lma-oppdatering.pdf.

[56] Norges vassdrags- og energidirektorat. "Kraftsituasjonen veke 17, 2022." Accessed: 7 May 2022. (2022), [Online]. Available: https://www.nve.no/media/13971/2022_17_kraftsituasjonen.pdf.

[57] Statnett. "Slik beregner vi tariffen." Accessed: 1 May 2022. (2021), [Online]. Available: https://www.statnett.no/for-aktorer-i-kraftbransjen/tariff/slik-beregnes-tariffen/.

[58] O. M. Ellefsen, personal communication, Research and Development coordinator at Greenstat, 2022.

[59] M. L. Hirth, D. Janzen, and K. U. Hove. "Hydrogen i Kvinnherad - En mulighetsstudie." Greensight AS, (In Norwegian) Accessed 05 June 2022. (2018), [Online]. Available: https://kvinnherad.custompublish.com/hydrogen-i-kvinnherad.483639.nn.html.

[60] "Lønn." Statistics Norway (SSB), Gjennomsnittlig månedslønn for ulike yrkesgrupper 2021, Accessed 08 June 2022. (2022), [Online]. Available: https://www.ssb.no/arbeid-og-lonn/lonn-og-arbeidskraftkostnader/statistikk/lonn.

[61] "Hydrogenpriser." HYDROGENPRIS UNOX-STASJONER, Accessed 27 June 2022. (2022), [Online]. Available: https://www.hydrogenbil.net/hydrogenpriser/.

[62] "Hva koster hydrogen?" Accessed 27 June 2022. (2022), [Online]. Available: https://hyop.no.

[63] K. Sundseth, S. Møller-Holst, K. Midthun, and V. Nørstebø, "Hydrogenproduksjon ved småkraftverk," no. 10-2019, 2019, Delprosjekt 3: Potensial for lønnsom utbygging av vassdrag i Rullestad, *Norges Vassdrags- og Energidirektorat*.

[64] "Prismodell." Statkraft Varme AS, Accessed 07 June 2022. (2022), [Online]. Available: https://www.statkraftvarme.no/kundeservice/priser/prismodell/.

[65] Olje- og energidepartementet, *Energiloven – enl*, §5-5, Lov om produksjon, omforming, overføring, omsetning, fordeling og bruk av energi m.m. (energiloven), Jan. 1, 1991.

[66] "Fjernvarme for bedrifter." Lyse AS, Priser for varme som bedriftskunde fra 1. januar 2022, Accessed 07 June 2022. (2022), [Online]. Available: https://www.lyse.no/bedrift/tjenester/fjernvarme.

[67] "Synergy Study: Heat Recovery From Hydrogen Production." A study on behalf of the Embassy of Denmark, Accessed 09 June 2022. (2022), [Online]. Available: https://storbritannien.um.dk/en/the-trade-council/projects/district-heating/heat-recovery-from-hydrogen-production.

[68] F. von Hepperger, "Implementation of water electrolysis in Växjö´s combined heat and power plant and the use of excess heat: A techno-economic analysis," M.S. thesis, Linnæus University, Sweden, 2021.

[69] A. Ottoson, "Integration of Hydrogen Production via Water Electrolysis at a CHP Plant: A feasibility study," M.S. thesis, Luleå University of Technology, Sweden, 2021.

[70] R. E. A. Løfblad. "Hydrogen production by electrolysis close to district heating plants in norway: Assessment of framework and profitability." accessed = 25 April 2022. (2019), [Online]. Available: https://nmbu.brage.unit.no/nmbu-xmlui/bitstream/handle/11250/2624149/Masteroppgave%5C%20Rikke%5C%20L%C3%B8fblad%5C%20.pdf?sequence=3%5C&isAllowed=y.

[71] Cost Estimate Classification System, *AACE International Recommended Practice No. 17R-97*. (1997), [Online]. Available: http://www.aacei.org.

[72] Viking Aqua AS, "The world's most sustainable circular-production salmon farm." Accessed 05 June 2022. (2022), [Online]. Available: https://www.vikingaqua.no.

[73] T. O. Høie, personal communication, Project Director at Viking Aqua, 2022.

[74] D. Parra and M. K. Patel, "Techno-economic implications of the electrolyser technology and size for power-to-gas systems," *International Journal of Hydrogen Energy*, vol. 41, no. 6, pp. 3748–3761, 2016, ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2015.12.160. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319915311411.

[75] M. Hermesmann and T. Müller, "Green, turquoise, blue, or grey? environmentally friendly hydrogen production in transforming energy systems," *Progress in Energy and Combustion Science*, vol. 90, p. 100 996, 2022, ISSN: 0360-1285. DOI: https://doi.org/10.1016/j.pecs.2022.100996. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360128522000053.

[76] D. E. Weir and NVE. "Nasjonal ramme for vindkraft – kart over produksjonskostnad for vindkraftutbygging i norge." Accessed 26 June 2022. (2018), [Online]. Available: https://www.nve.no/Media/6950/nasjonal-ramme-for-vindkraft-lcoe-kart.pdf.

[77] "Sea temperature." Accessed 25 June 2022. (2022), [Online]. Available: https://no.seatemperature.net/country/norway.

[78] K. O. Findley, S. K. Lawrence, and M. K. O'Brien, "Engineering challenges associated with hydrogen embrittlement in steels," *Encyclopedia of Materials: Metals and Alloys*, vol. 2, pp. 235–249, 2022. DOI: https://doi.org/10.1016/B978-0-12-819726-4.00086-7. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128197264000867.

[79] Aspen Technology Inc., *Aspen Physical Property System*, V8.4. Aspen Technology, Inc., 2013, Physical Property Methods. [Online]. Available: http://profsite.um.ac.ir/~fanaei/_private/Property%5C%20Methods%5C%208_4.pdf.

[80] M. H. Rennesund, Å. Jenssen, B. Tennbakk, *et al.*, "Power price risk hedging opportunities in the norwegian market," 2021, By THEMA Consulting Group, but

commissioned by Statnett. ISBN-number: 978-82-8368-090-4. [Online]. Available: https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/utvikling-av-kraftsystemet/power-price-risk-hedging-opportunities-in-the-norwegian-market.pdf.

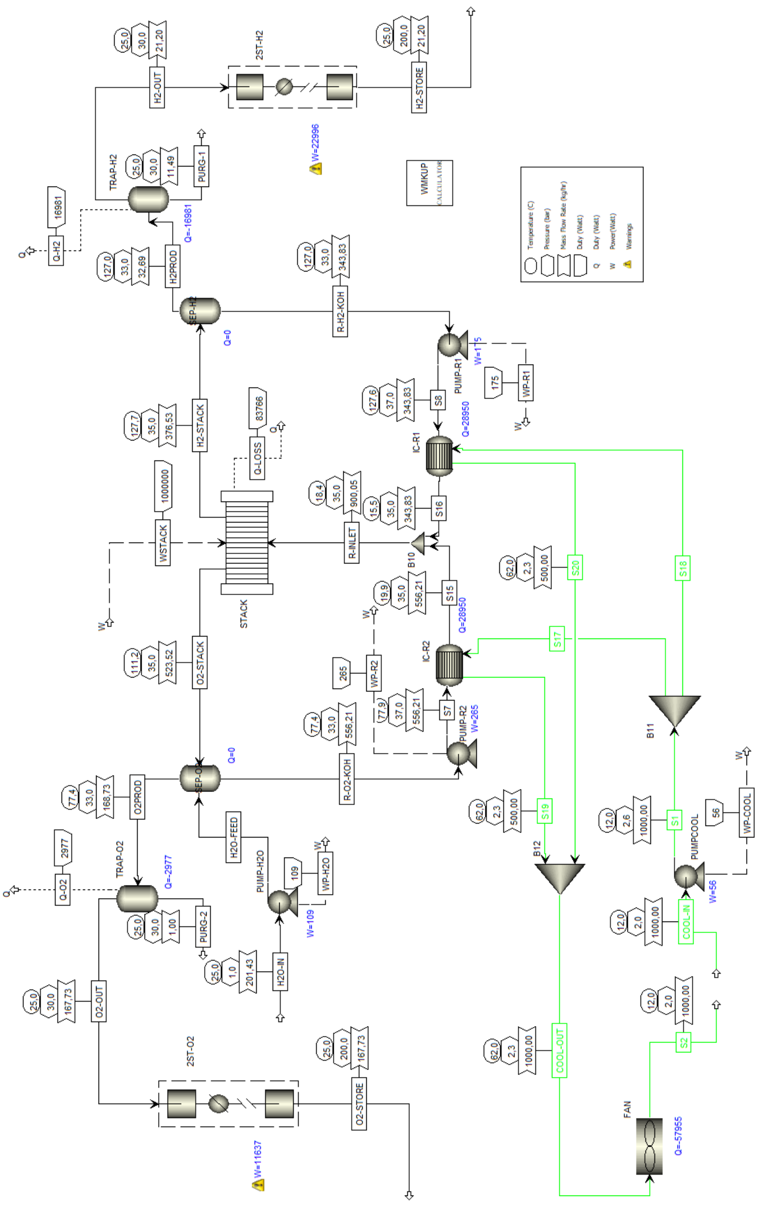
[81] J. Orellana, U. Waller, and B. Wecker, "Culture of yellowtail kingfish (seriola lalandi) in a marine recirculating aquaculture system (ras) with artificial seawater," *Aquacultural Engineering*, vol. 58, pp. 20–28, 2014, ISSN: 0144-8609. DOI: https://doi.org/10.1016/j.aquaeng.2013.09.004. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0144860913000873.

[82] L. V. Khoi and R. Fotedar, "Integration of western king prawn (penaeus latisulcatus kishinouye, 1896) and green seaweed (ulva lactuca linnaeus, 1753) in a closed recirculating aquaculture system," *Aquacultural*, vol. 322–323, pp. 201–209, 2011, ISSN: 0044-8486. DOI: https://doi.org/10.1016/j.aquaculture.2011.09.030. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0044848611007563.

[83] M. Naseer, T. Persson, I. Righini, C. Stanghellini, H. Maessen, and M. J. Verheul, "Bio-economic evaluation of greenhouse designs for seasonal tomato production in norway," *Biosystems Engineering*, vol. 212, pp. 413–430, 2021, ISSN: 1537-5110. DOI: https://doi.org/10.1016/j.biosystemseng.2021.11.005. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1537511021002725.

Appendix A

Aspen Plus flow diagram



Appendix B

Aspen Plus stream summary

Material

Stream Name	Units	COOL-IN	COOL-OUT	H2-OUT	H2-STACK	H2-STORE	H2O-FEED	H2O-IN	H2PROD	O2-OUT	O2-STACK	O2-STORE	O2PROD	PURG-1	PURG-2	R-H2-KOH	R-INLET	R-O2-KOH	S1	S2	S7	S8	S15	S16	S17	S18	S19	S20
From			B12	TRAP-H2	STACK	2ST-H2	PUMP-H2O		SEP-H2	TRAP-O2	STACK	2ST-O2	SEP-O2	TRAP-H2	TRAP-O2	SEP-H2	B10	SEP-O2	PUMPCOOL	FAN	PUMP-R2	PUMP-R1	IC-R2	IC-R1	B11	B11	IC-R2	IC-R1
To		PUMPCOOL	FAN	2ST-H2	SEP-H2		SEP-O2	PUMP-H2O	TRAP-H2	2ST-O2	SEP-O2		TRAP-O2			PUMP-R1	STACK	PUMP-R2	B11		IC-R2	IC-R1	B10	B10	IC-R2	IC-R1	B12	B12
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error							3,08E-06				5,231E-06																	
Phase		Liquid Phase	Liquid Phase	Vapor Phase			Liquid Phase	Liquid Phase	Vapor Phase	Vapor Phase			Vapor Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase
Temperature	C	12	62,000001	25	127,67663	25	25,470724	25	126,95604	25	111,17585	25	77,374411	25	25	126,95604	18,435464	77,374411	12,04946	12	77,886041	127,57412	19,893898	15,513344	12,04946	12,04946	62	62
Pressure	bar	2	2,3	30	35	200	6,7	1	33	30	35	200	33	30	30	33	35	33	2,6	2	37	37	35	35	2,6	2,6	2,3	2,3
Molar Vapor Fraction		0	0	1	0,4558954	0,9990991	0	0	1	1	0,2867886	0,9990975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Molar Liquid Fraction		1	1	0	0,5441046	0,0009009	1	1	0	0	0,7132114	0,0009025	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		0	0	1	0,0856492	0,9920354	0	0	1	1	0,3268983	0,9994853	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mass Liquid Fraction		1	1	0	0,9143508	0,0079646	1	1	0	0	0,6731017	0,0005147	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	J/kmol	-2,87E+08	-2,83E+08	-255445,3	-1,76E+08	-294969,2	-2,86E+08	-2,86E+08	-11186496	-255379	-2,26E+08	-294941,3	-1218801	-2,86E+08	-2,86E+08	-3,14E+08	-3,11E+08	-3,01E+08	-2,87E+08	-2,87E+08	-3,01E+08	-3,14E+08	-3,05E+08	-3,22E+08	-2,87E+08	-2,87E+08	-2,83E+08	-2,83E+08
Mass Enthalpy	J/kg	-15917588	-15708950	-125663	-11308104	-145106,2	-15862380	-15864320	-3787238	-8057,146	-8232620	-9305,326	-38626,13	-15863670	-15845801	-12023247	-13154131	-13481305	-15917386	-15917588	-13479592	-12021423	-13666963	-12324530	-15917386	-15917386	-15708950	-15708950
Molar Entropy	J/kmol-K	-166413,2	-154333,7	-28147,2	-79112,58	-44043,83	-163022,8	-163139,4	-21092,53	-27696,73	-99581,53	-43593,48	-23725,02	-163085,1	-163069,3	-127514,7	-153804,7	-142926,8	-166400,5	-166413,2	-142818,8	-127398,6	-155771,1	-150302,3	-166400,5	-166400,5	-154333,7	-154333,7
Mass Entropy	J/kg-K	-9237,334	-8566,822	-13846,65	-5089,804	-21666,78	-9049,139	-9055,611	-7140,969	-873,825	-3632,476	-1375,364	-751,891	-9055,96	-9047,026	-4878,888	-6508,257	-6406,107	-9236,631	-9237,334	-6401,267	-4874,447	-6981,801	-5750,773	-9236,631	-9236,631	-8566,822	-8566,822
Molar Density	kmol/cum	55,8643	53,149952	1,2102057	2,2059151	8,0742455	55,147787	55,172998	0,9919998	1,2102057	3,4886865	8,0742554	1,132318	55,150774	55,143706	28,27557	33,203932	35,402163	55,861688	55,8643	35,394688	28,270238	36,233685	29,228309	55,861688	55,861688	53,149952	53,149952
Mass Density	kg/cum	1006,411	957,51127	2,4600831	34,287303	16,413173	993,50282	993,957	2,930104	38,35864	95,639652	255,92134	35,728931	993,18783	993,94492	739,01106	784,68353	789,85826	1006,364	1006,411	789,69148	738,87127	808,41036	763,91143	1006,364	1006,364	957,51127	957,51127
Enthalpy Flow	Watt	-4421552	-4363597	-740,1326	-1182722	-854,6501	-887523,1	-887631,6	-34394,74	-375,3907	-1197205	-433,5447	-1810,386	-50635,62	-4411,865	-1148330	-3288704	-2082915	-4421496	-4421552	-2082651	-1148155	-2111600	-1177104	-2210748	-2210748	-2181799	-2181799
Average MW		18,01528	18,01528	2,032781	15,543347	2,032781	18,01528	18,01528	2,9537345	31,695968	27,41423	31,695968	31,553795	18,008593	18,02463	26,136027	23,632247	22,311017	18,01528	18,01528	22,311017	26,136012	22,311017	26,136012	18,01528	18,01528	18,01528	18,01528
Mole Flows	kmol/hr	55,508435	55,508435	10,430716	24,224283	10,430716	11,180798	11,180798	11,068797	5,2917681	19,096645	5,2917681	5,347377	0,6380801	0,0556089	13,155511	38,085542	24,930031	55,508435	55,508435	24,930031	13,155511	24,930031	13,155511	27,754218	27,754218	27,754218	27,754218
H2O	kmol/hr	55,508435	55,508435	0,0110185	10,991164	0,0110185	11,180798	11,180798	0,6488319	0,0055885	10,991173	0,0055885	0,0611597	0,6378134	0,0555712	10,342356	32,453133	22,110777	55,508435	55,508435	22,110777	10,342356	22,110777	10,342356	27,754218	27,754218	27,754218	27,754218
H2	kmol/hr	0	0	10,419698	10,425912	10,419698	0	0	10,419965	0,0508413	0,0509461	0,0508413	0,0508416	0,0002667	2,235E-07	0,0059474	0,0060519	0,0001045	0	0	0,0001045	0,0059474	0,0001045	0,0059474	0	0	0	0
O2	kmol/hr	0	0	0	0	0	0	0	0	5,2353382	5,2473182	5,2353382	5,2353757	0	3,744E-05	0	0,0119425	0,0119425	0	0	0,0119425	0	0,0119425	0	0	0	0	0
KOH	kmol/hr	0	0	0	2,8072071	0	0	0	3,525E-16	0	2,8072071	0	1,607E-19	0	0	2,8072071	5,6144143	2,8072071	0	0	2,8072071	2,8072071	2,8072071	2,8072071	0	0	0	0
Mole Fractions																												
H2O		1	1	0,0010564	0,453725	0,0010564	1	1	0,0586181	0,0010561	0,5755552	0,0010561	0,0114373	0,999582	0,9993227	0,7861615	0,8521116	0,8869133	1	1	0,8869133	0,7861615	0,8869133	0,7861615	1	1	1	1
H2		0	0	0,9989436	0,4303909	0,9989436	0	0	0,9413819	0,0096076	0,0026678	0,0096076	0,0095078	0,000418	4,02E-06	0,0004521	0,0001589	4,193E-06	0	0	4,193E-06	0,0004521	4,193E-06	0,0004521	0	0	0	0
O2		0	0	0	0	0	0	0	0	0,9893363	0,274777	0,9893363	0,9790549	0	0,0006733	0	0,0003136	0,000479	0	0	0,000479	0	0,000479	0	0	0	0	0
KOH		0	0	0	0,115884	0	0	0	3,184E-17	0	0,147	0	3,006E-20	0	0	0,2133864	0,1474159	0,1126034	0	0	0,1126034	0,2133864	0,1126034	0,2133864	0	0	0	0
Mass Flows	kg/hr	1000	1000	21,203363	376,52643	21,203363	201,4252	201,4252	32,694287	167,72771	523,51981	167,72771	168,73004	11,490924	1,0023296	343,83259	900,04694	556,21435	1000	1000	556,21435	343,83259	556,21435	343,83259	500	500	500	500
H2O	kg/hr	1000	1000	0,1985018	198,00889	0,1985018	201,4252	201,4252	11,688888	0,1006789	198,00907	0,1006789	1,10181	11,490387	1,0011311	186,32044	584,65229	398,33184	1000	1000	398,33184	186,32044	398,33184	186,32044	500	500	500	500
H2	kg/hr	0	0	21,004861	21,017388	21,004861	0	0	21,005398	0,10249	0,1027012	0,10249	0,1024905	0,0005376	4,506E-07	0,0119892	0,0121999	0,0002107	0	0	0,0002107	0,0119892	0,0002107	0,0119892	0	0	0	0
O2	kg/hr	0	0	0	0	0	0	0	0	167,52454	167,90789	167,52454	167,52574	0	0,001198	0	0,3821469	0,3821469	0	0	0,3821469	0	0,3821469	0	0	0	0	0
KOH	kg/hr	0	0	0	157,50015	0	0	0	1,978E-14	0	157,50015	0	9,017E-18	0	0	157,50015	315,00031	157,50015	0	0	157,50015	157,50015	157,50015	157,50015	0	0	0	0
Mass Fractions																												
H2O		1	1	0,0093618	0,5258831	0,0093618	1	1	0,3575208	0,0006003	0,3782265	0,0006003	0,00653	0,9999532	0,9988043	0,5418929	0,6495798	0,7161481	1	1	0,7161481	0,5418929	0,7161481	0,5418929	1	1	1	1
H2		0	0	0,9906382	0,0558192	0,9906382	0	0	0,6424792	0,0006111	0,0001962	0,0006111	0,0006074	4,679E-05	4,496E-07	3,487E-05	1,355E-05	3,789E-07	0	0	3,789E-07	3,487E-05	3,789E-07	3,487E-05	0	0	0	0
O2		0	0	0	0	0	0	0	0	0,9987887	0,3207288	0,9987887	0,9928626	0	0,0011952	0	0,0004246	0,000687	0	0	0,000687	0	0,000687	0	0	0	0	0
KOH		0	0	0	0,4182977	0	0	0	6,049E-16	0	0,3008485	0	5,344E-20	0	0	0,4580722	0,3499821	0,2831645	0	0	0,2831645	0,4580722	0,2831645	0,4580722	0	0	0	0
Volume Flow	cum/hr	0,9936298	1,0443741	8,6189618	10,981512	1,2918503	0,2027425	0,2026498	11,158064	4,3726188	5,4738782	0,6553878	4,7225046	0,0115697	0,0010084	0,4652604	1,147019	0,7041951	0,9936763	0,9936298	0,7043439	0,4653484	0,6880347	0,4500948	0,4968381	0,4968381	0,5221871	0,5221871

Stream Name	Units	COOL-IN	COOL-OUT	H2-OUT	H2-STACK	H2-STORE	H2O-FEED	H2O-IN	H2PROD	O2-OUT	O2-STACK	O2-STORE	O2PROD	PURG-1	PURG-2	R-H2-KOH	R-INLET	R-O2-KOH	S1	S2	S7	S8	S15	S16	S17	S18	S19	S20
From			B12	TRAP-H2	STACK	2ST-H2	PUMP-H2O		SEP-H2	TRAP-O2	STACK	2ST-O2	SEP-O2	TRAP-H2	TRAP-O2	SEP-H2	B10	SEP-O2	PUMPCOOL	FAN	PUMP-R2	PUMP-R1	IC-R2	IC-R1	B11	B11	IC-R2	IC-R1
To		PUMPCOOL	FAN	2ST-H2	SEP-H2		SEP-O2	PUMP-H2O	TRAP-H2	2ST-O2	SEP-O2		TRAP-O2			PUMP-R1	STACK	PUMP-R2	B11		IC-R2	IC-R1	B10	B10	IC-R2	IC-R1	B12	B12
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error							3,08E-06				5,231E-06																	
Vapor Phase																												
Molar Enthalpy	J/kmol			-255445,3	-10658404	-38225,91			-11186496	-255379	-5596962	-38159,58	-1218801															
Mass Enthalpy	J/kg			-125663	-3649974	-18938,63			-3787238	-8057,146	-179112,3	-1203,458	-38626,13															
Molar Entropy	J/kmol-K			-28147,2	-21487,18	-43936,72			-21092,53	-27696,73	-21738,11	-43485,85	-23725,02															
Mass Entropy	J/kg-K			-13846,65	-7358,291	-21768			-7140,969	-873,825	-695,6566	-1371,436	-751,891															
Molar Density	kmol/cum			1,2102057	1,0502295	8,0680378			0,9919998	1,2102057	1,0953204	8,0680378	1,132318															
Mass Density	kg/cum			2,4600831	3,0668086	16,284601			2,930104	38,35864	34,226939	255,82351	35,728931															
Enthalpy Flow	Watt			-740,1326	-32696,84	-110,6568			-34394,74	-375,3907	-8514,689	-56,0415	-1810,386															
Average MW				2,032781	2,9201318	2,0184091			2,9537345	31,695968	31,248334	31,708269	31,553795															
Mole Flows	kmol/hr			10,430716	11,043739	10,421319			11,068797	5,2917681	5,4766994	5,2869923	5,347377															
H2O	kmol/hr			0,0110185	0,6241684	0,0016474			0,6488319	0,0055885	0,1848202	0,0008343	0,0611597															
H2	kmol/hr			10,419698	10,41957	10,419672			10,419965	0,0508413	0,0508836	0,0508412	0,0508416															
O2	kmol/hr			0	0	0			0	5,2353382	5,2409957	5,2353168	5,2353757															
KOH	kmol/hr			0	3,587E-16	0			3,525E-16	0	2,532E-17	0	1,607E-19															
Mole Fractions																												
H2O				0,0010564	0,0565179	0,0001581			0,0586181	0,0010561	0,0337466	0,0001578	0,0114373															
H2				0,9989436	0,9434821	0,9998419			0,9413819	0,0096076	0,0092909	0,0096163	0,0095078															
O2				0	0	0			0	0,9893363	0,9569624	0,9902259	0,9790549															
KOH				0	3,248E-17	0			3,184E-17	0	4,623E-18	0	3,006E-20															
Mass Flows	kg/hr			21,203363	32,249172	21,034486			32,694287	167,72771	171,13774	167,64137	168,73004															
H2O	kg/hr			0,1985018	11,244569	0,0296779			11,688888	0,1006789	3,3295868	0,0150302	1,10181															
H2	kg/hr			21,004861	21,004603	21,004808			21,005398	0,10249	0,1025752	0,1024898	0,1024905															
O2	kg/hr			0	0	0			0	167,52454	167,70557	167,52385	167,52574															
KOH	kg/hr			0	2,012E-14	0			1,978E-14	0	1,42E-15	0	9,017E-18															
Mass Fractions																												
H2O				0,0093618	0,3486778	0,0014109			0,3575208	0,0006003	0,0194556	8,966E-05	0,00653															
H2				0,9906382	0,6513222	0,9985891			0,6424792	0,0006111	0,0005994	0,0006114	0,0006074															
O2				0	0	0			0	0,9987887	0,979945	0,999299	0,9928626															
KOH				0	6,24E-16	0			6,049E-16	0	8,3E-18	0	5,344E-20															
Volume Flow	cum/hr			8,6189618	10,515548	1,2916795			11,158064	4,3726188	5,0000889	0,6553009	4,7225046															

Stream Name	Units	COOL-IN	COOL-OUT	H2-OUT	H2-STACK	H2-STORE	H2O-FEED	H2O-IN	H2PROD	O2-OUT	O2-STACK	O2-STORE	O2PROD	PURG-1	PURG-2	R-H2-KOH	R-INLET	R-O2-KOH	S1	S2	S7	S8	S15	S16	S17	S18	S19	S20
From			B12	TRAP-H2	STACK	2ST-H2	PUMP-H2O		SEP-H2	TRAP-O2	STACK	2ST-O2	SEP-O2	TRAP-H2	TRAP-O2	SEP-H2	B10	SEP-O2	PUMPCOOL	FAN	PUMP-R2	PUMP-R1	IC-R2	IC-R1	B11	B11	IC-R2	IC-R1
To		PUMPCOOL	FAN	2ST-H2	SEP-H2		SEP-O2	PUMP-H2O	TRAP-H2	2ST-O2	SEP-O2		TRAP-O2			PUMP-R1	STACK	PUMP-R2	B11		IC-R2	IC-R1	B10	B10	IC-R2	IC-R1	B12	B12
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error							3,08E-06				5,231E-06																	
Liquid Phase																												
Molar Enthalpy	J/kmol	-2,87E+08	-2,83E+08		-3,14E+08	-2,85E+08	-2,86E+08	-2,86E+08			-3,14E+08	-2,85E+08		-2,86E+08	-2,86E+08	-3,14E+08	-3,11E+08	-3,01E+08	-2,87E+08	-2,87E+08	-3,01E+08	-3,14E+08	-3,05E+08	-3,22E+08	-2,87E+08	-2,87E+08	-2,83E+08	-2,83E+08
Mass Enthalpy	J/kg	-15917588	-15708950		-12025457	-15859944	-15862380	-15864320			-12143856	-15741052		-15863670	-15845801	-12023247	-13154131	-13481305	-15917386	-15917588	-13479592	-12021423	-13666963	-12324530	-15917386	-15917386	-15708950	-15708950
Molar Entropy	J/kmol-K	-166413,2	-154333,7		-127395,9	-162819,2	-163022,8	-163139,4			-130883,1	-162739,7		-163085,1	-163069,3	-127514,7	-153804,7	-142926,8	-166400,5	-166413,2	-142818,8	-127398,6	-155771,1	-150302,3	-166400,5	-166400,5	-154333,7	-154333,7
Mass Entropy	J/kg-K	-9237,334	-8566,822		-4877,31	-9060,279	-9049,139	-9055,611			-5058,771	-9002,249		-9055,96	-9047,026	-4878,888	-6508,257	-6406,107	-9236,631	-9237,334	-6401,267	-4874,447	-6981,801	-5750,773	-9236,631	-9236,631	-8566,822	-8566,822
Molar Density	kmol/cum	55,8643	53,149952		28,286602	55,024634	55,147787	55,172998			28,746706	54,977507		55,150774	55,143706	28,27557	33,203932	35,402163	55,861688	55,8643	35,394688	28,270238	36,233685	29,228309	55,861688	55,861688	53,149952	53,149952
Mass Density	kg/cum	1006,411	957,51127		738,84915	988,82886	993,50282	993,957			743,7495	993,86534		993,18783	993,94492	739,01106	784,68353	789,85826	1006,364	1006,411	789,69148	738,87127	808,41036	763,91143	1006,364	1006,364	957,51127	957,51127
Enthalpy Flow	Watt	-4421552	-4363597		-1150025	-743,9933	-887523,1	-887631,6			-1188689	-377,5032		-50635,62	-4411,865	-1148330	-3288704	-2082915	-4421496	-4421552	-2082651	-1148155	-2111600	-1177104	-2210748	-2210748	-2181799	-2181799
Average MW		18,01528	18,01528		26,12011	17,970658	18,01528	18,01528			25,872512	18,077672		18,008593	18,02463	26,136027	23,632247	22,311017	18,01528	18,01528	22,311017	26,136012	22,311017	26,136012	18,01528	18,01528	18,01528	18,01528
Mole Flows	kmol/hr	55,508435	55,508435		13,180544	0,0093974	11,180798	11,180798			13,619945	0,0047758		0,6380801	0,0556089	13,155511	38,085542	24,930031	55,508435	55,508435	24,930031	13,155511	24,930031	13,155511	27,754218	27,754218	27,754218	27,754218
H2O	kmol/hr	55,508435	55,508435		10,366995	0,0093712	11,180798	11,180798			10,806336	0,0047542		0,6378134	0,0555712	10,342356	32,453133	22,110777	55,508435	55,508435	22,110777	10,342356	22,110777	10,342356	27,754218	27,754218	27,754218	27,754218
H2	kmol/hr	0	0		0,0063418	2,621E-05	0	0			6,273E-05	1,281E-07		0,0002667	2,235E-07	0,0059474	0,0060519	0,0001045	0	0	0,0001045	0,0059474	0,0001045	0,0059474	0	0	0	0
O2	kmol/hr	0	0		0	0	0	0			0,0063448	2,146E-05		0	3,744E-05	0	0,0119425	0,0119425	0	0	0,0119425	0	0,0119425	0	0	0	0	0
KOH	kmol/hr	0	0		2,8072071	0	0	0			2,8072023	0		0	0	2,8072071	5,6144143	2,8072071	0	0	2,8072071	2,8072071	2,8072071	2,8072071	0	0	0	0
Mole Fractions																												
H2O		1	1		0,7865377	0,997211	1	1			0,7934199	0,9954807		0,999582	0,9993227	0,7861615	0,8521116	0,8869133	1	1	0,8869133	0,7861615	0,8869133	0,7861615	1	1	1	1
H2		0	0		0,0004812	0,002789	0	0			4,606E-06	2,682E-05		0,000418	4,02E-06	0,0004521	0,0001589	4,193E-06	0	0	4,193E-06	0,0004521	4,193E-06	0,0004521	0	0	0	0
O2		0	0		0	0	0	0			0,0004658	0,0044925		0	0,0006733	0	0,0003136	0,000479	0	0	0,000479	0	0,000479	0	0	0	0	0
KOH		0	0		0,2129811	0	0	0			0,2061097	0		0	0	0,2133864	0,1474159	0,1126034	0	0	0,1126034	0,2133864	0,1126034	0,2133864	0	0	0	0
Mass Flows	kg/hr	1000	1000		344,27726	0,1688768	201,4252	201,4252			352,3822	0,0863355		11,490924	1,0023296	343,83259	900,04694	556,21435	1000	1000	556,21435	343,83259	556,21435	343,83259	500	500	500	500
H2O	kg/hr	1000	1000		186,76432	0,1688239	201,4252	201,4252			194,67916	0,0856487		11,490387	1,0011311	186,32044	584,65229	398,33184	1000	1000	398,33184	186,32044	398,33184	186,32044	500	500	500	500
H2	kg/hr	0	0		0,0127844	5,283E-05	0	0			0,0001265	2,582E-07		0,0005376	4,506E-07	0,0119892	0,0121999	0,0002107	0	0	0,0002107	0,0119892	0,0002107	0,0119892	0	0	0	0
O2	kg/hr	0	0		0	0	0	0			0,2030263	0,0006865		0	0,001198	0	0,3821469	0,3821469	0	0	0,3821469	0	0,3821469	0	0	0	0	0
KOH	kg/hr	0	0		157,50015	0	0	0			157,49988	0		0	0	157,50015	315,00031	157,50015	0	0	157,50015	157,50015	157,50015	157,50015	0	0	0	0
Mass Fractions																												
H2O		1	1		0,5424823	0,9996871	1	1			0,5524659	0,9920449		0,9999532	0,9988043	0,5418926	0,6495798	0,7161481	1	1	0,7161481	0,5418929	0,7161481	0,5418929	1	1	1	1
H2		0	0		3,713E-05	0,0003129	0	0			3,589E-07	2,991E-06		4,679E-05	4,496E-07	3,487E-05	1,355E-05	3,789E-07	0	0	3,789E-07	3,487E-05	3,789E-07	3,487E-05	0	0	0	0
O2		0	0		0	0	0	0			0,0005762	0,0079521		0	0,0011952	0	0,0004246	0,000687	0	0	0,000687	0	0,000687	0	0	0	0	0
KOH		0	0		0,4574806	0	0	0			0,4469575	0		0	0	0,4580719	0,3499821	0,2831645	0	0	0,2831645	0,4580722	0,2831645	0,4580722	0	0	0	0
Volume Flow	cum/hr	0,9936298	1,0443741		0,4659642	0,0001708	0,2027425	0,2026498			0,4737915	8,687E-05		0,0115697	0,0010084	0,4652607	1,147019	0,7041951	0,9936763	0,9936298	0,7043439	0,4653484	0,6880347	0,4500948	0,4968381	0,4968381	0,5221871	0,5221871

Appendix C

Growth model and oxygen demand template (Excel)

CASE 1 SMOLT (start - 100g)										
Week number	Quantity	Average weight gram	Biomass tonne	Temp °C	SGR	O2 demand mg O2/kg fish/min	Oxygen g/min	Oxygen t/day	Oxygen t/week	
1	13000000	0,50	6,5	12	4,94	14,63	95,12	0,14	0,96	
2	12908235	0,70	9,0	12	4,94	13,68	123,73	0,18	1,25	
3	12817118	0,98	12,6	12	4,94	12,79	160,94	0,23	1,62	
4	12726645	1,38	17,5	12	4,14	11,95	209,35	0,30	2,11	
5	12636809	1,83	23,1	12	4,14	11,29	260,89	0,38	2,63	
6	12547608	2,43	30,5	12	4,14	10,67	325,11	0,47	3,28	
7	12459037	3,23	40,2	12	4,14	10,08	405,15	0,58	4,08	
8	12371091	4,29	53,0	12	4,14	9,52	504,89	0,73	5,09	
9	12283766	5,69	69,9	12	2,48	9,00	629,19	0,91	6,34	
10	12197057	6,76	82,4	12	2,48	8,69	716,61	1,03	7,22	
11	12110960	8,02	97,2	12	2,48	8,40	816,18	1,18	8,23	
12	12025471	9,52	114,5	12	2,48	8,12	929,58	1,34	9,37	
13	11940585	11,30	135,0	12	2,48	7,84	1058,74	1,52	10,67	
14	11856298	13,42	159,1	12	2,48	7,58	1205,85	1,74	12,15	
15	11772607	15,93	187,5	12	1,89	7,32	1373,39	1,98	13,84	
16	11689506	18,16	212,3	12	1,89	7,13	1514,45	2,18	15,27	
17	11606992	20,70	240,3	12	1,89	6,95	1670,00	2,40	16,83	
18	11525060	23,60	272,0	12	1,89	6,77	1841,52	2,65	18,56	
19	11443707	26,91	307,9	12	1,89	6,59	2030,65	2,92	20,47	
20	11362928	30,68	348,6	12	1,42	6,42	2239,22	3,22	22,57	
21	11282719	33,86	382,0	12	1,42	6,30	2406,09	3,46	24,25	
22	11203076	37,37	418,7	12	1,42	6,18	2585,40	3,72	26,06	
23	11123996	41,25	458,8	12	1,42	6,05	2778,07	4,00	28,00	
24	11045473	45,53	502,9	12	1,42	5,94	2985,10	4,30	30,09	
25	10967505	50,25	551,1	12	1,42	5,82	3207,56	4,62	32,33	
26	10890088	55,46	604,0	12	1,42	5,71	3446,60	4,96	34,74	
27	10813216	61,21	661,9	12	1	5,59	3703,45	5,33	37,33	
28	10736888	65,63	704,7	12	1	5,52	3888,03	5,60	39,19	
29	10661098	70,36	750,2	12	1	5,44	4081,81	5,88	41,14	
30	10585843	75,44	798,6	12	1	5,37	4285,25	6,17	43,20	
31	10511120	80,88	850,2	12	1	5,29	4498,82	6,48	45,35	
32	10436924	86,72	905,0	12	1	5,22	4723,05	6,80	47,61	
33	10363251	92,97	963,5	12	1	5,15	4958,45	7,14	49,98	
34	10290099	99,68	1025,7	12	1	5,08	5205,58	7,50	52,47	
								714,31	714,31	t/year
								3,00	3,00	t/day

CASE 2 POSTSMOLT (start - 1000g)										
Week	Quantity	Average weight	Biomass	Temp	SGR	O2 demand	Oxygen	Oxygen	Oxygen	
number		gram	tonne	°C		mg O2/kg fish/min	g/min	t/day	t/week	
1	17500000	0,50	8,8	12	4,94	14,63	128,05	0,18	1,29	
2	17376471	0,70	12,2	12	4,94	13,68	166,56	0,24	1,68	
3	17253813	0,98	16,9	12	4,94	12,79	216,66	0,31	2,18	
4	17132022	1,38	23,6	12	4,14	11,95	281,82	0,41	2,84	
5	17011090	1,83	31,1	12	4,14	11,29	351,19	0,51	3,54	
6	16891011	2,43	41,0	12	4,14	10,67	437,65	0,63	4,41	
7	16771781	3,23	54,1	12	4,14	10,08	545,39	0,79	5,50	
8	16653392	4,29	71,4	12	4,14	9,52	679,66	0,98	6,85	
9	16535838	5,69	94,1	12	2,48	9,00	846,98	1,22	8,54	
10	16419115	6,76	111,0	12	2,48	8,69	964,67	1,39	9,72	
11	16303215	8,02	130,8	12	2,48	8,40	1098,70	1,58	11,07	
12	16188134	9,52	154,2	12	2,48	8,12	1251,36	1,80	12,61	
13	16073864	11,30	181,7	12	2,48	7,84	1425,23	2,05	14,37	
14	15960402	13,42	214,2	12	2,48	7,58	1623,26	2,34	16,36	
15	15847740	15,93	252,4	12	1,89	7,32	1848,80	2,66	18,64	
16	15735874	18,16	285,8	12	1,89	7,13	2038,68	2,94	20,55	
17	15624797	20,70	323,5	12	1,89	6,95	2248,07	3,24	22,66	
18	15514504	23,60	366,2	12	1,89	6,77	2478,96	3,57	24,99	
19	15404990	26,91	414,5	12	1,89	6,59	2733,57	3,94	27,55	
20	15296249	30,68	469,2	12	1,42	6,42	3014,33	4,34	30,38	
21	15188276	33,86	514,2	12	1,42	6,30	3238,97	4,66	32,65	
22	15081064	37,37	563,6	12	1,42	6,18	3480,35	5,01	35,08	
23	14974610	41,25	617,7	12	1,42	6,05	3739,71	5,39	37,70	
24	14868906	45,53	676,9	12	1,42	5,94	4018,41	5,79	40,51	
25	14763949	50,25	741,9	12	1,42	5,82	4317,87	6,22	43,52	
26	14659733	55,46	813,0	12	1,42	5,71	4639,65	6,68	46,77	
27	14556253	61,21	891,0	12	1	5,59	4985,41	7,18	50,25	
28	14453503	65,63	948,6	12	1	5,52	5233,88	7,54	52,76	
29	14351478	70,36	1009,8	12	1	5,44	5494,74	7,91	55,39	
30	14250174	75,44	1075,0	12	1	5,37	5768,60	8,31	58,15	
31	14149584	80,88	1144,4	12	1	5,29	6056,11	8,72	61,05	
32	14049705	86,72	1218,3	12	1	5,22	6357,95	9,16	64,09	
33	13950530	92,97	1297,0	12	1	5,15	6674,83	9,61	67,28	
34	13852056	99,68	1380,7	12	1	5,08	7007,51	10,09	70,64	
35	13852056	100	1385,2	12	2,09	5,07	7025,61	10,12	70,82	
36	13846829	116	1600,4	12	2,09	4,93	7885,45	11,36	79,49	
37	13841604	134	1849,1	12	2,09	4,79	8850,51	12,74	89,21	
38	13836380	154	2136,3	12	2,09	4,65	9933,68	14,30	100,13	
39	13831159	178	2468,2	12	2,09	4,52	11149,42	16,06	112,39	
40	13825940	206	2851,7	12	1,89	4,39	12513,95	18,02	126,14	
41	13820722	235	3249,9	12	1,89	4,27	13892,08	20,00	140,03	
42	13815507	268	3703,6	12	1,89	4,16	15421,98	22,21	155,45	
43	13810294	306	4220,6	12	1,72	4,06	17120,36	24,65	172,57	
44	13805082	344	4754,0	12	1,72	3,96	18828,88	27,11	189,80	
45	13799873	388	5354,7	12	1,72	3,87	20707,91	29,82	208,74	
46	13794665	437	6031,4	12	1,58	3,78	22774,45	32,80	229,57	
47	13789460	488	6728,4	12	1,58	3,69	24854,78	35,79	250,54	
48	13784256	545	7506,0	12	1,46	3,61	27125,14	39,06	273,42	
49	13779055	603	8304,4	12	1,36	3,54	29407,58	42,35	296,43	
50	13773855	662	9124,5	12	1,36	3,47	31706,50	45,66	319,60	
51	13768657	728	10025,6	12	1,28	3,41	34185,14	49,23	344,59	
52	13763462	796	10955,0	12	1,28	3,35	36694,94	52,84	369,88	
53	13758268	870	11970,6	12	1,21	3,29	39389,00	56,72	397,04	
54	13753076	946	13017,1	12	1,14	3,24	42117,46	60,65	424,54	
55	13747886	1025	14086,8	12	1,09	3,18	44860,77	64,60	452,20	
								5764,14	5764,14	t/year
								14,97	14,97	t/day

CASE 3 POST SMOLT (start - 1kg)									
Week	Quantity	Average weight	Biomass	Temp	SGR	O2 demand	Oxygen	Oxygen	Oxygen
number		gram	tonne	°C		mg O2/kg fish/min	g/min	t/day	t/week
1	14000000	0,50	7,0	12	4,94	14,63	102,44	0,15	1,03
2	13901176	0,70	9,7	12	4,94	13,68	133,25	0,19	1,34
3	13803051	0,98	13,6	12	4,94	12,79	173,32	0,25	1,75
4	13705617	1,38	18,9	12	4,14	11,95	225,45	0,32	2,27
5	13608872	1,83	24,9	12	4,14	11,29	280,95	0,40	2,83
6	13512809	2,43	32,8	12	4,14	10,67	350,12	0,50	3,53
7	13417425	3,23	43,3	12	4,14	10,08	436,32	0,63	4,40
8	13322713	4,29	57,1	12	4,14	9,52	543,73	0,78	5,48
9	13228671	5,69	75,3	12	2,48	9,00	677,59	0,98	6,83
10	13135292	6,76	88,8	12	2,48	8,69	771,73	1,11	7,78
11	13042572	8,02	104,6	12	2,48	8,40	878,96	1,27	8,86
12	12950507	9,52	123,3	12	2,48	8,12	1001,09	1,44	10,09
13	12859092	11,30	145,4	12	2,48	7,84	1140,18	1,64	11,49
14	12768321	13,42	171,3	12	2,48	7,58	1298,60	1,87	13,09
15	12678192	15,93	202,0	12	1,89	7,32	1479,04	2,13	14,91
16	12588699	18,16	228,6	12	1,89	7,13	1630,95	2,35	16,44
17	12499838	20,70	258,8	12	1,89	6,95	1798,46	2,59	18,13
18	12411603	23,60	292,9	12	1,89	6,77	1983,17	2,86	19,99
19	12323992	26,91	331,6	12	1,89	6,59	2186,86	3,15	22,04
20	12236999	30,68	375,4	12	1,42	6,42	2411,46	3,47	24,31
21	12150620	33,86	411,4	12	1,42	6,30	2591,17	3,73	26,12
22	12064851	37,37	450,9	12	1,42	6,18	2784,28	4,01	28,07
23	11979688	41,25	494,1	12	1,42	6,05	2991,77	4,31	30,16
24	11895125	45,53	541,5	12	1,42	5,94	3214,72	4,63	32,40
25	11811160	50,25	593,5	12	1,42	5,82	3454,30	4,97	34,82
26	11727787	55,46	650,4	12	1,42	5,71	3711,72	5,34	37,41
27	11645002	61,21	712,8	12	1	5,59	3988,33	5,74	40,20
28	11562802	65,63	758,9	12	1	5,52	4187,11	6,03	42,21
29	11481183	70,36	807,9	12	1	5,44	4395,79	6,33	44,31
30	11400139	75,44	860,0	12	1	5,37	4614,88	6,65	46,52
31	11319667	80,88	915,6	12	1	5,29	4844,89	6,98	48,84
32	11239764	86,72	974,7	12	1	5,22	5086,36	7,32	51,27
33	11160424	92,97	1037,6	12	1	5,15	5339,86	7,69	53,83
34	11081645	99,68	1104,6	12	1	5,08	5606,00	8,07	56,51
35	11081645	100	1108,2	12	2,09	5,07	5620,49	8,09	56,65
36	11077463	116	1280,3	12	2,09	4,93	6308,36	9,08	63,59
37	11073283	134	1479,2	12	2,09	4,79	7080,41	10,20	71,37
38	11069104	154	1709,1	12	2,09	4,65	7946,95	11,44	80,11
39	11064927	178	1974,6	12	2,09	4,52	8919,54	12,84	89,91
40	11060752	206	2281,4	12	1,89	4,39	10011,16	14,42	100,91
41	11056578	235	2599,9	12	1,89	4,27	11113,66	16,00	112,03
42	11052406	268	2962,9	12	1,89	4,16	12337,58	17,77	124,36
43	11048235	306	3376,5	12	1,72	4,06	13696,29	19,72	138,06
44	11044066	344	3803,2	12	1,72	3,96	15063,11	21,69	151,84
45	11039898	388	4283,8	12	1,72	3,87	16566,33	23,86	166,99
46	11035732	437	4825,1	12	1,58	3,78	18219,56	26,24	183,65
47	11031568	488	5382,7	12	1,58	3,69	19883,82	28,63	200,43
48	11027405	545	6004,8	12	1,46	3,61	21700,11	31,25	218,74
49	11023244	603	6643,5	12	1,36	3,54	23526,06	33,88	237,14
50	11019084	662	7299,6	12	1,36	3,47	25365,20	36,53	255,68
51	11014926	728	8020,5	12	1,28	3,41	27348,11	39,38	275,67
52	11010769	796	8764,0	12	1,28	3,35	29355,95	42,27	295,91
53	11006614	870	9576,5	12	1,21	3,29	31511,20	45,38	317,63
54	11002461	946	10413,7	12	1,14	3,24	33693,97	48,52	339,64
55	10998309	1025	11269,4	12	1,09	3,18	35888,62	51,68	361,76

CASE 3 SLAUGHTER SIZE (1 - 5kg)

Week number	Quantity	Average weight gram	Biomass tonne	Temp °C	SGR	O2 demand mg O2/kg fish/min	Oxygen g/min	Oxygen t/day	Oxygen t/week
55	5533034	1025	5669,4	12	1,09	3,18	18054,86	26,00	181,99
56	5530946	1105	6114,1	12	1,04	3,14	19177,68	27,62	193,31
57	5528859	1188	6570,9	12	1,04	3,09	20313,98	29,25	204,76
58	5526772	1278	7061,7	12	1	3,05	21517,59	30,99	216,90
59	5524687	1370	7568,3	12	0,96	3,00	22742,04	32,75	229,24
60	5522602	1465	8088,7	12	0,92	2,96	23982,91	34,54	241,75
61	5520518	1562	8621,0	12	0,89	2,93	25235,42	36,34	254,37
62	5518435	1662	9169,1	12	0,86	2,89	26509,17	38,17	267,21
63	5516352	1764	9731,9	12	0,83	2,86	27800,87	40,03	280,23
64	5514271	1869	10307,7	12	0,8	2,82	29106,98	41,91	293,40
65	5512190	1977	10894,9	12	0,78	2,79	30423,71	43,81	306,67
66	5510110	2087	11499,5	12	0,76	2,76	31764,69	45,74	320,19
67	5508030	2201	12120,8	12	0,76	2,73	33127,94	47,70	333,93
68	5505952	2320	12775,7	12	0,71	2,70	34549,69	49,75	348,26
69	5503874	2438	13419,3	12	0,71	2,68	35932,45	51,74	362,20
70	5501797	2562	14095,3	12	0,67	2,65	37370,55	53,81	376,70
71	5499721	2685	14764,2	12	0,67	2,63	38779,83	55,84	390,90
72	5497646	2813	15464,9	12	0,64	2,60	40242,26	57,95	405,64
73	5495571	2941	16165,0	12	0,64	2,58	41690,20	60,03	420,24
74	5493497	3076	16896,9	12	0,61	2,56	43190,24	62,19	435,36
75	5491424	3210	17625,1	12	0,61	2,53	44669,61	64,32	450,27
76	5489352	3349	18384,7	12	0,58	2,51	46199,65	66,53	465,69
77	5487281	3488	19137,0	12	0,58	2,49	47702,36	68,69	480,84
78	5485210	3632	19920,1	12	0,56	2,47	49253,95	70,93	496,48
79	5483140	3776	20706,3	12	0,54	2,45	50799,41	73,15	512,06
80	5481071	3921	21493,7	12	0,54	2,43	52335,03	75,36	527,54
81	5479003	4072	22311,0	12	0,52	2,42	53917,07	77,64	543,48
82	5476935	4223	23127,2	12	0,52	2,40	55485,08	79,90	559,29
83	5474868	4379	23973,2	12	0,51	2,38	57098,70	82,22	575,55
84	5472802	4538	24832,9	12	0,49	2,36	58726,52	84,57	591,96
85	5470737	4695	25687,6	12	0,49	2,35	60333,46	86,88	608,16
86	5468673	4859	26571,7	12	0,49	2,33	61984,38	89,26	624,80
87	5466609	5028	27486,3	12	0,47	2,32	63680,48	91,70	641,90

Appendix D

Case budget accounts from Enova template (Excel)

	CASE 1 - 1 MW facility	*Legg inn selskapsnavn*			
		Legg inn prosjekt-tittel			
1	Avkastningskrav [%]	4,8 %	*Legg inn verdi*	H2 produsert [kg/år]	149796
2	Levetid [driftstid]	20	*Fast verdi på 15 år*	O2 produsert [kg/år]	1187221
3	Start drift [årstall]	2023	*Legg inn forventet oppstart*	Strømpris [øre/kWh]	60
4	Enova støtte [kr]	14 762 245	*Legg inn forventet støtte*	Nettleie pris [øre/kWh]	5,15
5	Støttesats godkjente kostnader produksjon [%]	45 %	*Legg inn forventet sats*	Total strømpris [øre/kWh]	81,44
6	Støttesats nødvendig infrastuktur [%]		*Legg inn forventet sats*	Fjernvarmepris vinter [øre/kWh]	60
7	Total Investeringskostnad [kr]	32 804 988	*Formel - skal ikke endres*	Sommer/vintertid faktor	5 %
8	Godkjent investeringskostnad [kr]	32 804 988	*Formel - skal ikke endres*		
9	Total Investeringskostnad uten komp. Og lagrig [kr]	15 684 214			
10	Valutakurs EUR/NOK (14.juni 2022)	10,35			
11	Valutakurs USD/NOK (14.juni 2022)	9,9			
12					
13					

14	Prosjektår	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
15	Driftsår		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
16	Egne timer [kr]																					
17	Kompressor og lagring [kr]	15 419 317																				
18	Elektrolysør [kr]	10 194 750																				
19	Bygninger [kr]																					
20	Annet (reinvest i år 2033 cellestack) [kr]	1 701 457																				
21	Anleggsbidrag [kr]																					
22	**Total Investeringskostnad produksjon [kr]**	27 315 524	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	Egne timer [kr]																					
24	Innkjøp av tjenester [kr]	2 352 627																				
25	Utstyr og maskiner [kr]																					
26	Bygninger [kr]	3 136 837																				
27	Annet [kr]																					
28	Anleggsbidrag [kr]																					
29	**Total Investeringskostnad infrastruktur [kr]**	5 489 464	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	Elektrisitets kostnad [kr]		6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533	6 420 533
31	Drifts- og vedlikeholdskostnader [kr]		1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249	1 640 249
32	Personellkostnader		5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800
33	Andre kostnader [kr]																					
34	**Total driftskostnad [kr]**	-	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582	13 183 582
35	Salgsvolum hydrogen [kg/år]		149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796	149 796
36	Salgspris hydrogen [kr/kg]		105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29	105,29
37	Inntekt salg hydrogen [kr]	-	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485	15 771 485
38	Fjernvarme inntekter [kr]		905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635	905 635
39	Anleggsbidrag [kr] (inntekt i år 20 uten avskrivning)																					
40	**Total inntekt [kr]**	-	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119	16 677 119
41																						
42	**Kontantstrøm uten støtte [kr]**	-32 804 988	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537
43	**Enova støtte [kr]**	14 762 245																				
44	**Kontantstrøm med støtte [kr]**	-18 042 744	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537	3 493 537

45			
46	**NNV uten støtte [kr]**	**11 480 082**	
47	**NNV inkl støtte [kr]**	**26 242 327**	
48	**Internrente uten støtte**	**8,6 %**	
49	**Internrente med støtte**	**18,74 %**	
50			
51		**kr/kg H2**	**kr/kg O2**
52	**LCOH Uten støtte [kr/kg H2]**	**105,29**	**13,28**
53	**LCOH Med støtte [kr/kg H2]**	**97,51**	**12,30**
54	**LCOH Uten kompressor og lagring uten støtte [kr/kg H2]**	**96,27**	**12,15**
	LCOH Uten kompressor og lagring med støtte [kr/kg H2]	**92,55**	**11,68**

	CASE 2 - 5 MW facility	*Legg inn selskapsnavn*			
		Legg inn prosjekt-tittel			
1	Avkastningskrav [%]	4,8 %	*Legg inn verdi*	H2 produsert [kg/år]	747977
2	Levetid [driftstid]	20	*Fast verdi på 15 år*	O2 produsert [kg/år]	5936104
3	Start drift [årstall]	2023	*Legg inn forventet oppstart*	Strømpris [øre/kWh]	60
4	Enova støtte [kr]	63 315 483	*Legg inn forventet støtte*	Nettleie [øre/kWh]	5,15
5	Støttesats godkjente kostnader produksjon [%]	45 %	*Legg inn forventet sats*	Total strømpris [øre/kWh]	81,44
6	Støttesats nødvendig infrastuktur [%]		*Legg inn forventet sats*	Fjernvarmepris vinter [øre/kWh]	60
7	Total Investeringskostnad [kr]	140 701 074	*Formel - skal ikke endres*	Sommer/vintertid faktor	5 %
8	Godkjent investeringskostnad [kr]	140 701 074	*Formel - skal ikke endres*		
9	Total Investeringskostnad uten komp. Og lagrig [kr]	78 421 164			
10	Valutakurs EUR/NOK (14.juni 2022)	10,35			
11	Valutakurs USD/NOK (14.juni 2022)	9,9			
12					
13					

14	Prosjektår	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
15	Driftsår		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
16	Egne timer [kr]																					
17	Kompressor og lagring [kr]	53 772 624																				
18	Elektrolysør [kr]	50 973 750																				
19	Bygninger [kr]																					
20	Annet (reinvest i år 2033 cellestack) [kr]	8 507 286																				
21	Anleggsbidrag [kr]																					
22	**Total Investeringskostnad produksjon [kr]**	113 253 660	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	Egne timer [kr]																					
24	Innkjøp av tjenester [kr]	11 763 179																				
25	Utstyr og maskiner [kr]																					
26	Bygninger [kr]	15 684 235																				
27	Annet [kr]																					
28	Anleggsbidrag [kr]																					
29	**Total Investeringskostnad infrastruktur [kr]**	27 447 414	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	Elektrisitets kostnad [kr]		32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663	32 102 663
31	Drifts- og vedlikeholdskostnader [kr]		5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043	5 628 043
32	Personellkostnader		5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800
33	Andre kostnader [kr]																					
34	**Total driftskostnad [kr]**	-	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505	42 853 505
35	Salgsvolum hydrogen [kg/år]		747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977	747 977
36	Salgspris hydrogen [kr/kg]		72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13	72,13
37	Inntekt salg hydrogen [kr]	-	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058	53 953 058
38	Fjernvarme inntekter [kr]		4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218	4 313 218
39	Anleggsbidrag [kr] (inntekt i år 20 uten avskrivning)																					
40	**Total inntekt [kr]**	-	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275	58 266 275
41																						
42	**Kontantstrøm uten støtte [kr]**	-140 701 074	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770
43	**Enova støtte [kr]**	63 315 483																				
44	**Kontantstrøm med støtte [kr]**	-77 385 591	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770	15 412 770

45			
46	**NNV uten støtte [kr]**	**54 675 569**	
47	**NNV inkl støtte [kr]**	**117 991 052**	
48	**Internrente uten støtte**	**9,0 %**	
49	**Internrente med støtte**	**19,34 %**	
50			
51		**kr/kg H2**	**kr/kg O2**
52	**LCOH Uten støtte**	**72,13**	**9,09**
53	**LCOH Med støtte**	**65,45**	**8,25**
54	**LCOH Uten kompressor og lagring uten støtte**	**65,56**	**8,26**
	LCOH Uten kompressor og lagring med støtte	**61,84**	**7,79**

	CASE 3 - 15 MW facility	Legg inn selskapsnavn			
		Legg inn prosjekt-tittel			
1	Avkastningskrav [%]	4,8 %	Legg inn verdi	H2 produsert [kg/år]	2 243 931
2	Levetid [driftstid]	20	Fast verdi på 15 år	O2 produsert [kg/år]	17 808 312
3	Start drift [årstall]	2023	Legg inn forventet oppstart	Strømpris [øre/kWh]	60
4	Enova støtte [kr]	91 599 380	Legg inn forventet støtte	Nettleie [øre/kWh]	3,568
5	Støttesats godkjente kostnader produksjon [%]	45 %	Legg inn forventet sats	Total strømpris [øre/kWh]	79,46
6	Støttesats nødvendig infrastuktur [%]		Legg inn forventet sats	Fjernvarmepris vinter [øre/kWh]	60
7	Total Investeringskostnad [kr]	203 554 178	Formel - skal ikke endres	Sommer/vintertid faktor	5 %
8	Godkjent investeringskostnad [kr]	203 554 178	Formel - skal ikke endres		
9	Total Investeringskostnad uten komp. Og lagrig [kr]	103 914 000			
10	Valutakurs EUR/NOK (14.juni 2022)	10,35			
11	Valutakurs USD/NOK (14.juni 2022)	9,9			
12					
13					

14	Prosjektår	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
15	Driftsår		1	2	3	4	5	6	7	8	9	10
16	Egne timer [kr]											
17	Kompressor og lagring [kr]	88 367 383										
18	Elektrolysør [kr]	67 544 100										
19	Bygninger [kr]											
20	Annet (reinvest i år 2033 cellestack) [kr]	11 272 795										
21	Anleggsbidrag [kr]											
22	Total Investeringskostnad produksjon [kr]	167 184 278	-	-	-	-	-	-	-	-	-	-
23	Egne timer [kr]											
24	Innkjøp av tjenester [kr]	15 587 100										
25	Utstyr og maskiner [kr]											
26	Bygninger [kr]	20 782 800										
27	Annet [kr]											
28	Anleggsbidrag [kr]											
29	Total Investeringskostnad infrastruktur [kr]	36 369 900	-	-	-	-	-	-	-	-	-	-
30	Elektrisitets kostnad [kr]		93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396
31	Drifts- og vedlikeholdskostnader [kr]		6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625
32	Personellkostnader		5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800
33	Andre kostnader [kr]											
34	Total driftskostnad [kr]	-	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821
35	Salgsvolum hydrogen [kg/år]		2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931
36	Salgspris hydrogen [kr/kg]		54,04	54,04	54,04	54,04	54,04	54,04	54,04	54,04	54,04	54,04
37	Inntekt salg hydrogen [kr]	-	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696
38	Fjernvarme inntekter [kr]		12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877
39	Anleggsbidrag [kr] (inntekt i år 20 uten avskrivning)											
40	Total inntekt [kr]	-	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573
41												
42	Kontantstrøm uten støtte [kr]	-203 554 178	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752
43	Enova støtte [kr]	91 599 380										
44	Kontantstrøm med støtte [kr]	-111 954 798	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752

14	Prosjektår	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
15	Driftsår	11	12	13	14	15	16	17	18	19	20
16	Egne timer [kr]										
17	Kompressor og lagring [kr]										
18	Elektrolysør [kr]										
19	Bygninger [kr]										
20	Annet (reinvest i år 2033 cellestack) [kr]										
21	Anleggsbidrag [kr]										
22	Total Investeringskostnad produksjon [kr]	-	-	-	-	-	-	-	-	-	-
23	Egne timer [kr]										
24	Innkjøp av tjenester [kr]										
25	Utstyr og maskiner [kr]										
26	Bygninger [kr]										
27	Annet [kr]										
28	Anleggsbidrag [kr]										
29	Total Investeringskostnad infrastruktur [kr]	-	-	-	-	-	-	-	-	-	-
30	Elektrisitets kostnad [kr]	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396	93 969 396
31	Drifts- og vedlikeholdskostnader [kr]	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625	6 106 625
32	Personellkostnader	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800	5 122 800
33	Andre kostnader [kr]										
34	Total driftskostnad [kr]	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821	105 198 821
35	Salgsvolum hydrogen [kg/år]	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931	2 243 931
36	Salgspris hydrogen [kr/kg]	54,04	54,04	54,04	54,04	54,04	54,04	54,04	54,04	54,04	54,04
37	Inntekt salg hydrogen [kr]	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696	121 256 696
38	Fjernvarme inntekter [kr]	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877	12 922 877
39	Anleggsbidrag [kr] (inntekt i år 20 uten avskrivning)										
40	Total inntekt [kr]	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573	134 179 573
41											
42	Kontantstrøm uten støtte [kr]	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752
43	Enova støtte [kr]										
44	Kontantstrøm med støtte [kr]	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752	28 980 752

45			
46	NNV uten støtte [kr]	163 814 050	
47	NNV inkl støtte [kr]	255 413 430	
48	Internrente uten støtte	13,0 %	
49	Internrente med støtte	25,62 %	
50			
51		kr/kg H2	kr/kg O2
52	LCOH Uten støtte	54,04	6,81
53	LCOH Med støtte	50,82	6,40
54	LCOH Uten kompressor og lagring uten støtte	50,53	6,37
	LCOH Uten kompressor og lagring med støtte	48,89	6,16