POTENTIAL USE AND MARKET OF OXYGEN AS A BY-PRODUCT FROM HYDROGEN PRODUCTION

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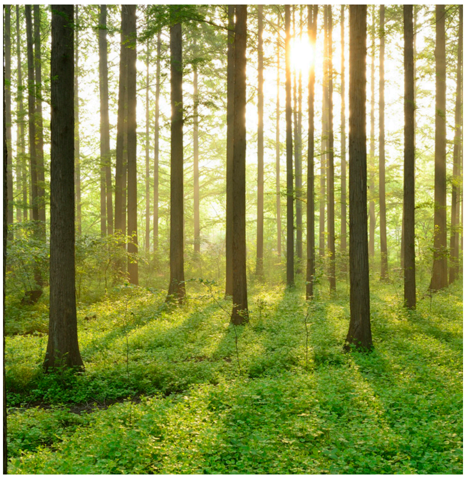

VÄTGASENS ROLL I ENERGI-
OCH KLIMATOMSTÄLLNINGEN

Energiforsk

Potential use and market of Oxygen as a by-product from hydrogen production

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Foreword

Hydrogen is expected to be an important piece of the energy transition puzzle. Hydrogen can be used in many applications and areas, such as feedstock in industry processes and in iron and steel production as well as a fuel in transportation and as energy storage.

Consideration to the full range of by-products can further strengthen the sustainability profile of the produced hydrogen and, in the end, also the final products or energy services considered where the hydrogen is used. In this project, the potential use and market for oxygen as a by-product of hydrogen production has been investigated. The definition of production scenario and production cases for hydrogen is the point of departure for this report, and thereby also the resulting oxygen cases. The report then outlines the end-use opportunities in Sweden, applying both a technical and a market perspective.

The project has been carried out by a joint team from IVL Swedish Environmental Research Institute and SWECO consisting of Mathias Gustavsson (project leader), Mirjam Särnbratt, Theo Nyberg, Maria Hernández Leal, Olga Lysenko, Magnus Karlsson, Linus Karlsson, Linda Önnby from IVL and Erik Östling, Elin Lindblad, Mikael Elevant, Kenneth Lundkvist from SWECO.

The study has been conducted within the Energiforsk programme *The Role of Hydrogen in the Energy and Climate Transition* and has been financed by the foundation SIVL and Energiforsk. The programme is financed by nearly 40 companies and organisations. The programme goal is to facilitate the integration of hydrogen and to increase knowledge of hydrogen technology, market conditions and the potential for various applications from a systems perspective. It also aims to support business development and growth in the hydrogen area as well as bring together the ongoing hydrogen research in different parts of the country under the same umbrella.

Sara Hugestam and Bertil Wahlund

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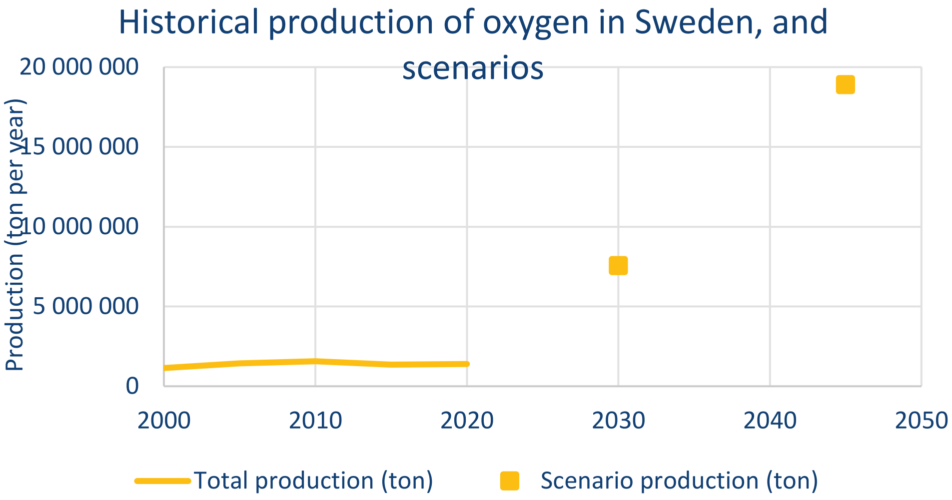
These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

In Sweden there are high expectations to make transitional changes in industry, transport, and energy sectors utilising hydrogen to cut greenhouse gas emissions. The hydrogen considered will be based on hydrolysis of water where hydrogen gas (H_2) will be the main product, but in the process oxygen (O_2) is also an output and there is also some heat generated. In the conversion process there is 8 kg of oxygen for each kilogram of hydrogen produced. This report focuses the opportunities for using the oxygen resulting as a by-product from the electrolysers as part of the new hydrogen investments done in Sweden. The scope is primarily on the end-use opportunities but also includes consideration of transport, storage and economy. The report has an exploratory approach and as the expansion of hydrogen production from electrolysers is rapidly changing, the knowledge of the market and opportunities to use the oxygen is increasing.

The report takes its point of departure in defining production scenario and production cases for hydrogen, and thereby also the resulting oxygen cases. The proposal for a Swedish hydrogen strategy by proposed by the Swedish Energy Agency sets the goal of having 5 GW installed electrolyser capacity by 2030 and 15 GW by 2045. Industrial hydrogen projects have stated an accumulative interest in installing around 5-8 GW of electrolyser capacity within a near future. An estimation of 6 GW corresponds to a hydrogen production around 0.9 million tonnes of hydrogen per year. Along with the hydrogen production 7.2 million tonnes of oxygen will be produced as a by-product.

The total oxygen production in Sweden in 2020 was about 1.4 million tonnes. The corresponding volumes of available oxygen from the electrolysers in the Swedish scenario is about 7.5 million tonnes in 2030 and almost 19 million tonnes in 2045.

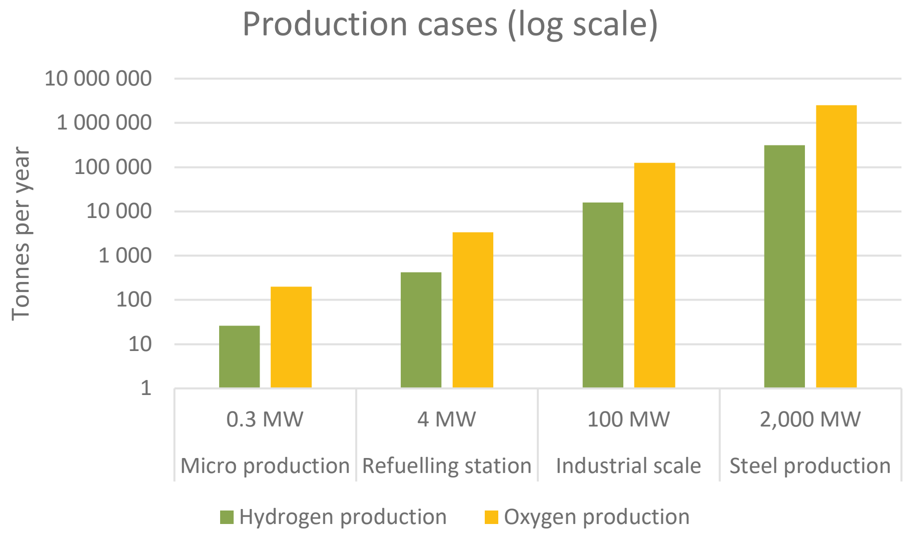


The oxygen market in Sweden is rather specialised and many of the large users have oxygen production on-site. Transport costs is a major challenge. Average price for the gas has been ranging between 0.8 and 1.0 SEK/kg (0.08-0.1 €/kg) in recent years. There are however different qualities of oxygen where the industrial oxygen has a lower market value, while oxygen with high purity and special quality control such as the medical oxygen will have much higher prices.

Based on present plans and scenarios in Sweden for the hydrogen production, four different sizes of hydrogen production cases can be identified and has been considered in this project.

1. A **micro case** which has an installed electrolyser capacity of 0.3 MW giving a hydrogen production capacity of about 6 kg per hour which would serve a small hydrogen demand. Likely, this small production unit is not dimensioned to constantly operate with full capacity due to a low demand. The resulting amount of oxygen as by-product is then 200 tonnes per year.
2. **Refuelling stations** are considered for locations throughout the country. These are decentralized, target within Repower EU is to have a refuelling station every 100 km on the TEN T road network. Installed capacity about 2,000 kg hydrogen per day, corresponding to a 4 MW electrolyser. The resulting amount of oxygen as by-product is 3.4 ktonnes per year.
3. An **industry park** with a hydrogen demand is seen in several transition away from fossil resources projects. The economy of scale is a vital ingredient in hydrogen plants and sizes are at least 100 MW electrolyser that provides one or multiple industries with renewable hydrogen. High utilization rate resulting in about 15 ktonnes hydrogen per year and subsequent oxygen production of 126 ktonnes per year.
4. **Steel production** will use large quantities of hydrogen in their processes when shifting away from their fossil coal dependent production. The installed electrolysis capacity for one steel production site would be in the magnitude of 2 GW providing about 0.3 million tonnes of hydrogen per year, with about 2.5 million tonnes of oxygen produced per year.

The production cases illustrates that any use of the oxygen will depend on the type of production unit considered and the location which means that the potential uses are strongly contextualised.



There are several potential uses for oxygen, several already exploited today. The new situation is that there will be oxygen available as a by-product in several places and in some in significant volumes. There are different functions that the oxygen will have in the processes and can provide a guidance the categorisation of potential uses.

Supporting breathing in living (larger) organisms. In the category opportunities for medical oxygen, aquaculture and oxygen enriched environment for protein production with eg insects. The special characteristics here is to ensure the quality and purity of the oxygen. The volumes needed for these applications are typically not that large. In the case of the medical oxygen there is a higher price, but also strict purity and quality control.

Promoting efficient microbial growth applications are similar to those for the larger organisms. Here the use of oxygen in brewery is one application. The other application with higher volumes associated are to support the nitrification processes in wastewater treatment. Today blowers are used to blow air, while pure oxygen could reduce required volumes and thus save energy.

Support ecosystems with targeted actions on for example seabed aeration is one potential application. Seabeds in the Baltic Sea are suffering from lack of dissolved oxygen at the seabeds which results in conditions where higher animal life in aquatic ecosystems cease. Experience from artificially oxygenate water areas have been gained worldwide, from lakes and water reservoirs while experiences from the oxygenation of coastal and marine areas is more limited. Cost effectiveness of this solution as compared to other strategies for improving seabeds is good.

Oxygen enriched combustion provides other uses of the oxygen. Applications where heat and power plants increase the oxygen will affect the formation of nitrous oxides. Higher temperature leads to increased formation (+), while the reduced content of nitrogen in the combustion air will reduce (-) the nitrous oxides, the overall result should be a decrease in nitrous oxide formation. Oxygen enriched incineration is used for destruction of hazardous waste, mainly with higher temperatures. This is already existing application. Opting for combustion with 100% oxygen, so called oxy-fuel, would result in very low formation nitrous oxides and have a flue gas with high concentration of carbon dioxide. In applications with carbon capture this can be a benefit as collecting the carbon dioxide is easier than with conventional combustion. The power plant needs to be designed for this application.

Oxygen as a reactant/feedstock in industrial applications. Oxygen assisted gasification provides an opportunity to reduce the share of nitrogen in the syngas. By using higher concentration of oxygen in the gasifier the quality of the syngas is improved. Another application of oxygen here is to LoTOx application process. LoTOx will provide a cost-effective opportunity to reduce nitrous oxides in the flue gas. The oxygen will have to be turned into ozone (O_3) for these applications. Oxygen is already used in steel making for reducing the carbon content in the pig iron into crude steel. Oxygen can also be used to have enriched combustion in the blast furnaces. In scrap-steel plants oxygen is used in the electric arc furnaces. Other application includes use of the oxygen in fuel cell applications and also in mineral extraction. Another big industrial application is found in the pulp and paper industry where oxygen is used in several of the process steps including lignin removal, reduce discharge of sulphur (during black liquor combustion) and bleaching. Oxygen is also used in some food packaging (eg red meat) to control certain bacterial growth.

The report provides further details on Oxygen enriched combustion in heat and power production (case 1), Oxygen enriched combustion engines (case 2), Seabed aeration (case 3), Sewage treatment (case 4) and aquaculture (case 5) where cases are considered.

Oxygen enriched combustion in heat and power production (case 1) concludes that real applications of oxygen enrichment in CHP-plants have not been relevant from a historical perspective, the costs for oxygen transports have never been economically feasible. With hydrogen production nearby, enabling oxygen streams for the possible utilization in the combustion process, the economic aspects are less likely an issue. From the technical perspective oxygen enrichment and effects on combustion and flue gas cleaning processes are not controversial to handle. Some uncertainties and problems will need to be overcome, but process issues arising already have working technical solutions to solve them.

The positive effects of better fuel utilization, lower flue gas flows and emissions give good economic potential for investments but are of course closely linked to the hydrogen production system and where it is placed. Calculating economic feasibility is somewhat complex since three different areas intertwine: Hydrogen production, oxygen enrichment and a possible CCS-plant.

Oxygen enriched combustion engines (case 2) is mainly focusing marine engines and concludes that the application of oxygen in oxygen enriched maritime engines is not a currently ongoing activity, however it does have promising potential. With ports turning into hydrogen hubs, oxygen will already be close to the end-user, allowing for synergies in logistics. While uncertainties remain over the effect on NOx emissions, other environmental aspects are more clearly positive, such as the decrease in fuel consumption as well as the positive effect on emissions of hydrocarbons, carbon monoxide and soot. Lastly, the application also holds promising commercial potential, as ports and hydrogen producers could add value through the handling and offsetting of biproduct oxygen, and for shipping companies that could possibly save fuel costs and thus benefit from better profitability. The larger uncertainties that remain are whether this is practically implementable in ports and at ships, if the possible cost savings can compensate for the added costs from oxygen handling, if increases in NOx emissions can be avoided or even reversed and if safety issues of storing oxygen onboard can be overcome.

For **Seabed aeration (case 3)** a special focus is on a case outside Gotland. The conclusions are that seabed aeration is a realistic case for use of the oxygen from electrolysers and the potential demand can be quite high. The location of the demand is fairly well defined, and this will represent substantial challenges in terms of transportation costs. In the case that the electrolysers are found on long distances away from these sites the transport costs will be substantial. Seabed aeration does not represent a monetary value in terms of the product, meaning that you cannot sell the seabed aeration service as a product today. The support to establish functional and resilient ecosystems will create several benefits in terms of ecosystem services such as improved fish stocks. The initial studies show that the alternative actions for improving the seabed via for example dredging or aluminium treatment of sediments will have higher costs. The opportunity here is strong in terms of improving the environmental profile of the hydrogen value chain.

Sewage treatment (case 4) is done all over Sweden and under the right conditions and by comparing with air supply using blower systems, supplying pure oxygen shows great potential for aerobic water treatment processes. There is a limitation with the supply of oxygen to the activated sludge process, which is linked to the fact that the sludge age needs to be maintained and that the Mixed liquor suspended solids (MLSS) content should not be too low. Ozonation (i.e. oxidation of the water solution using ozon) can be expected to be implemented at more and more wastewater treatment plants. By calculating the total volume of effluent wastewater of the 10 largest treatment plants in Sweden, assuming that 50% of them will implement ozonation, we have estimated the total use of oxygen to be from 15,000 - 25,000 tons per year, which corresponds to a market value from 220 - 365 million SEK when a unit price of 15,000 SEK/ton is considered. From rough calculation for nitrification at treatment plants (> 10,000 pe) north of Norrtälje city in Sweden, the annual oxygen demand is summed up to approx. 10,500 tons of O_2, which corresponds to an energy saving of 1.5 to 4 GWh as compared to aerating with blowers.

Aquaculture (case 5) could use the oxygen to increase the levels of dissolved oxygen in the water. Some fish farms utilize oxygen cones to achieve a sufficient level of dissolved oxygen. Other use air that is pumped to the water. With an electrolyser available close to the farm there are some potential synergetic effects. Both the oxygen for oxygenation, but also the waste heat from the electrolyser. Temperature is very important for aquaculture, and usually the heat demand is high. Furthermore, fish living in water with higher temperatures also has a higher demand for oxygen. Hence, the combination of hydrogen production and aquaculture might lead to possibilities of breeding fish species that are not common in Sweden. The oxygen demand for fish farms is low compared to the amounts of oxygen available from the hydrogen production cases. Only 10 % of the oxygen by-product from the micro production case would be necessary for a large aquaculture system with a volume of 50,000 m^3. Consequently, aquaculture applications are only reasonable for small hydrogen production units.

Based on the analysis of the production cases there are some aspects that will define what is feasible or not. The identified aspects for consideration are:

- Size of production of oxygen and variability in the production
- Transport and storage requirements
- Need for treatment of the raw-oxygen from the electrolyser to receive oxygen of a useable/saleable quality
- Willingness to pay of the final user considering the changed market

The first aspect is defined via the ***hydrogen production*** considered and provides the scale of operation, variation in operation and also the location of the electrolyser. The two following dimensions are ***technical dimension*** for recovering the oxygen, potential treatment for making it useful and transport requirements and lastly the ***market*** dimension that relates to the economic value and willingness to pay for the gas and the proposed business model. *The study identifies that additional research is needed for the two technical aspects of transport and storage as well as need for treatment. The investors in electrolysers need to understand the costs and operational parameters for these systems.*

The scale of market may bring additional opportunities in productive uses of the oxygen and with an increased market for oxygen from electrolysers an increased understanding of the required treatment as well as suitable transportation options. The proper use and management of the oxygen is a hygiene factor for the hydrogen production. Consideration to the full range of by-products, including the heat, can further strengthen the sustainability profile of the hydrogen produced and, in the end, also the final products or energy services considered where the hydrogen is used.

Proper use of the oxygen from electrolysers producing hydrogen will be increasingly important as volumes of hydrogen increase. It is motivated by resource efficiency and ensuring safe handling of the gas. There are arguments that demonstrations of oxygen applications attached to the electrolyser systems should be supported similar to what is seen for hydrogen production. Establishing pilots and demonstration will accumulate knowledge on operational parameters and also on market aspects.

Keywords

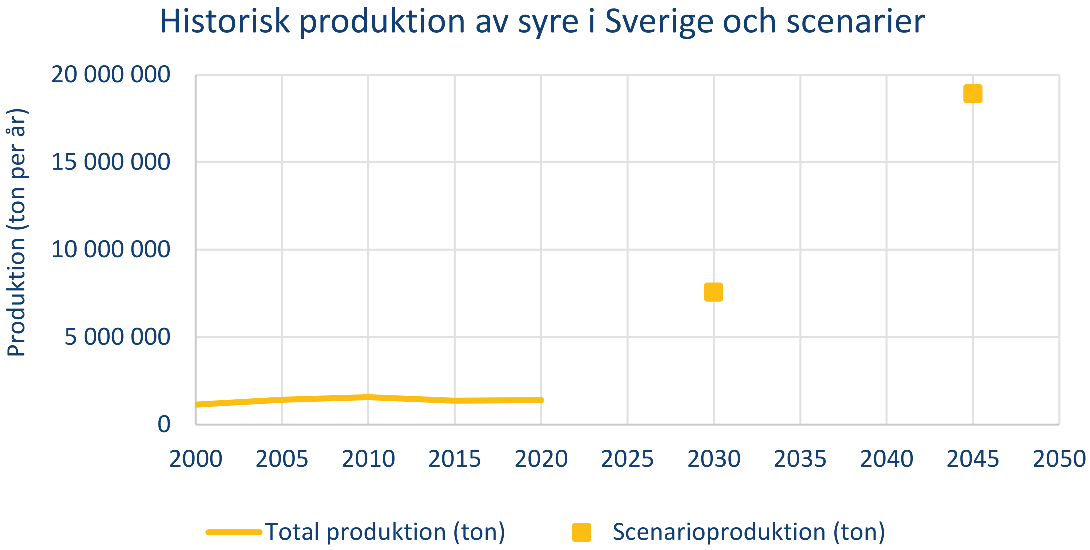
Hydrogen, oxygen, by-product, Sweden

Sammanfattning

I Sverige finns det stora förväntningar på att genomföra övergångsförändringar inom industri-, transport- och energisektorerna med hjälp av vätgas för att minska utsläppen av växthusgaser. Vätgasen kommer att baseras på hydrolys av vatten där vätgas (H_2) kommer att vara huvudprodukten, men i processen produceras även syre (O_2) och det genereras även en del värme. I omvandlingsprocessen uppstår 8 kg syre för varje kg vätgas som produceras. Denna rapport fokuserar på möjligheterna att använda det syre som uppstår som en biprodukt från elektrolysörer som en del av de nya vätgasinvesteringar som görs i Sverige. Omfattningen är i första hand på slutanvändningsmöjligheterna men inkluderar även hänsyn till transport, lagring och ekonomi. Rapporten har en utforskande ansats och i takt med att expansionen av vätgasproduktion från elektrolysörer förändras snabbt ökar kunskapen om marknaden och möjligheterna att använda syret.

Rapporten tar sin utgångspunkt i att definiera produktionsscenarier och produktionsfall för vätgas, och därmed även de resulterande syrefallen. I Energimyndighetens förslag till svensk vätgasstrategi fastställs målet att ha 5 GW installerad elektrolysörkapacitet år 2030 och 15 GW år 2045. Industriella vätgasprojekt har visat ett ackumulerat intresse för att installera omkring 5-8 GW elektrolysörkapacitet inom en nära framtid. En uppskattning av 6 GW motsvarar en vätgasproduktion på cirka 0,9 miljoner ton vätgas per år. Tillsammans med vätgasproduktionen kommer 7,2 miljoner ton syre att produceras som en biprodukt.

Den totala syreproduktionen i Sverige år 2020 var cirka 1,4 miljoner ton. Motsvarande volymer av tillgängligt syre från elektrolysörerna i det svenska scenariot är cirka 7,5 miljoner ton år 2030 och nästan 19 miljoner ton år 2045.



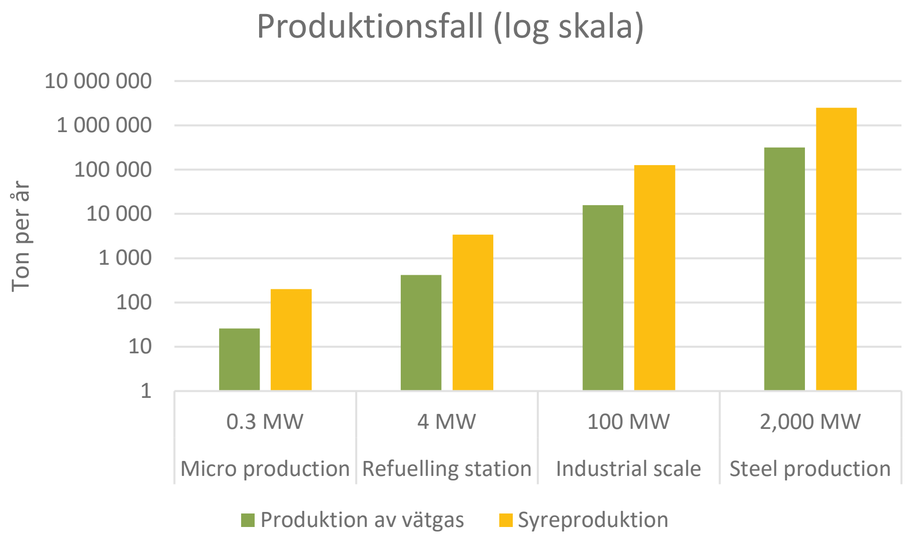
Marknaden för syrgas i Sverige är ganska specifik och många stora användare kan ha syrgasproduktion på sitt fabriksområde. Transportkostnaderna är en stor utmaning. Genomsnittspriset för gasen har legat mellan 0,8 och 1,0 SEK/kg (0,08-0,1 euro/kg) under de senaste åren. Det finns dock olika kvaliteter av syre där industriellt syre har ett lägre marknadsvärde, medan syre med hög renhet och särskild kvalitetskontroll, t.ex. medicinskt syre, har mycket högre priser.

Fyra olika storlekar av väteproduktionsfall identifierades i denna studie på grundval av nuvarande planer och scenarier kring vätgasproduktion (primärproduktionen).

1. Ett **mikrofall med** en installerad elektrolysörkapacitet på 0,3 MW som ger en vätgasproduktionskapacitet på cirka 6 kg per timme, vilket skulle täcka ett litet vätgasbehov. Det är troligt att denna lilla produktionsenhet inte är dimensionerad för att ständigt arbeta med full kapacitet på grund av den låga efterfrågan. Den resulterande mängden syre som biprodukt är då 200 ton per år.
2. **Tankställen** övervägs på platser i hela landet. Dessa är decentraliserade, och Repower EU:s mål är att ha en tankstation var 100:e kilometer på TEN T-vägnätet. Installerad kapacitet ca 2 000 kg vätgas per dag, vilket motsvarar en elektrolyser på 4 MW. Den resulterande mängden syre som biprodukt är 3,4 kton per år.
3. En **industripark** med en efterfrågan på väte ses i flera projekt för övergång från fossila resurser. Stordriftsfördelar är en viktig ingrediens i vätgasanläggningar och storleken är minst 100 MW elektrolyser som förser en eller flera industrier med förnybar vätgas. Hög utnyttjandegrad som resulterar i cirka 15 kton vätgas per år och efterföljande syreproduktion på 126 kton per år.
4. **Stålproduktionen** kommer att använda stora mängder väte i sina processer när den övergår från sin fossila kolberoende produktion. Den installerade elektrolyskapaciteten för en stålproduktionsanläggning skulle vara i

storleksordningen 2 GW och ge cirka 0,3 miljoner ton väte per år, med cirka 2,5 miljoner ton syre producerat per år.

Produktionsfallen illustrerar att potentiella användningsområden av syrgasen beror på vilken typ av produktionsenhet som avses och var den är belägen, vilket innebär att de potentiella användningsområdena är starkt kontextualiserade.



Det finns flera potentiella användningsområden för syre, varav flera redan utnyttjas i dag. Den nya situationen är att syre kommer att finnas tillgängligt som en biprodukt på flera ställen och i vissa fall i betydande mängder. Det finns olika funktioner som syret kommer att ha i processerna och kan ge vägledning för kategoriseringen av potentiella användningsområden.

Stödjer andningen i (större) levande organismer. I denna kategori ses möjligheter för medicinskt syre, vattenbruk och syreberikad miljö för proteinproduktion t.ex. insekter. De särskilda egenskaperna här är att garantera syrets kvalitet och renhet. De volymer som behövs för dessa tillämpningar är vanligtvis inte så stora. När det gäller medicinskt syre finns det ett högre pris, men också en strikt renhets- och kvalitetskontroll.

För att **främja en effektiv mikrobiell tillväxt** finns liknande tillämpningar som för större organismer. Användningen av syre i bryggerier är ett exempel på detta. En annan tillämpning med större volymer är att stödja nitrifikationsprocesser vid rening av avloppsvatten. I dag används blåsmaskiner för att blåsa luft, medan rent syre skulle kunna minska de volymer som krävs och därmed spara energi.

En potentiell tillämpning är att **stödja ekosystemen** med riktade åtgärder, t.ex. syresättning av syrefattiga havsbottnar. Havsbottnarna i Östersjön lider brist på löst syre, vilket i sin tur resulterar i förhållanden där det högre djurlivet i vattenekosystemen upphör. Erfarenheter från konstgjord syresättning av vattenområden har vunnits över hela världen, från sjöar och vattenreservoarer, medan erfarenheterna från syresättning av kust- och havsområden är mer begränsade. Kostnadseffektiviteten för denna lösning är god jämfört med andra strategier för att förbättra havsbottnarna.

Syreberikad förbränning är ett annat potentiellt användningsområde för syrgasen. Tillämpningar där kraftvärmeverk ökar syretillförseln i förbränningen kommer påverka bildandet av kväveoxider. Högre temperatur leder till ökad kväveoxidbildning (+), medan det minskade kväveinnehållet i förbränningsluften kommer att minska (-) lustgaserna, och det övergripande resultatet ger en minskad bildning av lustgas. Syreberikad förbränning ger högre förbränningstemperaturer och används för destruktion av farligt avfall. Detta är en redan befintlig tillämpning. Om man väljer förbränning med 100 % syre, s.k. *oxyfuel*, får man en mycket låg bildning av kväveoxider samt en rökgas med hög koncentration av koldioxid. I tillämpningar med koldioxidavskiljning kan detta vara en fördel eftersom det är lättare att samla in koldioxiden än vid konventionell förbränning. Förbränningsanläggningen måste utformas för denna tillämpning.

Syre som reaktant/insatsmaterial i industriella tillämpningar. Syreassisterad förgasning ger en möjlighet att minska kväveandelen i syntesgasen. Genom att använda en högre koncentration av syre i förgasaren förbättras kvaliteten på syntesgasen. Ett annat användningsområde för syre är LoTOx-applikationsprocessen. LoTOx ger en kostnadseffektiv möjlighet att minska kväveoxiderna i rökgasen. Syret måste omvandlas till ozon (O_3) för dessa tillämpningar. Syre används redan vid ståltillverkning för att minska kolinnehållet i råjärn till råstål. Syre kan också användas för att få en bättre förbränning i masugnarna. I skrotstålsfabriker används syre i ljusbågsugnarna. Andra tillämpningar är användning av syre i bränsleceller och vid mineralutvinning. En annan stor industriell tillämpning finns inom massa- och pappersindustrin, där syre används i flera av processtegen, bl.a. för att avlägsna lignin, minska utsläppen av svavel (vid förbränning av svartlut) och blekning. Syre används också i vissa livsmedelsförpackningar (t.ex. rött kött) för att kontrollera viss bakterietillväxt.

Rapporten innehåller ytterligare detaljer om syreberikad förbränning inom värme- och elproduktion (fall 1), syreberikade förbränningsmotorer (fall 2), luftning av havsbottnar (fall 3), rening av avloppsvatten (fall 4) och vattenbruk (fall 5) där fall beaktas.

I fall 1, syreberikad förbränning i värme- och elproduktion, dras slutsatsen att verkliga tillämpningar av syreberikning i kraftvärmeverk inte har varit relevanta ur ett historiskt perspektiv, eftersom kostnaderna för syretransporter aldrig har varit ekonomiskt genomförbara. Med vätgasproduktion i närheten, som möjliggör syreflöden för eventuellt utnyttjande i förbränningsprocessen, är de ekonomiska aspekterna mindre troliga att bli ett problem. Ur teknisk synvinkel är syreberikning och effekterna på förbrännings- och rökgasreningsprocesser inte kontroversiella att hantera. Vissa osäkerheter och problem måste övervinnas, men för de processfrågor som uppstår finns det redan fungerande tekniska lösningar för att lösa dem.

De positiva effekterna av bättre bränsleutnyttjande, lägre rökgasflöden och utsläpp ger goda ekonomiska möjligheter för investeringar, men är naturligtvis nära kopplade till vätgasproduktionssystemet och var det placeras. Att beräkna den ekonomiska genomförbarheten är något komplicerat eftersom tre olika områden är sammanflätade: vätgasproduktion, syreberikning och en eventuell CCS-anläggning.

Syreberikade förbränningsmotorer (fall 2) fokuserar främst på marina motorer och drar slutsatsen att tillämpningen av syre i syreberikade motorer för sjöfart inte är en pågående verksamhet, men att den har en lovande potential. I och med att hamnarna förvandlas till vätgasnav kommer syret redan att vara nära slutanvändaren, vilket möjliggör synergier inom logistiken. Även om det fortfarande råder osäkerhet om effekten på NOx-utsläppen är andra miljöaspekter klart positiva, t.ex. den minskade bränsleförbrukningen och den positiva effekten på utsläppen av kolväten, kolmonoxid och sot. Slutligen har tillämpningen också en lovande kommersiell potential, eftersom hamnar och vätgasproducenter skulle kunna skapa mervärde genom hantering och kompensation av syre som biprodukt, och för rederier som eventuellt skulle kunna spara bränslekostnader och därmed få bättre lönsamhet. De större osäkerheter som kvarstår är om detta är praktiskt genomförbart i hamnar och på fartyg, om de möjliga kostnadsbesparingarna kan kompensera för de extra kostnaderna för syrehantering, om ökningen av NO_x-utsläppen kan undvikas eller till och med vändas och om säkerhetsproblemen med lagring av syre ombord kan övervinnas.

När det gäller **luftning av havsbotten (fall 3) ligger** fokus på ett fall utanför Gotland. Slutsatserna är att luftning av havsbottnar är ett realistiskt fall för användning av syre från elektrolysörer och att den potentiella efterfrågan kan vara ganska stor. Var efterfrågan finns är ganska väldefinierad, och detta kommer att innebära stora utmaningar när det gäller transportkostnader. Om elektrolysörerna finns på långa avstånd från dessa platser kommer transportkostnaderna att bli betydande. Luftning av havsbottnar har inget monetärt värde i form av en produkt, vilket innebär att man inte kan sälja luftningstjänsten för havsbottnar som en produkt i dag. Stödet för att skapa funktionella och motståndskraftiga ekosystem kommer att skapa flera fördelar i form av ekosystemtjänster, t.ex. förbättrade fiskbestånd. De inledande studierna visar att de alternativa åtgärderna för att förbättra havsbottnen genom t.ex. muddring eller aluminiumbehandling av sediment kommer att ha högre kostnader. Här finns stora möjligheter att förbättra miljöprofilen för vätgasvärdekedjan.

Reningsverk (fall 4) återfinns över hela Sverige och här kan syrgas användas i olika delar av processen. Under rätt förhållanden, och vid jämförelse med lufttillförsel med blåsmaskiner, visar att tillförsel av syrgas att det finns stor potential för vinster i det aeroba steget i vattenreningsprocessen. Det finns en begränsning när det gäller tillförsel av syre till processen med aktiverat slam, vilket är kopplat till att slamåldern måste bibehållas och att halten suspenderade ämnen i blandad vätska (MLSS) inte får vara för låg. Ozonering kan förväntas införas i allt fler avloppsreningsverk. Genom att beräkna den totala volymen av utgående avloppsvatten från de tio största reningsverken i Sverige, och genom att anta att 50 % av dem kommer att införa ozonering, har vi beräknat den totala användningen av syre till 15 000-25 000 ton per år, vilket motsvarar ett marknadsvärde på 220-365 miljoner kronor om man räknar med ett enhetspris på 15 000 kronor/ton. Enligt en grov beräkning för nitrifikation vid reningsverk (> 10 000 pe) norr om Norrtälje stad i Sverige uppgår det årliga syrebehovet till ca 10 500 ton O_2, vilket motsvarar en energibesparing på 1,5 till 4,0 GWh jämfört med luftning med blåsmaskiner.

I **vattenbruk (fall 5)**, såsom fiskodlingar, kan syrgas användas för att öka halten av löst syre i vattnet. Vissa fiskodlingar använder syrekoner för att uppnå en tillräcklig nivå av löst syre. Andra använder luft som pumpas till vattnet. Med en elektrolysör i närheten av odlingen finns det potential att använda syrgas i fiskodlingen, men även spillvärmen från elektrolysören kan användas till fiskodlingen. Temperaturen är mycket viktig för vattenbruk, och vanligtvis är värmebehovet stort. Dessutom har fiskar som lever i vatten med högre temperaturer även ett högre behov av syre. Kombinationen av vätgasproduktion och vattenbruk kan därför leda till möjligheter att odla fiskarter som inte är vanliga i Sverige. Syrebehovet för fiskodlingar är lågt jämfört med de mängder syre som finns tillgängliga från vätgasproduktionsfallen. Endast 10 % av syrebiprodukten från mikroproduktionsfallet skulle behövas för ett stort vattenbrukssystem med en volym på 50 000 m^3 . Följaktligen är vattenbrukstillämpningar endast rimliga för små vätgasproduktionsenheter.

Baserat på analysen av potentiella användningsområden finns det några aspekter som står ut kring om syrgasen som skapas i elektrolysören är praktiskt och ekonomiskt möjlig att nyttiggöra:

- Storleken på syreproduktionen och variationen i produktionen.
- Behov av transport till användningsplats samt lagring
- Behov av behandling av syrgasen från elektrolysören för att få användbar/säljbar kvalitet.
- Slutanvändarens betalningsvilja.

Den första aspekten definieras genom den ***väteproduktion som*** beaktas och anger driftskalan, variationen i drift och även elektrolysörens placering. De två följande dimensionerna är den ***tekniska dimensionen*** för återvinning av syre, potentiell behandling för att göra det användbart och transportkrav samt slutligen marknadsdimensionen som avser det ekonomiska värdet och betalningsviljan för gasen och den föreslagna affärsmodellen. *Resultaten visar att ytterligare forskning behövs för de två tekniska aspekterna transport och lagring samt behovet av behandling. Investerare i elektrolysörer måste förstå kostnaderna och driftsparametrarna för dessa system.*

Marknadens storlek kan resultera i nya möjligheter för användningen av syrgasen – enligt scenarierna för vätgas i Sverige redan 2030 kommer resulterande syrgas vara många gånger större än den totala användningen idag. Med en ökad marknad för syrgas från elektrolysörerna ökar förståelsen för den behandling som krävs och för lämpliga transportalternativ. Korrekt användning och hantering av syre är en hygienfaktor för vätgasproduktionen. Om man tar hänsyn till alla biprodukter, inklusive värme, kan man ytterligare stärka hållbarhetsprofilen för den vätgas som produceras och i slutändan även för de slutprodukter eller energitjänster som används när vätgasen används.

Korrekt användning av syret från elektrolysörer kommer att bli allt viktigare i takt med att vätgasvolymerna ökar. Detta motiveras av resurseffektivitet och säker hantering av gasen. Det finns argument för att demonstrationer av syretillämpningar i anslutning till elektrolysörsystemen bör stödjas på samma sätt som för vätgasproduktion. Genom att inrätta pilotprojekt och demonstrationer kan man samla kunskap om driftsparametrar och marknadsaspekter.

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Abbreviations

AS	Activated sludge
BDMT	Bone dry metric ton
BeCCS	Bioenergy with Carbon Capture and Storage
BFB	Bubbling fluidized bed
BTE	Break thermal efficiency
CCS	Carbon capture and storage
CFB	Circulation fluidized bed
CHP	Combined heat and power
CLP	Classification, labelling and packaging (EU regulation 1272/2008)
DCS	Distributed control system
DO	Dissolved oxygen
EFI	Electronic fuel injection
EUR	Euro (1 Euro ≈ 10 SEK)
FGC	Flue gas cleaning
FGF	Flue gas fan
H2	Hydrogen
HHV	Higher heating Value
IVL	IVL Swedish Environmental Research Institute
LOX	Liquid oxygen system
LOX	Liquid oxygen
MBBR	Moving bed biofilm reactor
MBR	Membrane bioreactors
MLSS	Mixed liquid suspended solids
MSB	Swedish Civil Contingencies Agency
NWCO	Neutralized waste cooking oil
O2	Oxygen
OTE	Oxygen transfer efficiency
PEM	Proton exchange membrane
PO	Pressurized oxygen
PSA	Pressure-swing adsorption
RAS	Recirculating aquaculture systems
RCCI	Reactivity controlled compression ignition
SCR	Selective catalytical reduction

SCR	Selective catalytic reduction
SEK	Swedish Krona
SEPA	Swedish Environmental Protection Agency
SNCR	Selective non catalytical reduction
SNCR	Selective non-catalytic reduction
TRL	Technology Readiness Level
VOC	Volatile hydrocarbons
WHO	World Health Organization
WTE	Waste to energy
WWTP	wastewater treatment plants
ZVS	zero-valent sulphur

1 Introduction

Hydrogen has received a key-role in industrial and energy transitions in Sweden. It is not long ago that hydrogen (H_2) was not part of the narrative of transforming industry, transports and energy systems. The transformation narrative that is found in Sweden today is relying on a large expansion of hydrogen production and use. The steel sector was a forerunner in this respect. The opportunities to produce a carbon neutral steel for the global market provides the existing mining and steel sector in Sweden to make the shift away from relying on fossil resources for the processing of the ore. In the production sector further industries see hydrogen as a potential solution to transform existing production processes towards net-zero greenhouse gas emission processes.

Today 96 % of the worldwide hydrogen production is derived from fossil fuels, making it responsible for 5 % of the global greenhouse gas emissions. Present hydrogen use in Sweden is about 6TWh (Fossilfritt Sverige 2021) where the production is mainly from steam reformed fossil gas. In the future scenarios the hydrogen is exclusively made from non-fossil resources, where the most commonly found production solution is hydrogen produced in an electrolyser using renewable electricity generated from for example wind power. In this process a direct current is used to split water, H_2O, into its component's hydrogen, H_2, and O_2. The reaction is non-spontaneous, which is why current is needed to separate the water molecule. The reaction of electrolysis is:

$$2\ H_2O\ [water] \rightarrow\ 2\ H_2[hydrogen] + O_2[oxygen]$$

Due to the stoichiometry and the different molar weights, the production of oxygen in terms of weight is 8 times higher than the hydrogen production so for every kilo of hydrogen that is produced, there is 8 kg of oxygen gas generated.

Oxygen is a natural part of the atmosphere where about 21 percent of the atmosphere is oxygen, with other main part being nitrogen (78%). Oxygen is what we as humans' breath and use in our metabolism. It is not a toxic gas to humans and animals but will be dangerous as it can make other objects to ignite and burn much more quickly, oxygen is not flammable in itself.

The magnitude on which Sweden now are discussing the expansion of hydrogen production will thus also come with resulting by-products in the form of oxygen. Oxygen gas is already used in different productive purposes in Sweden today, including industrial, medical, food processing and other. The gas can come in various qualities depending on the purpose. The price will also differ between the different qualities oxygen that is sold, but on average the price has been 0.9–1.0 SEK/kg. Production volumes in Sweden has been around 1.25–1.50 million tonnes per year (Figure 1).

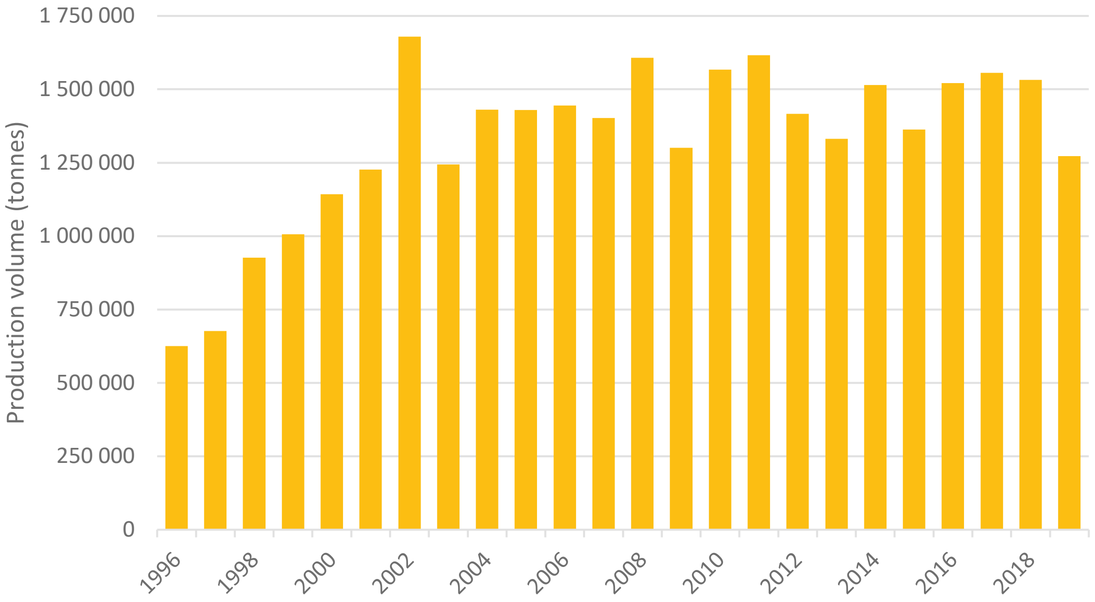


Figure 1: Production of oxygen gas in Sweden, and average selling price. Based on SCB statistics.

The production scenario of hydrogen would indicate something like 7.5 million tonnes of oxygen resulting from the electrolysers in 2030. This is about 6-7 times the oxygen production for Sweden today. Oxygen is without doubt a gas that can have productive purposes and this report is sprung out of the question on what this by-product can resulting from the hydrogen production be used for.

The aim of this report is to provide an introduction to the potential uses, associated benefits and markets for the industrial oxygen resulting from the foreseen expansion of hydrogen production in Sweden. The hydrogen production considered is based on electrolysers where the main product is hydrogen for different purposes, including energy and industrial uses. The oxygen is thus considered a by-product.

In order to close in on the aim consideration of place and also scale of operations of the hydrogen production will have to be considered. The scale will vary depending on the site and hydrogen demand and production capacity. In the steel sector the production will be very large, but there are several small-scale solutions also considered for filling stations and for industrial applications. The question on *where* the electrolysers are found will also define what the oxygen can be used for. Transporting the gas will result in additional costs.

The focus is on potential production and uses from a Swedish perspective. Sweden has already started to actions for hydrogen production, and it will not be long before the electrolyser capacity in the country has increased, and thus also the production of oxygen as a by-product. This means that experiences from Sweden could also provide experiences to other countries that start to pursue increased hydrogen use in their energy, transport and industrial sector.

The report does not include consideration of the excess heat that will also be the result of the production of hydrogen in the electrolyser. The excess heat will also be considerable and can have productive uses. In Sweden there are good opportunities for using this in for example district heating. This will also require further detailed considerations that are not considered here.

1.1 METHODS

This report was exploratory in its approach, aiming and explore the options for productive uses and further guide the reader on these. The magnitude on which oxygen will be produced as a by-product in the hydrogen scenarios for Sweden is on a scale not seen before. This also means that the present oxygen uses, where basically the oxygen is produced dedicated for the specific purpose, is perhaps not always what should be concentrated on. The question is on the value of this by-product. As of now, the value is defined by present production models, business cases and uses. The report is acknowledging these challenges and provides introduction to the different perspectives and boundaries that will have to be considered for further detailing potential uses and actions.

The potential productive uses of oxygen produced from production of hydrogen in electrolysers will depend on size of electrolyser and site. The quality specifications in terms of purity of the oxygen will also play a role. In order to capture these aspects a set of scenarios for the different production cases were the point of departure in the project. The scenarios and production cases are based on the now existing plans and studies on use of hydrogen in Sweden (Energimyndigheten 2021a; Energimyndigheten 2021b; Fosilfritt Sverige 2021; IVA 2022). These scenarios, as presented in chapter 2, provides results on the potential demand for hydrogen in the future and based on this the resulting oxygen by-product can be calculated. In Sweden it is expected that all hydrogen as part of this green transition will exclusively be produced by renewable energy thus having *green hydrogen* and not hydrogen based on fossil natural gas. The demand was then divided into typical production cases which provide typical sizes and oxygen production considering application. Background aspects linked to for example transportation and storage of oxygen will define the practical/economic potential for different solutions. The boundary conditions (chapter 3) provide a background for the discussion.

The productive uses were then pursued in a process where the *function* of the oxygen in the process was the point of departure. So by defining functions such as *supporting breathing in living organisms* or *oxygen as reactant* further sub categories could be defined. The categorization was used after project team workshops based on long-lists of potential uses. The functional categories would then also generate additional potential uses.

Each identified use would then be presented in some detail on a more generic level (chapter 4). This would include certain parameters defining the application and also overview of the application. A further detailing of some selected cases provides further insights and details (chapter 5). The selection of cases was based on analysis of different production cases, economic feasibility, attractiveness to the sector. These cases should *not* be seen as examples of the most attractive solutions. The best solution will be contextualized.

The report is based on both primary and secondary information that are found for the different applications. Interviews with sector as well as developing calculations for the applications considered have been made. These primary data is used in combination with secondary information from reports, web and articles. The market for oxygen in the hydrogen future defined in the scenarios will not be the same as is found today. Basing market and existing uses for oxygen for future applications is not possible. Whereas oxygen is produced in dedicated processes, the oxygen from the electrolyser is a by-product and need to be managed in some controlled way. Letting the oxygen out in the atmosphere is the easiest way, but from a resource point of view less efficient. It is foreseen that permits for establishing hydrolysers will include parts where the management of the oxygen will have to be presented, so might also be the case for the excess heat.

Hurskainen (2017) closes in on a similar question, the potential for the oxygen use from hydrogen production in electrolysers, in Finland. In Hurskainen (2017) the approach is more technical and focus present use. In this report it is acknowledged that the potential production of oxygen in Sweden may increase well beyond present use and thus additional and potential uses should be investigated.

2 Scenarios for hydrogen production and resulting oxygen

The production of renewable hydrogen is a vital part in transitioning the energy system. The interest in hydrogen has never been this big, and the number of planned projects within Sweden is continually growing. Hydrogen initiatives in northern Sweden will produce and consume very large amounts of hydrogen. Since the production method will be electrolysis, immense amounts of oxygen will be produced as a by-product and hence will be available. In order to grasp the amounts of oxygen available in the future, this report will quantify the amounts of oxygen from typical hydrogen production cases.

The proposal to a Swedish hydrogen strategy claims the goal of having 5 GW installed electrolyser capacity by 2030 and 15 GW by 2045, proposed by the Swedish Energy Agency (Energimyndigheten, 2021). However, the industrial engagement in hydrogen is increasing. LKAB alone has amplified their hydrogen targets in the spring of 2022, stating an electricity consumption of 20 TWh for hydrogen production. Correspondingly, their electrolyser capacity would be more than 2 GW.

Industrial hydrogen projects have stated an accumulative interest in installing around 5-8 GW of electrolyser capacity within a near future. An estimation of 6 GW corresponds to a hydrogen production around 0.9 million tonnes of hydrogen per year. **Along with the hydrogen production 7.2 million tonnes of oxygen will be produced as a by-product**. In context, the total oxygen production in Sweden in 2003 was about 1.25 million tonnes (Saxe & Alvfors, 2007) (Saxe and Alvfors 2007). In terms of medical oxygen tanks, Linde’s largest gas tank contains 50 L oxygen with a pressure of 200 bar, resulting in a weight of 14.3 kg (Linde, 2022a). Hence, the by-product from electrolysis is comparable to 500 million oxygen tanks for medical usage. In terms of tube trailer transportation, a 40’ ISO standard trailer is capable of transporting 30.6 m^3 of oxygen carrying around 8.7 tonnes with the same pressure as previously (UMOE Advanced Composites, 2022). Subsequently, the yearly amount of oxygen from electrolysis corresponds to 800,000 tube trailers.

Table 1. Selection of hydrogen projects initiated in Sweden.

Project/ Company	Location	Electrolyser capacity	Description
HYBRIT	Luleå	500-600 MW	Fossil free steel production (Hybrit, 2022)
LKAB	Gällivare Kiruna	2300 MW	Production of fossil free sponge iron (LKAB, 2022)
Inlandsbanan	Northern Sweden	100 MW (?)	Hydrogen trains (Inlandsbanan, 2022)
H2 Green Steel	Boden	1000 MW	Fossil free steel production (Montel, 2021)
Flagship ONE (Liquid Wind)	Örnsköldsvik	70 MW	Production of e-methanol. (Liquid Wind, 2022a)
Flagship TWO (Liquid Wind)	Sundsvall	140 MW	Production of e-methanol for shipping. (Liquid Wind, 2022b)
Fertiberia	Boden-Luleå	>600 MW	Production of green ammonia. Daily production of 1 500 tonnes ammonia, industry products and fertilizer (Industry Europe, 2021)
SkyFuelH2 (Uniper)	Sollefteå	150 MW	Jetfuel production from hydrogen and biomass in Fischer-Tropsch (Uniper, 2022).
Bothnialänken H2 (Uniper, Luleå Hamn, ABB)	Luleå	100 MW 500 MW in the future	Hydrogen hub to the regional process industry. Electrofuels for shipping or export (Uniper, 2021).
Ovako, Hitachi ABB, H2GS, Nel	Hofors	17 MW	Heating of steel using hydrogen (Ovako, 2022).

2.1 PRODUCTION CASES

In the project “Oxygen as a by-product from hydrogen production: potential use and market” a need to quantify typical hydrogen production was identified. The amounts of oxygen as by-product were calculated for the chosen characteristic hydrogen applications in the process of recognizing potential oxygen uses.

The first case is named a micro case which has an installed electrolyser capacity of 0.3 MW. The hydrogen production capacity is 6 kg per hour, serving a small hydrogen need. Likely, this small production unit is not dimensioned to constantly operate with full capacity due to a low demand. Hence, the usage is estimated to 50 % of the time on a yearly basis. The resulting amount of oxygen as by-product is then 200 ton per year.

Secondly, a hydrogen refuelling station case is considered. Refuelling stations will be located throughout the country. The question of decentralized versus centralized production is crucial in this estimation. However, a target within Repower EU is to have a refuelling station every 100 km on the TEN T road network. The installed capacity should be 2,000 kg hydrogen per day, corresponding to a 4 MW electrolyser. The utilization rate is assumed to be 60 % of the time throughout the year due to an inconsistent hydrogen demand. Conclusively, the refuelling production case equals 3,400 tons of oxygen per year.

Another production case was identified as an industry park with a hydrogen demand. Industrial applications including hydrogen will be important in the transition from fossil fuels. The economy of scale is a vital ingredient in hydrogen plants which makes centralized production more relevant. Thus, this production case includes a 100 MW electrolyser that provides one or multiple industries with renewable hydrogen. The utilization rate is assumed to be 90 % as industrial production is easier to plan. The subsequent oxygen as by-product was calculated to 126,000 tons per year.

The last production case is a steel production site. A site where hydrogen is utilized in the reduction of iron ore instead of the traditional method with fossil fuels. The steel industry in Sweden has transformed their climate targets drastically and wants to transform their production sites. Luossavaara-Kiirunavaara (LKAB) is a large mining company who wants to transition to fossil free sponge iron. By 2030 LKAB claim to have a need of 20 TWh of electricity mainly needed for hydrogen production through electrolysis (LKAB, 2022). Correspondingly, the installed electrolysis capacity would be in the magnitude of 2 GW. The resulting amount of oxygen as by-product is 2,500,000 tons of oxygen per year.

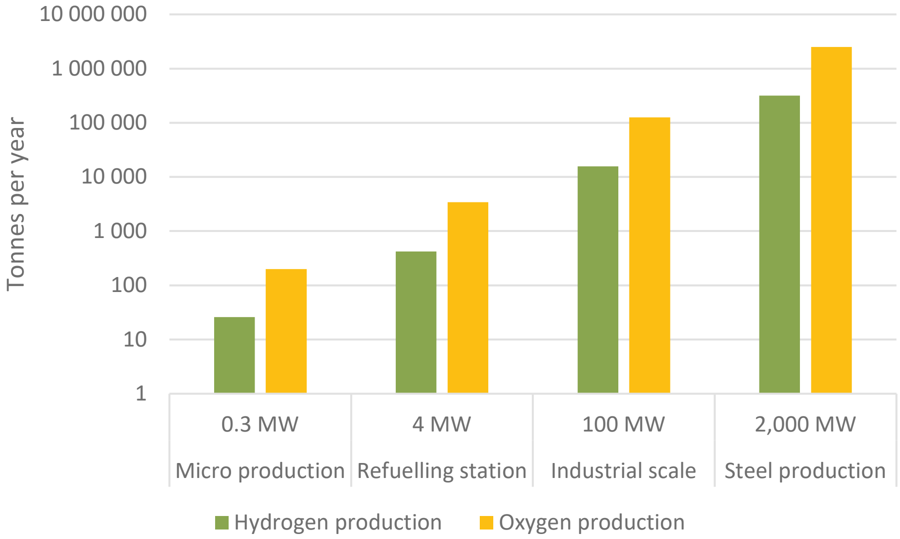


Figure 2. Production of oxygen and hydrogen in the four production cases (log scale).

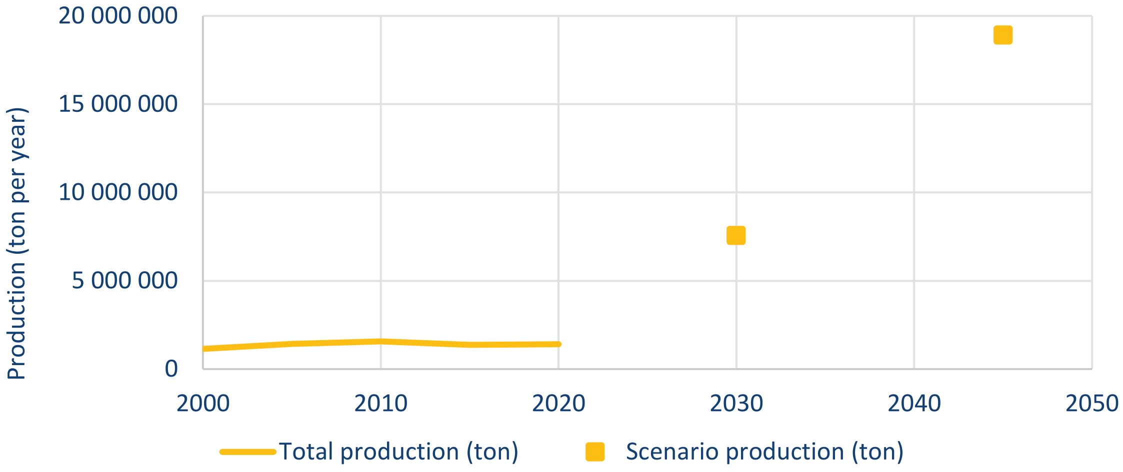


Figure 3: Historical production of oxygen and scenario of generated oxygen from electrolysers (Sweden only)

3 Conditions for managing the oxygen gas

3.1 ECONOMIC AND MARKET ASPECTS OF OXYGEN GAS

Production of oxygen today is typically as a primary product. The end-use and quality of the oxygen product to be sold defines the price. The purity of both oxygen and hydrogen varies depending on which electrolyser technology is utilized. The gaseous products are separated, but hydrogen can occur in the oxygen stream and vice versa, which must be controlled. In an alkaline electrolyser, which is the most economically viable and hence most common, treatments are needed to get rid of residue alkali that might end up in the oxygen gas. For example, chlorine gas might follow the oxygen which would be toxic to inhale. In a proton exchange membrane (PEM) electrolyser the gases have a higher purity, but the electrolyser is more expensive (Tata Consulting Engineers, 2021). However, even the alkaline electrolysers are usually equipped with gas treatment to attain pure streams of both hydrogen and oxygen. Potassium hydroxide is recirculated from the oxygen which increases the purity substantially. Studies show that oxygen purity from electrolysis is very high, with 99.7% as the highest reported achievement (Zeng & Zhang, 2010). Table 1 describes the purity from numerous electrolyser suppliers. The required oxygen gas purity depends on application, but an example is medical oxygen where a minimum of 99.5% oxygen is mandatory.

Even though a sufficient oxygen gas purity is relatively easy to obtain it must not be forgotten that there is a cost to clean the gas. Without any application for the oxygen, the gas is usually flared to the atmosphere. Even though it is a by-product, some costs are added to remove impurities. In some cases, the oxygen is also humid and might need dehumidification. The gas stream from each electrolyser must be analysed and adapted to the end application.

Table 1. Oxygen gas purity from different electrolyser suppliers (Zeng & Zhang, 2010).

Supplier	**De Nora**	**Norsk Hydro**	**Electrolyser Corp.**	**Teledyne Energy systems**	**General Electric**
Oxygen purity [%]	99.6	99.3-99.7	99.7	> 98.0	> 98.0

The price data for Sweden can be obtained as an average price for the produced oxygen in Sweden (Figure 4). This price does not distinguish between the different qualities and purity levels.

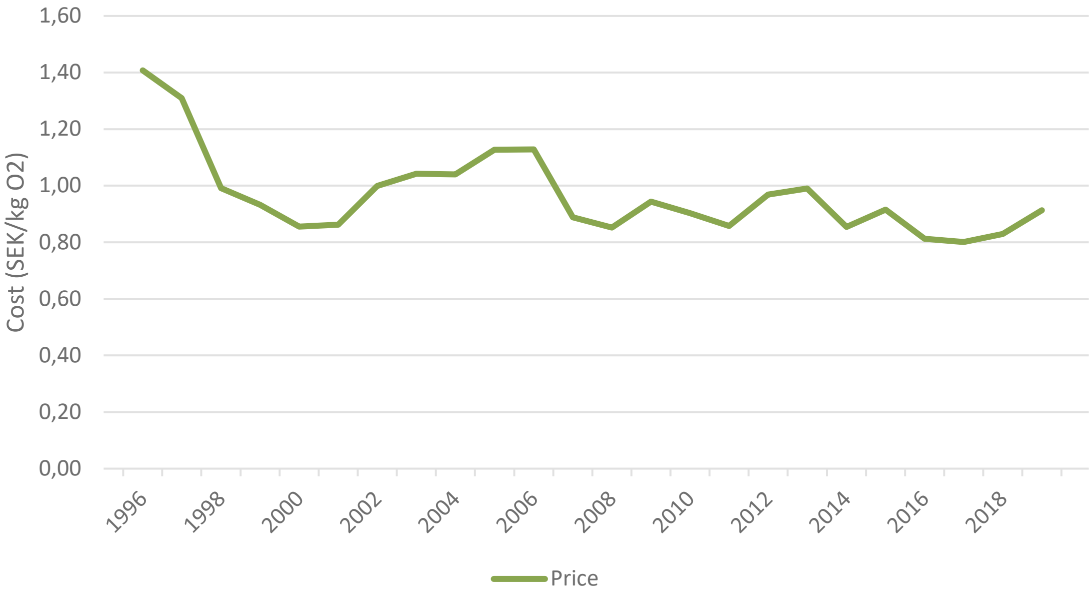


Figure 4: Cost of oxygen produced in Sweden (source SCB)

The cost range of about 1 SEK/kg, corresponding to 0.1 EUR/kg, is an average number and will include some more exclusive products that have higher prices. A business case for hydrogen production in Smöla in Norway puts the potential price for oxygen to be used in aquaculture to 0.1 EUR/kg (MRCC *et al.* 2021). The average price reported by Hurskainen (2017) was ~0.073 EUR/kg (0.73 SEK/kg).

Squadrito *et al.* (2021) discuss the opportunity to look at the hydrolyser as a producer of oxygen and what the price level needs to make it profitable. Their conclusion indicates that a price of at least 3 EUR/kg would be needed to find motivation for the hydrolyser considering a hydrogen price of 10 €/kg. According to Italian data set on tenders the price received were 1.4-4.2 EUR/kg for pressurized oxygen with purity of 99.5%-99.995% (Nicita *et al.* 2020), while for the liquid oxygen same price was about 0.3-0.5 EUR/kg (prices excludes transport and special handling).

The price level is thus difficult to assess in detail as it will depend on the quality and business case suggested. In the scope of this report the focus is on oxygen as a by-product from hydrogen production, but a potential alternative way is to see the electrolyser producing *both* oxygen and hydrogen where optimisation of the oxygen product is done.

3.2 TRANSPORT OPTIONS OF THE OXYGEN GAS

Oxygen is mainly transported by cylinder delivery, bulk liquid trucking or pipelines, see Figure 5, and it is transported in compressed or liquid form.

Figure 5. Transportation alternatives

Cylinders are used for transporting smaller amounts of low- or high-pressure gas, such as oxygen. A standard cylinder is 50 litres, or 14 kg oxygen, and transportation can be managed by car or trailer (Linde, 2022a). A car can take up to ten cylinders, depending on size, and a trailer approximately 200 cylinders which is equal to 3 tonnes of compressed oxygen. Cylinder transportation is identified to be technologically suitable for the *micro production case* or the *refueling station production case*, but it is unclear whether it would be economically viable due to today’s low value of oxygen.

Bulk deliveries are larger size deliveries conducted with liquid oxygen stored in cryogenic tanks. Truck sizes can range between 1,000 to more than 100,000 litres. A standard truck in Sweden is assumed to carry around 30 tonnes of oxygen The liquid is stored in -196°C and low pressures (SafeRack, 2022). The cost of oxygen transportation by truck ranges from 45 to 60 EUR per tonne oxygen according to one study by Sweco in 2022. A study by (Rivarolo et al., 2014) showed a trucking cost of 22 EUR per tonne oxygen for a 350 km distance in Paraguay and that trucking was a lower cost option compared to a pipeline for up to 322 tonnes of oxygen per day. When the oxygen volume is 655 tonnes per day or more, a pipeline was shown to have a lower cost per tonne oxygen than trucking. Liquid oxygen transportation is technologically viable for somewhat larger operations with no need for constant oxygen delivery, as one truck is assumed to carry around 30 tonnes. The *industrial scale production case* is assumed to be of relevant size. A common benchmark in Sweden is that liquid oxygen can be transported a maximum of 200-300 km before the costs are too high. Further, liquid oxygen requires additional infrastructure compared to compressed oxygen, such as a liquefier and special vehicles.

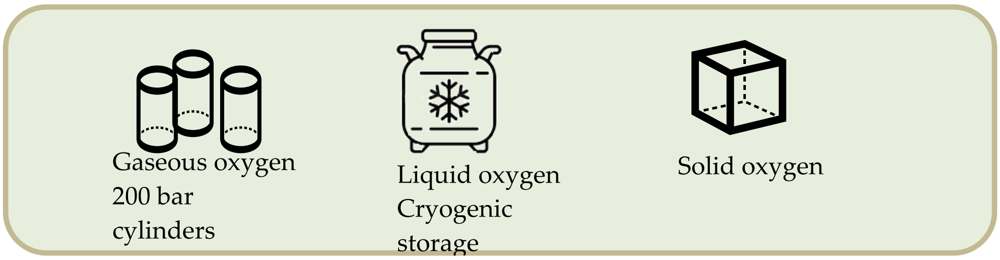
Pipelines are used for large-scale oxygen operations such as steel plants or the petrochemical industry, as well as for regional distribution. (Rivarolo et al., 2014) calculated a transportation cost of 33 EUR per tonne oxygen for pipeline transportation at a rate of 322 tonnes of oxygen per day, 16 EUR at 655 tonnes and 8 EUR at 1 310 tonnes per day. Pipeline transportation can be viable for the *industrial scale production case* and the *steel production case*, but also lower daily volumes could be relevant if there’s a dedicated off-taker.

3.3 STORAGE OPTIONS FOR OXYGEN GAS

Oxygen can be stored both in gaseous form, usually with an elevated pressure, or in liquid form if the temperature is decreased below the boiling point of -183 °C. Even if the oxygen is not flammable, the storage might involve risks due to high pressures or cold temperatures. Unlike hydrogen, there is no needed permission from the Fire and Rescue Service to handle oxygen. However, it is recommended that the gas is treated similarly (Tibbelin et al., 2022).

Even though permission is required from the Fire and Rescue Service, they provide guidance in handling the gas. However, this is mainly in form of oxygen tanks for welding or for medical use. The experience from large scale oxygen storage is scarce. The Fire and Rescue Service in eastern Skaraborg claims that large-scale oxygen storage units are very rare in Sweden (Tibbelin et al., 2022). Regulations are also found in the Seveso legislation. Furthermore, the legislation for both hydrogen and oxygen are inadequate.

Oxygen is stored in either gaseous form in cylinders, liquid form in cryogenic storage or in solid state.



When oxygen is stored in gaseous form the pressure is usually 200 bar. The tanks from Air Liquid go up to 50 L, and can thereafter be bought in multiples of 50 L tanks (Air Liquide, 2022). It is important to handle the tanks and the bottle valves carefully when transporting storage tanks. The high pressure might transform the tank to dangerous a dangerous projectile if the bottle valves brakes (Vårdhandboken, 2022). Furthermore, pressurized gas cylinders are dangerous in case of fire and should be evacuated quickly by the Fire and Rescue Service. Oxygen with high pressure is classified as a Hazard Statement Code H270 (may cause or intensify fire; oxidiser) in the CLP regulation. Hence, warning signs for Flame over circle and Gas cylinder ought to be utilized (Vårdhandboken, 2022).

Another option is to store oxygen in liquid form which takes up 800 times less volume compared to oxygen at atmospheric pressure and 0 °C. The weight for the cryogenic liquid is also lower than for gas storage (Vårdhandboken, 2022). Even though it is utilized mostly in gaseous form, the storage is usually in liquid form. It is less bulky and is less costly compared to high pressure gas storage. Typically, for example at Swedish hospitals, the storage system contains one liquid storage tank, one or multiple vaporizers and compressors. Liquid storage is the most economical option for large quantities (Sagaya, 2021)

Furthermore, oxygen can be stored in solid state or in chemical oxygen generators where oxygen is stored in the chemical composition. Solid state is obtained at temperatures below -219 °C for atmospheric pressure but is not a common storage method for oxygen. Chemical oxygen generators releases oxygen as a result from a chemical reaction. This storage method is utilized in airplanes to generate emergency oxygen to passengers if the cabin pressure decreases. However, this is not a conventional method to store oxygen in a larger scale.

3.4 SAFETY REQUIREMENTS/ HANDLING OXYGEN GAS

Oxygen gas is an oxidant that can cause or contribute to the formation of a fire when the right conditions of oxygen, fuel and heat amount are met. This is described by the fire triangle. Cylinders containing oxygen are pressurized and should be regularly inspected to avoid leakages. Leakages can occur as a result of damaged hoses, pipes and valves, worn fittings and loose connection or by simple leaving valves unintentionally opened. When oxygen gas is stored in cylinders the concentrations are almost 100%, which is higher than the oxygen in atmosphere (21%). Leakage of this gas in close places creates an oxygen rich environment where fires can ignite more easily and burn hotter(Sutton, 2017), and it makes it very difficult to extinct the fire.

When storing oxygen in a cylinder, the place must be dry (made of non-flammable materials) and sheltered from weather and fire hazards. It is important to avoid the contact of pure oxygen with incompatible materials such as oil and grease. Hair and clothing could also easily catch fire in an oxygen rich environment, putting people at a higher risk.(Ingles, n.d.). Air liquid is an oxygen supplier for industry and healthcare. They advise that, if possible, cylinders should be located outside workshops or laboratories and on the ground floor. The storage should also have extractor hoods and gas detectors. The cylinder being used must be fastened to the wall to avoid falling. This can be done with a metallic ring. If the cylinders fall it could explode. When opening and closing the valve, this should be done slowly, and force should not be needed. If the valve is difficult to open, the supplier should be contact (Air liquide, n.d.).

Another risk for oxygen containing cylinders is the exposure to heat. Heat increases the volume of gas which would lead to explosion of the cylinder. When transporting the cylinders, this must be placed in a trolley and be fastened. They must never be rolled or dragged. The cylinder must never be picked up by the cap or valve. The person moving the cylinder must wear protective footgear and gloves(Air liquide, n.d.)

When using oxygen from the cylinders and the pressure is so low that the flow decreases, to increase the flow rate some cylinders can be connected in parallel to supply simultaneously. Staff working the oxygen should be trained in safety handling and storage of oxygen before they use it.

3.5 ENVIRONMENTAL ASPECTS OF OXYGEN GAS EMISSIONS

Oxygen does not reflect infrared light and will thus not have a global warming potential when increasing the concentrations. Oxygen concentration does however affect several other processes that will have positive and negative contributions to climate affecting processes (Poulsen *et al.* 2015). So even though there is no carbon dioxide equivalent factor for oxygen, changing concentrations on a large scale may have both positive, and negative contributions to reducing the process of climate change as well as have other impacts on the environment.

On a timescale of millions of years, the oxygen concentration in the atmosphere has changed. There were only small levels of oxygen in the atmosphere before photosynthesis had evolved. Oxygen then formed the life of our planet in the way that we today experience it. The levels of oxygen in the atmosphere have ranged from around 10% to 35%. The life of the planet will find adapt to the conditions. These are very slow changes, and for setting the time scale in relation the last ice age affecting Sweden ended about 10,000 years ago, then it had lasted for about 100,000 years.

The concentration of oxygen in the atmosphere is slowly decreasing at a rate of about 19 molecules per million per year, according to measurements made since 1989. This trend will continue, and the concentration is projected to decrease from 20.946% to 20.825% by 2100, or an average of about 0.0015% per year. The rate of change is affected by both changes in oxygen production and consumption, and may be parabolic rather than linear, and so the concentration will drop to zero in about 4,400 years. To affect human health, the concentration must be below about 19.5%. The current rate of oxygen decline is sufficient to contribute to global warming. (Huang et al., 2018)

Increased oxygen levels will affect the environment but possibly not directly be harmful. Certain functions linked to metabolism and other will operate at other conditions. These impacts will depend on the concentration levels as well as the time exposed. The increased risk of fire is one immediate risk.

Inhaled oxygen from the air enters the lungs and enters the bloodstream. Oxygen enters all parts of the body through the blood and maintains the normal functioning of organs and tissues. Too high oxygen level can injury tissues of lung. Alveoli in the lungs can become filled with fluid or stop inflating. In this case, the lungs cannot breathe air normally, and it is more difficult for the lungs to supply oxygen to the blood. Oxygen toxicity is also one of the reasons of central nervous system symptoms. (Andrew D Schriber MD et al., 2022). Breathing 50-100% oxygen at normal pressure over a prolonged period of time can cause lung damage. People who work under the exposure of pure oxygen should take lung function test before and after working in that environment.

Oxygen is highly reactive, and this ability of oxygen increases with increasing pressure, temperature, and concentration. Special knowledge and understanding of ignition mechanisms, material properties and design methods and test data are required in the design, development, and operation of oxygen systems. When designing risk management in oxygen systems, special attention must be paid to limiting the amount of oxygen available, using materials that are resistant to ignition and combustion, limiting the amount of heat generated by oxygen in systems, and limiting exposure to personnel and equipment. The pressure and concentration of oxygen can have a significant effect on its flammability. Materials ignite and burn more easily as pressure or oxygen concentration increases, so oxygen systems should be operated at the lowest possible pressure and oxygen concentration (Pedley, 2009).

4 Potential uses

This chapter provides overview of different potential uses of oxygen. There are different groups of potential uses which are based on the function of the oxygen. The listed uses here is a non-exhaustive list. The functions are divided into:

- Supporting breathing in living (larger) organisms.
- Promoting efficient microbial growth
- Support ecosystems
- Oxygen enriched combustion
- Oxygen as a reactant/feedstock in industrial applications.

The point of departure in function, rather than production sector or industry, may also trigger imagination on new opportunities if oxygen is available.

4.1 SUPPORTING BREATHING IN LIVING (LARGER) ORGANISMS

4.1.1 Medical oxygen

Oxygen is an important medicine for many different treatments and is used at all levels at the healthcare system. The gas is utilized in surgery, trauma, heart failure, asthma, pneumonia and maternal and childcare. For example, pneumonia is a serious disease worldwide where it is estimated that 20-40 % of deaths could have been avoided with oxygen therapy (World Health Organization, 2021). Oxygen in the blood is a vital condition for life. Too low oxygen saturation is detrimental to the human body, and saturation levels below 70% is life threatening (Vårdhandboken, 2022). Oxygen treatment is therefore also used for decompression sickness, carbon monoxide poisoning and other diseases. Oxygen is also widely utilized in the intensive care, either in a mix with other gases or alone. The gas has been vital in the treatment for Covid-19 where oxygen treatment saved lives. Other than in the intensive care, Covid-19 could cause blood oxygen drops down to mortal levels (Colarossi, 2020). Hence, the pandemic intensified the global demand for oxygen and made deliveries urgent. As a consequence, the World Health Organization (WHO) helped to scale up the oxygen supply in vulnerable countries in 2021 (World Health Organization, 2021).

As mentioned in 3.3, Swedish hospitals usually have a storage system with liquid oxygen which is then vaporized and distributed to cylinders before usage. MSB (Swedish Civil Contingencies Agency) states that production of oxygen on the hospital area would increase the robustness in times of crisis. However, this independent oxygen production occurs in other countries but is not common in Sweden (MSB, 2021). The requirement on gas purity for medical oxygen is a minimum of 99.5 %.

Regarding the oxygen demand for hospitals, an economic feasibility study on hydrogen and oxygen production mentioned an equation derived from the gas consumption on 12 Spanish hospitals between 2008-2016. A correlation between the number of hospital beds and the annual gas consumption was found (Gómez-Chaparro et al., 2018):

$$Oxygen\ cons. = 8.3 * (hospital\ beds)^{1.814} \quad [Nm^3/year]$$

For Danderyd hospital in Stockholm with 510 hospital beds, the annual average oxygen consumption would be around 700,000 Nm^3. Converted to mass it corresponds to 1,000,000 kg oxygen.

4.1.2 Aquaculture

Aquaculture is the controlled formed of farming organisms in water. The most common form is cultivation of fish, but also includes crustaceans, algae, and aquatic plants. The cultivation could be performed in fish tanks, ponds or ocean enclosures, mostly for food. Oxygen is mandatory for almost all living organisms and the amount of dissolved oxygen in the water is a crucial parameter for growing fish and plants (Go Green Aquaponics, 2021). Sufficient levels of dissolved oxygen increase the productivity and overall health in aquaculture. Furthermore, improper usage of oxygen might be harmful. A controlled environment is optimal, just like with temperature and food (Linde, 2022b). A study on the Norwegian island Smøla claims that both by-products from electrolysis, oxygen and heat, could be significant incomes if it is utilized in local aquaculture (Møre and Romsdal County Council et al., 2021).

A more specific technique is named aquaponics. The process integrates aquaculture with hydroponics, hence growing plants in water and using this as a habitat for cultivating fish too. This sustainable growing method is dependent on the nitrogen cycle. Ammonia, a waste product from the respiratory cycle and a toxic for fish in high concentrations, is broken down by bacteria to form a great nutrient source for plants. Consequently, the plants utilize nutrients to grow while simultaneously cleaning the water to make the recycled water safe for the fish (Agriculture Academy, 2020). Both oxygen and heat need to be supplied in controlled forms to achieve a successful aquaponic farming (Tibbelin et al., 2022).

It should be noted that the Swedish aquaculture industry is limited in size - the total aquaculture fish production in 2012 was 12 500 tonnes, compared to 1,3 million tonnes in Norway the same year (Susanne Eriksson, et al., 2019). Nevertheless, fish farming is identified as an important industry of the future by the Swedish Board of Agriculture (in Swedish *Jordbruksverket*) and is one of the fastest growing food sectors globally.

The number of aquaculture facilities in Sweden have decreased somewhat between 2010-2021, see Figure 6 below, but the total volume produced has increased (Jordbruksverket, 2021). The traditional open- and semi-open systems such as cages and dams are dominating the market, but there's an increase in the number of closed recirculating facilities. The volumes produced in recirculating, land-based, facilities amounted to 200-250 tonnes per year nation-wide in 2019 (Hydén, 2019).

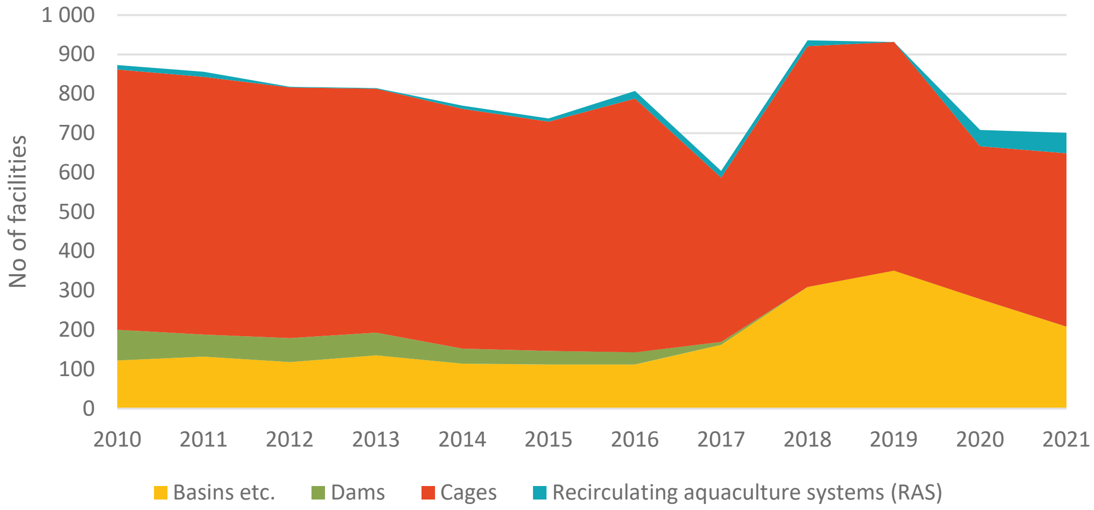


Figure 6. Facilities for the cultivation of food fish, food crayfish and hatchery fish by type of facility (Jordbruksverket, 2021)

Open systems, where the farm is directly connected to the surrounding environment such as the sea or a lake, are oxygenated by the natural flow of water (Jordbruksverket, 2021). Semi-open and closed aquaculture systems need added energy and oxygen. It is therefore assumed that it is to these facilities that the potential for delivering hydrogen related oxygen lie.

4.1.3 Oxygen enriched environment for insects

Insect farming is considered an important aspect in increasing future food supply, and in particular feeding urban populations (Gahukar, 2016). During specific circumstances, some insects can be farmed using less resources than conventional livestock and insect farming is also considered to have less animal welfare risks as many naturally live during crowded conditions. Insect farming is still mainly manual, but some industrial level enterprises have been expanding their business, in particular in Europe and USA.

It is known that exposure to increased oxygen levels leads to increased sizes of some insects (Geological Society of America, 2010), and several research initiatives have been identified which uses oxygen enriched environments to increase insect output. The results are varied, with some leading to increased yield while others do not. Anna Jansson, professor in domestic animal physiology at the department of anatomy, physiology and biochemistry at Swedish University of Agricultural Sciences (SLU) mentions that the effect of adding oxygen to insect farms undoubtedly is dependent on insect species, and that it would be interesting to do pilot studies on the topic (A. Jansson, personal communication, October 21, 2022). Another potentially advantageous aspect of insect farming in connection to electrolyser facilities is that insects need added heat as well, which could make the farms suitable off-takers for both oxygen and residual heat.

4.2 PROMOTING EFFICIENT MICROBIAL GROWTH

4.2.1 Wastewater treatment (nitrification)

In many of the biological processes that are used to treat wastewater oxygen is consumed. Oxygen then acts as an electron acceptor when organic material is oxidized to carbon dioxide or when ammonium is oxidized to nitrate. Oxygen is also used when wastewater is ozonated to further degrade micropollutants in wastewater that are not degraded biologically. The implementation ozonation at wastewater treatment plants is growing as an increasing amount of research is showing the negative environmental effects of micropollutants that leave the wastewater treatment plants.

Today oxygen is supplied to the biological process with blowers that consume significant amounts of energy. Blowers typically use 30-50 percent of the total energy consumption at wastewater treatment plants. There are also older methods to supply oxygen that mechanically force air into the water though mixing (Bengtsson et al., 2019). In an ozonation step oxygen is used to produce ozone. Oxygen is normally supplied through a liquid oxygen system (LOX) and transported on site with a tanker truck.

Using oxygen to treat wastewater is today very costly and there are therefore few commercial applications, except for ozonation. If oxygen could be delivered at a lower cost, there are though several potential advantages for the treatment process that could be further assessed. In this chapter potential applications are listed together potential advantages. Further assessment of costs and advantages is necessary to determine whether any of the proposed applications could have a market potential.

4.2.2 Yeast fungi in brewing processes

Oxygen could be used in brewing processes, especially in the brewing of beer. In this area, oxygen plays a dual role: it is essential to the yeast once injected in the wort, creating an aerobic environment and supporting the respiration and thus metabolism of the yeast cells (Brenner et al., 1967; Elshani et al., 2018). The yeast metabolism rate furthermore affects the formation of higher alcohols such as n-propanol, isobutanol and 2- and 3-methyl butanol, which all contribute to the typical beer flavour (Lehnert et al., 2008). Yet, oxygen could cause undesired flavour (from e.g., carbonyls) when present after the fermentation process and may oxidize the naturally present sugars and organic acids (Elshani et al., 2018; Lehnert et al., 2008). The oxygen concentration in the beginning of the fermentation must therefore neither be too low nor too high: the wort should contain about 6-8 mg/L of oxygen by the time yeast is injected (Lehnert et al., 2008).

As a reference for potential uptake, Ossett Brewery, located in the United Kingdom, uses 50 litres of oxygen supplied at a pressure of about 6 bars to a 6,500 litre brew using a batch (as opposed to a continuous) brewing method (Bronkhorst, 2022). The potential thus depends on the size and prevalence of breweries in the close proximity of the source of air.

4.3 SUPPORTING ECOSYSTEMS

4.3.1 Seabed aeration

Without access to dissolved oxygen, conditions for higher animal life in aquatic ecosystems cease. Oxygen deficiency is a common phenomenon in coastal sea areas (Diaz & Rosenberg, 2008). In many regions, oxygen deficiency is considered to have arisen after 1950 as an effect of human influence through the supply of fertilizing substances that stimulated the production of phytoplankton above all (Breitburg et al., 2018). As plankton and other organic matter sink to the bottom, it begins to decompose, consuming oxygen. If the supply of organic material is greater than the supply of the amount of oxygen required to break down the material, the oxygen supply is gradually depleted.

The immediate effect of lack of oxygen is that fish escape and bottom-dwelling animals are eliminated, which also has consequences at other trophic levels in the ecosystem. The bottom-dwelling animals fulfil an essential function as decomposers of settling material. The benthic animals, in turn, become food for higher organisms such as fish and birds (Casini et al., 2021). Fish species are also dependent on the presence of oxygen at the depths where the eggs hatch (Hinrichsen et al., 2009)

Another adverse effect of lack of oxygen is that the ability of the sediments to bind the nutrient phosphorus decreases at low oxygen levels. In oxidized conditions, phosphorus is bound from the material that settles in salts with various metals (iron, manganese, aluminium, and calcium). Under reduced conditions, iron loses its ability to bind phosphorus. The phosphorus instead leaks back into the water mass as bioavailable dissolved phosphate (Figure 7). The released phosphorus can once again contribute to the production of phytoplankton and, under certain conditions, lead to unpleasant so-called algal blooms. Some researchers believe that the systems are stuck in a vicious circle (Vahtera et al., 2007) - as long as there is a lack of oxygen, phosphorus constantly circulates in the system and perpetuates the production of organic material, which in turn leads to continued strained oxygen conditions.

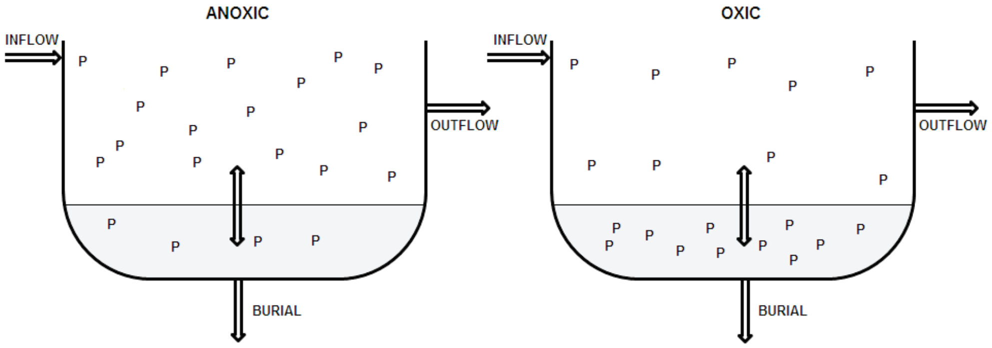


Figure 7. Principal illustration of the distribution of phosphorus (P) between water and sediment in an anoxic (left) versus an oxic (right) system. When oxygen is present (oxic system), a more significant fraction of P is bound to sediments, reducing the risks for algal blooms in the water column. From Malmaeus och Karlsson, 2012.

A possible measure to break the vicious circle could be to oxygenate the water artificially. Efforts to artificially oxygenate water areas have been carried out in many places worldwide, preferably in lakes and water reservoirs. Experience from the oxygenation of coastal and marine areas is more limited. Preece et al. (2019) stated that in several cases, artificial oxygenation has reduced the internal load of nutrients and resulting cyanobacteria blooms and increased the living space for cold-water fish species and vertically migrating zooplankton. There are also examples where the method has not worked (Horppila et al., 2017). Gantzer et al. (2019) found through investigations in three North American lakes and water reservoirs that after long-term oxygenation (up to 10 years), oxygen consumption in the bottom water decreases, which was interpreted as oxidation and breakdown of the organic material " the oxygen debt" taking place over time in the sediments. In the cases in question, oxygen was pumped down and spread using so-called bubble plume diffusers (Figure 8).

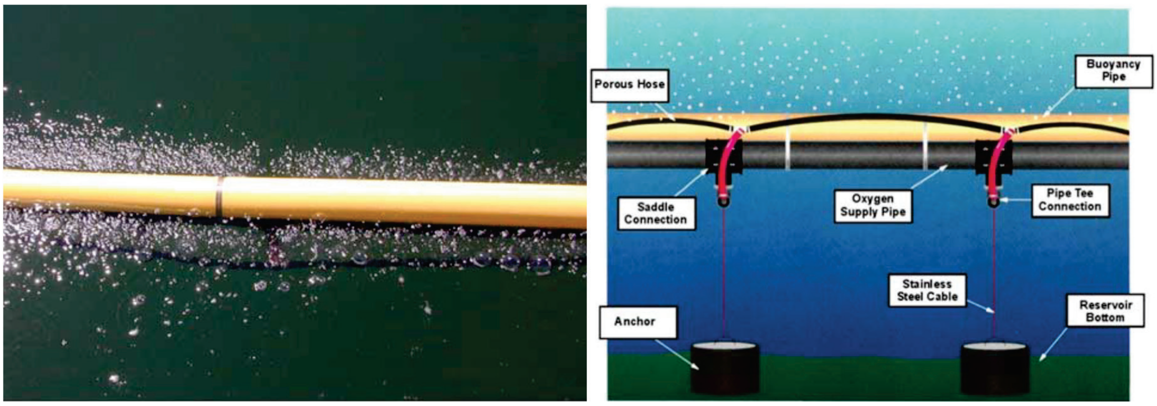


Figure 8: Photograph and schematic illustration of linear bubble plume diffuser in Spring Hollow Reservoir, Virginia. (from Singleton et al., 2007)

A negative effect that can occur from oxygenation is gas bladder disease (diver's disease) in fish due to gas oversaturation in the water. Another potentially harmful effect is the release of environmentally hazardous substances from the sediments either for purely chemical equilibrium reasons through changed redox conditions or indirectly through benthic bioturbation of the sediments (Granberg et al., 2008). However, experiences from areas historically burdened by environmentally hazardous substances where the oxygen conditions have improved in recent years do not indicate that this process has been significant for developing the environmental state (Sandström et al., 2016). Another question to be answered is whether the oxidation of the sediments, on the one hand, would lead to a release of carbon in the form of carbon dioxide that would otherwise be stored in the sediments or whether this is offset by a reduced formation of the potent greenhouse gas methane that occurs during reduced conditions (Lehoux et al., 2021).

Overall, it can be stated that society today devotes relatively large resources to the restoration of aquatic ecosystems. There is a considerable potential to use excess oxygen nationally and internationally for environmental purposes. Much speaks for that oxygenation is a relatively cost-effective measure in situations where the method works. At the same time there are significant technical challenges to be solved in terms of how oxygen is to be distributed to the water so that it provides a maximum positive effect on the oxygen conditions in the water while minimizing adverse side effects.

4.4 OXYGEN ENRICHED COMBUSTION

With excess volumes of oxygen produced in the vicinity of a combustion plant, or processes including combustion technology, the idea of utilizing oxygen within the combustion process lies close at hand. From a technical point of view mixing oxygen into the combustion air will theoretically reduce the flue gas heat loss, since less inert nitrogen (from combustion air) is passed through the combustion process. The nitrogen heats up passing through the combustion process and exits through the smokestack, thus inducing a temperature loss, aka. loss in overall efficiency. A decrease of total gas flow will decrease the fan work for transporting the gas volumes through the process, thereby reducing the electrical power consumption needed.

For carbon dioxide (CO_2) removal, oxygen enriched combustion increases concentration of CO_2 in flue gas, again because of lower levels of nitrogen gas. A CO_2-rich flue gas volume, increase the efficiency of Carbon Capture and Storage systems (CCS) post combustion.

As simple as it sounds, there are some technical challenges of implementing the concept of oxygen enriched combustion, even if the amount of needed equipment is low.

A combustion process is normally designed to use ambient, or preheated air (with 79 vol-% Nitrogen (N_2) and 21 vol-% Oxygen (O_2)). This means that all radiation and heat absorbing surfaces are designed for a certain amount of radiation heat and a certain amount of conductive/convective heat at the different heat absorbing surfaces.

By increasing the amount of O_2 in the combustion air, two important things occur that needs to be handled by the combustion process:

1. The rate of combustion increases in an oxygen rich environment. The chemical reactions will occur faster and results in a larger heat flux and thereby increasing combustion temperature.
2. The combustion air-, and thus the flue gas flow will decrease slightly.

If the amount of oxygen is kept at a low level and with some adjustments for volume changes – the combustion process will work within the load range. The amount of oxygen that can be added to the combustion air will differ between boiler types and fuel selection. A fuel with high moisture content, such as woodchips, would render a higher possible oxygen enrichment than a dry fuel. The moisture has a cooling effect on the combustion temperature and the water vapor limits the mixing of combustibles. The two effects slow down the combustion rate and counteract the effect from the extra oxygen added.

A wet fuel might be possible to use with the excess oxygen without any further modifications, but in practice this would lead to higher risks for local hotspots with sintering of ash and/or thermal ware on the furnace. A dry fuel or waste fuel (with lower ash melting temperatures) will need flue gas recirculation for controlling the combustion process.

Controlling the combustion temperature will be done with a variable flue gas recirculation flow back to the furnace. The flue gas will both make up for the gas volume decrease and slow the combustion rate down. Therefore, it will balance the combustion temperatures, and enable a wider fuel span, and a more controlled combustion process.

The boiler type will also limit the amount of oxygen added. Bubbling fluidized bed (BFB) boilers and Circulation fluidized bed (CFB) are more sensitive to the combustion temperature since the technique use sand in the process, that might produce sintering at locally higher temperature. The gas flow through the bed is very important for the fluidization process and heat transfer meaning that the combustion is highly sensitive for both changes in temperature and gas volumes.

Addition of extra oxygen in a BFB-boiler should be done at the secondary or tertiary air stage, giving a higher combustion rate above the bed, thus minimizing the risk for bed sintering. For grate fired boilers the air would also typically be added at a secondary or tertiary air stage to keep the main combustion suspended above the grate in gas phase combustion. The same can be done for burner boilers (for wood powder, oil or gas) without any heavy impacts on the hardware.

The result of addition of oxygen in a combustion process can be summed up as a mismatch in heat transfer, that needs to be controlled and handled by the process, not unlike what occurs when fuel converting a plant.

The added oxygen and the higher combustion temperatures give an increase of radiation heat and a decrease of convective heat. Like stated in the section above this phenomenon is controlled by flue gas recirculation – maintaining temperatures and gas flows much like the original conditions, except with a different flue gas composition. Similar gas flow volumes will mean that the flue gas cleaning (FGC) system will work with approximately the same conditions as designed. The flue gas composition will shift to higher concentrations of carbon dioxide (CO_2) and a decrease in nitrogen (N_2) making a carbon capture system (CCS) more efficient.

The possibility of a low or high blend in of oxygen will in the end be set by the design parameters of every individual plant regarding to boiler type, fuels and load ranges.

4.4.1 Enriched combustion in heat and power plants

The system for an oxygen enriched combustion will typically comprise of following equipment:

- Oxygen tank(s) with filling- and evacuation system, compressor, fans, piping, valves, instrumentation and automation system for filling, storage, and adding oxygen to the combustion air. Tanks and piping should be placed separately in vented areas secluded from areas where fuel and dust are handled.

- The plants distributed control system (DCS) will control the automatic valves for oxygen flow within the combustion process loop. An implementation will need a total upgrade of steering parameters, combustion curves etc. within the DCS-system.
- Safety systems for detection and evacuation of an oxygen leakage, fire protection etc.
- The oxygen adding system will work closely connected to the combustion air-, flue gas recirculation-, and flue gas systems. This ensures the operation and control of combustion process and maintains the boiler pressure and volume flows through the entire load range of the boiler.

Addition of oxygen to the combustion air system is made from automatic valves directly to the combustion air duct. The connections are made in one or several inlets located between the air fan(s) and air inlets to the furnace. Added oxygen needs to be perfectly mixed with the combustion air before entering the combustion zone. The Oxygen system is constantly kept at a higher pressure than the combustion air system for ensuring that oxygen penetrates and mixes with the combustion air. The control and function of the oxygen addition is depending on input process data from the DCS, such as: furnace temperatures, pressure, oxygen levels in flue gas after furnace, air/flue gas flows and temperatures.

Addition of O_2 give two different effects on the formation of nitrous oxides (NO_x). The increase in combustion temperatures lead to an increase in formation of thermal NO_x from nitrogen in the combustion air. The formation rate increases exponentially with high temperature. At the same time a decrease in nitrogen in the combustion air, and the use of more recirculating flue gas reduce the formation of NO_x. Mainly the added flue gas leads to reduced NO_x-formation.

The O_2 enrichment to a combustion process may change the conditions for a furnace selective non-catalytic reduction (SNCR) system. The SNCR system injects ammonia into the furnace where it reacts with NOx to form Water and nitrogen. The change can decrease the reduction rate in some cases as well as increase it in other applications.

4.4.2 Incineration of hazardous waste - destruction

The same combustion theory applies for incineration of hazardous waste. Maintaining a high temperature in the incineration process is vital for ensuring complete destruction and decomposition of the hazardous waste. Oxygen enrichment increases temperature as previously discussed making use of oxygen boosting very interesting. The upside is lower fuel consumption while maintaining a high combustion temperature, thus ensuring the purpose of the process – to incinerate the hazardous waste. The downside being the risk of higher NO_x emissions.

4.4.3 Oxyfuel

The concept of Oxyfuel is a relevant variation of enriched combustion and can be said to lie on the opposite end of a line starting with normal combustion with air (Figure 9).

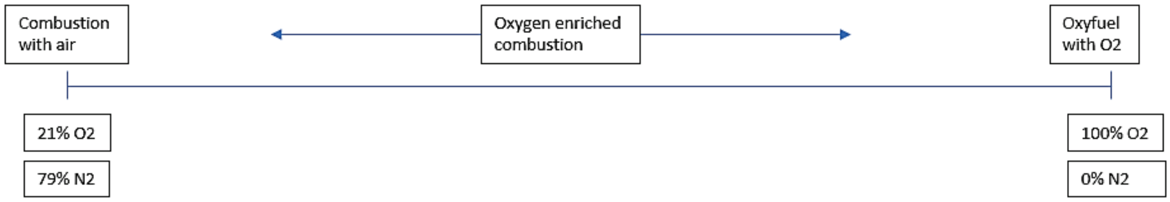


Figure 9: Normal combustion (to the left) and oxygen enriched combustion cases (towards the right).

Using pure oxygen for combustion and combining it with recirculated flue gas eliminates nitrogen in the process. The benefit is a CO_2-rich flue gas highly suitable for carbon capture. The main difference from oxygen enriched combustion is the absence of nitrogen.

The flue gas will consist of CO_2 and water vapor making the CO_2 capture a less complicated process as compared to CO_2 capture with a mixed flue gas. In the oxyfuel application the flue gas cleaning and condensation unit is all that is needed. After dust- and water removal the flue gas consists of only CO_2.

The combustion air volumes and the corresponding flue gas volumes decrease in the oxyfuel process thus lowering the electrical consumption for the process fans and increasing the efficiency by reducing the heat loss from flue gases.

An oxyfuel process is more compact than an ordinary combustion plant and will give a much smaller footprint. For a new combustion plant with integrated carbon capture, the oxyfuel process with its “integrated” CO_2 separation should be highly competitive to the normal combustion plant with a carbon capture system based on extraction CO_2 from a nitrogen rich flue gas.

The opportunities for supporting revenues in this case may come from negative carbon credits if the oxyfuel process with carbon capture and storage is based on bioenergy.

4.5 OXYGEN AS A REACTANT/FEEDSTOCK IN INDUSTRIAL PROCESSES

4.5.1 Oxygen assisted gasification

Biomass feedstocks can be recycled to syngas by biomass gasification to produce electricity, heat, fuels, or chemicals otherwise fossil fuels can be used for that. Usually, biomass gasifiers are manufactured by air-blown technology. Syngas that produced in that process roughly contains 50% nitrogen gas (N_2). This gas is high inert, and it means that the syngas low energy content. If compared to natural gas it has approximately 7 times less higher heating value (HHV) (5.5 MJ/N m3). Due to nitrogen gas (N_2) impurity the syngas cleaning up and utilization become more costly, and the equipment have to be sized to handle greater volumes of gas. Oxygen, oxygen-enriched air, or oxygen/steam mixtures can be use as gasification agents to improve all these failings. All these strategies of syngas production have less inert gas content and much high energy content per unit volume. To promotes H_2 production via the water–gas shift reaction and control temperature in the gasifier water steam is commonly used.

From one side, studies of steam and oxygen blown gasification provides rare because of equipment and operational complexity if compared to air gasification. But from other side studies of gasification with steam and oxygen-enriched air are more common, they have operating characteristics that lies between air gasification and steam and oxygen gasification. (Broer et al., 2015)

The oxygen-enriched air agent gasification has some advantages if compared to the gasification providing with air. The thermal input of the gasification plant has to be kept constant because it is reduced nitrogen amount in the gasifying agent, and it can let operate the process of gasification with a reactor, and all equipment that related to the plant operation. It reduces size of consequent capital investment costs. The higher production of a gas with a lower heating value (LHV) can affect to the internal combustion engine. From the other side the availability of such a gas as a fuel can allow the use of smaller and cheaper internal combustion engines. Also, the availability of a such technology that is built on enriched-air gasification can do it appropriate for refuse-derived fuel (RDF) gasification, and it expands the fields of its pertinency. Research on low-cost technology for oxygen-enriched air production are giving an important sustenance to the possibility of such applications.(Barisano et al., 2016). An illustration of the gasifier and feed system is shown in Figure 10.

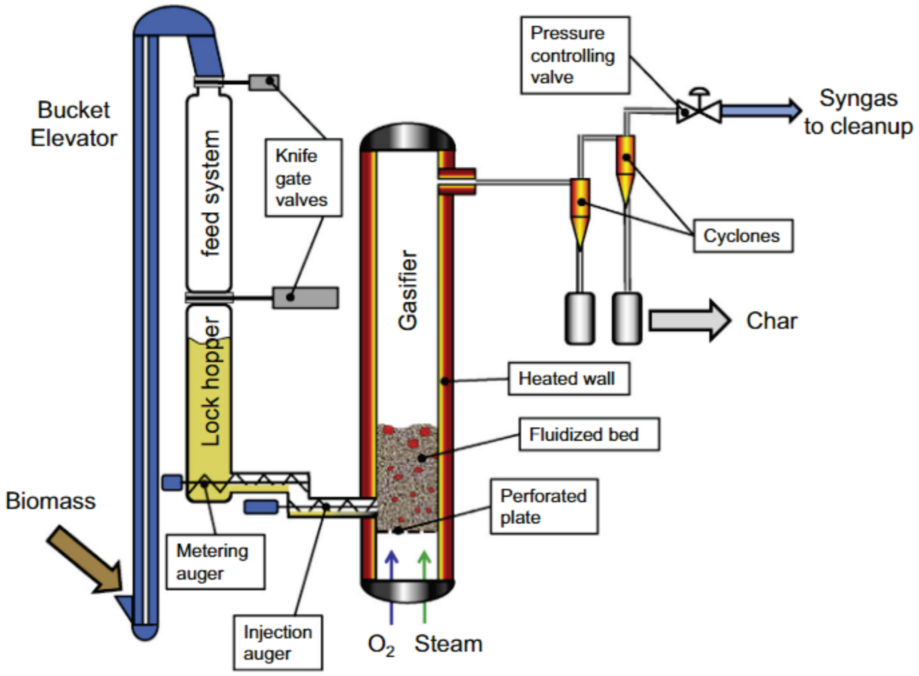


Figure 10: The feed system and fluidized bed gasifier (Broer et al., 2015)

4.5.2 LoTox – production of O3 for NOx filtration

The amounts of O_2 available near/or at the combustion plant makes the NOx-reduction process of LoTOx highly interesting. The LoTOx process can be seen in Figure 11.

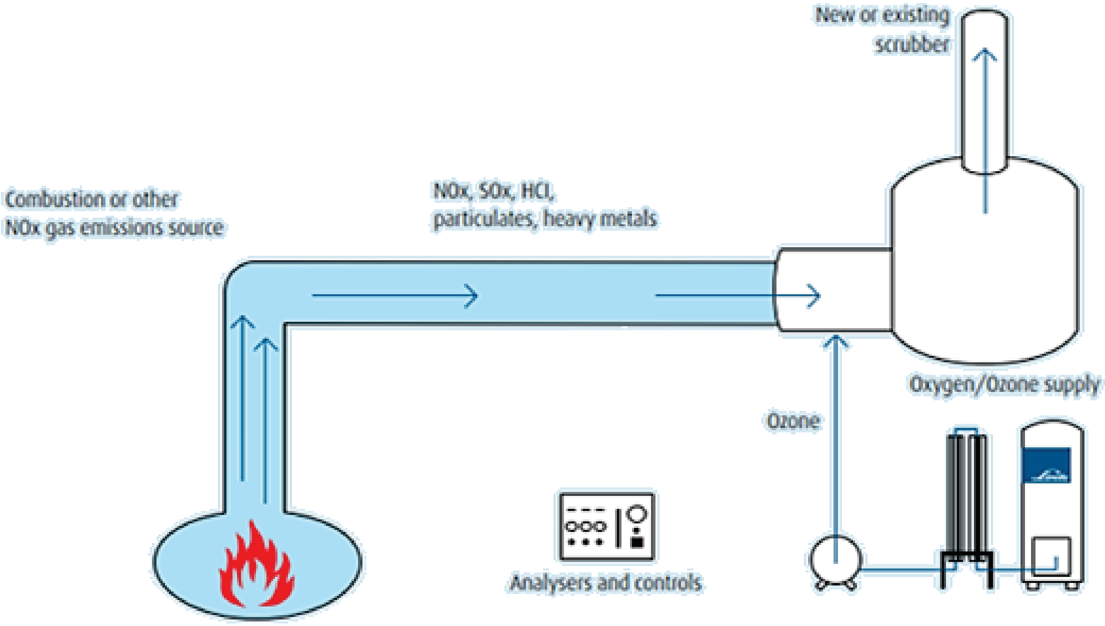


Figure 11: Simplified process of the LoTOx technology. Source: Linde Gas

The process uses ozone, produced from O_2 to react with NOx in accordance with the chemical reactions 1 and 2 to Nitrogenpentaoxide (N_2O_5). The nitrogenpentaoxide will react with water in accordance with reaction 3 to form nitric acid.

1. $NO + O_3 \rightarrow NO_2 + O_2$
2. $2NO_2 + O_3 \rightarrow N_2O_5 + O_2$
3. $N_2O_5 + H_2O \rightarrow 2HNO_3$

Ozone is highly selective for reactions with NOx (Both NO and NO_2) rapidly forming the water-soluble pentavalent form N_2O_5. The resulting N_2O_5 can be absorbed by wet or semi dry flue gas cleaning (FGC) systems as nitric acid with reduction levels of up to +95%.

The usage of existing wet flue gas cleaning systems can with smaller adjustments work well for NOx reduction from an existing plant and by far outperform an SNCR system. This may also compete with the more expensive Selective catalytic reduction (SCR) systems for NO_x reduction. The excess oxygen thus gives new options for alternative NOx reduction systems than the well-established SNCR/SCR systems widely used today in industrial and heat and power production.

4.5.3 Steel production

The steel sector is the sector that use the main share of total oxygen in Sweden today. In beginning of 2000 this was in the range of 65% of the total demand[1]. There are several stages in the steel making process where oxygen is used.

Oxygen is used in primary steel production through a process called *basic oxygen steelmaking* (also *Lind-Donawitz steelmaking* or *oxygen converter process*). This process is used to turn pig iron into steel, by decreasing the concentration of primarily carbon (C) but also silicon (Si) and phosphorous (P) in the pig iron. By blowing pure oxygen into a reactor of molten blast-furnace pig iron, the impurities are oxidized in reactions that generate large amounts of heat. Using pure oxygen allows for higher production rates, less labour and steel with lower nitrogen content (Encyclopaedia Britannica, 2017). In scrap-steel plants oxygen is used in the electric arc furnaces.

The connection of having hydrogen production close to the steel processing plants will allow for some use of the oxygen in the processes. It should be pointed out that amount of oxygen from the electrolysers for one of the steel cases will produce oxygen roughly similar to the total production of oxygen in Sweden today. Still, if oxygen is available at the sites there could be potential to increase use of oxygen use in the steel sector.

4.5.4 Fuel cell applications

Fuel cell is a device that produces electricity when hydrogen (fuel) reacts with oxygen (oxidizing agent) by means of a redox reaction.

Anode: $2\,H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$

Cathode: $O_2 + 4e^- \rightarrow 2O^{2-}$

Overall reaction: $2H_2 + O_2 \rightarrow 2H_2O$

Fuel cells are used both as *stationary power* and *transportation*. The first category refers to power supply or backup supply in the industry, residential areas or in remote locations. The second category refers to the supply of electricity to drive different vehicles such as cars, trucks, trains, ferries, etc. Hydrogen fuel is needed as the main source of fuel, whereas in normal applications the oxygen is taken from the atmosphere. This is the in many ways the reversed process as the one that we see in the electrolyser, while in the electrolyser electricity is added to divide the hydrogen and oxygen atoms, here energy is released as part of the oxidation process.

4.5.5 Mineral extraction

For base metals like nickel and cobalt extraction from laterite ores the sulphur-enhanced bioleaching usually has been most intensively explored. The metal ores reductive bio-processing that usually calls as “biomining in reverse gear” because

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[1] In Saxe et al (2007) the share of oxygen demand between sectors is given to 65% metal processing industries, 15% in pulp and paper industry and 15% in chemical industries. 5% is on other.

it uses opposite principles biomining conventional though both operate at low pH. It characterizes a completely new way for mineral bioprocessing.

$S^0 + 1.5\ O_2 + H_2O \rightarrow HSO_4^- + H^+$

As shown in Reaction (1), some acidophilic bacteria can produce acid straight from elemental or zero-valent sulphur (ZVS). But this needs oxygen that conventionally prevents the iron reduction. To promote acid production and to generate reducing conditions alternating cycles of active aeration and zero aeration have been used to solve this issue. (Johnson, 2018)

For example, bioleaching of Au from refractory mineral ores uses both bio-oxidation and bio cyanidation (Fig. 1), and is provided by bacteria, archaea, and eukaryotes.   In bio-oxidation process, the iron and sulphur are oxidized by acidophilic bacteria which oxidize the metal sulphide to metal ions and sulphate, that improve the Au accessibility. (Karthikeyan et al., 2015)

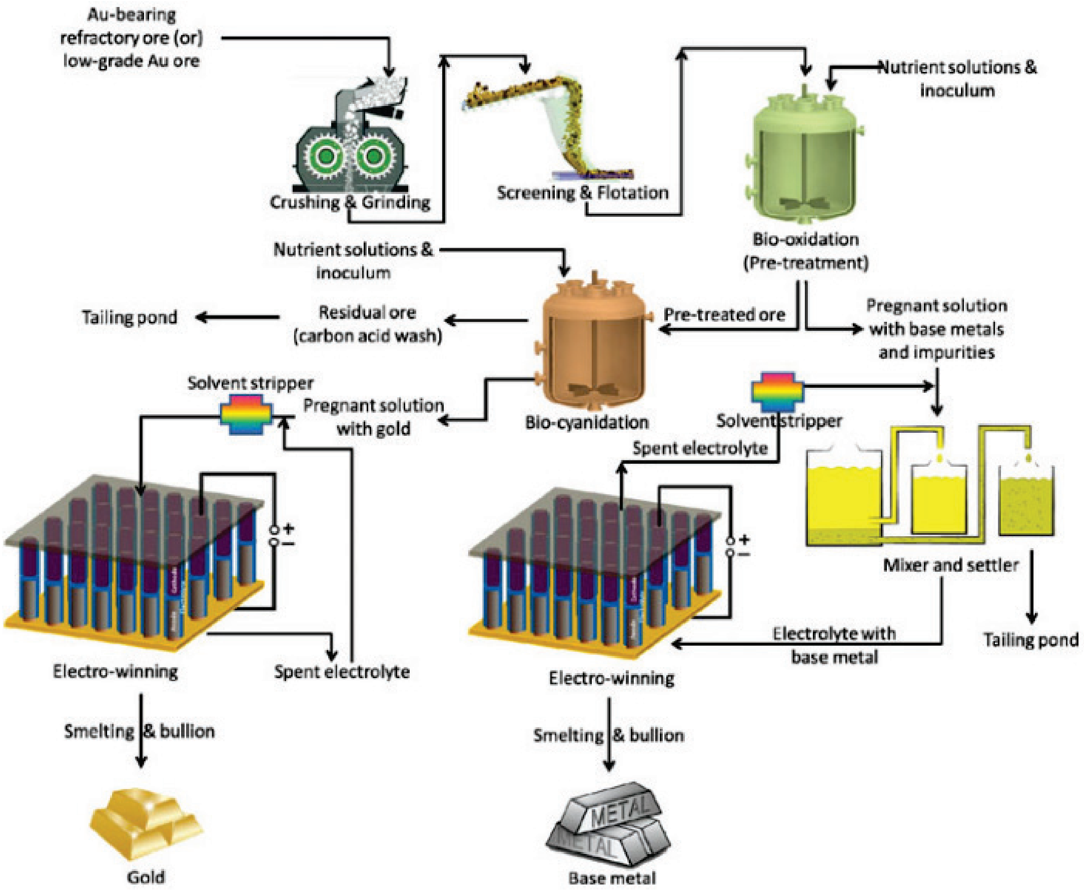

Figure 12: Process flow of bio-oxidation and bio cyanidation of Au bearing refractory mineral ore

For the refractory Au-mineral ores the partial bio-oxidation under pH 2 and bio reduction under pH 5 is used. Under the partial bio-oxidation conditions, bacteria are expected to regenerate Fe3+ from Fe2+ for the bioleaching of other metal ions from the refractory ores as given in Reaction 2:

$Fe2^{+} + 1/4O_2 + H^{+} \rightarrow Fe3^{+} + 1/2H_2O$

The oxygen concentration is kept lower than 100 litres/minute to decrease the quantity of H_2SO^4 generated by the system. The partial bio-oxidation process decreases the quantity of oxygen provided to the system and it minimizes the operating costs.(Karthikeyan et al., 2015)

4.5.6 Pulp and paper

Oxygen is used in the pulp and paper industry in several of their process steps. The most common one is for lignin removal which can be done by oxygen delignification or bleaching. The first process consumes 20-30 kg O_2 per bone dry metric ton (BDMT) of pulp (PCI oxygen solutions, n.d.). The second consumes 10-15 kg O_2/BDMT (PCI oxygen solutions, n.d.). A higher oxygen consumption takes place in the black liquor oxidation step where up to 100 kg O_2/BDMT (PCI oxygen solutions, n.d.) is used to reduce the discharge of sulphur pollutants into the atmosphere when the black liquor is combusted in the recovery boiler. In the wastewater treatment step also large amounts of oxygen is needed. The main process in the treatment consumes up to 50 kg O_2/BDMT (PCI oxygen solutions, n.d.)

The use of oxygen for the oxidation of lignin became possible in 1970:s when small amounts of magnesium salts were added to the alkaline oxygen stage, right after the cooking step and before bleaching. The addition of magnesium protected the pulp from degradation. The use of oxygen before bleaching made it possible to change to elemental chlorine bleaching and even total chlorine free bleaching, making the process more careful with the environment (Ek et al., 2009). The success of this change has been driven by the environmental regulations and awareness, as well as advances in technology. In Sweden, nearly 100% of the bleached pulp has been through oxygen delignification (Ek et al., 2009).

4.5.7 Food packaging

Oxygen is used in some food packaging to preserve quality and prolong shelf-life. The designation of oxygen is E948. The oxygen will reduce certain bacterial growth and through this preserve the foodstuff. This is especially relevant for meat. Oxygen levels required to achieve the result anticipated will depend on the type of meat but for red meat levels of 60-80% oxygen and rest carbon dioxide is found. It is the redness of the meat that will be affected by the bacteria. This means that for lighter meat other gases may be more effective. Typical shelf life for red meat in air packaging may be around 2-4 days, while in packaging with a modified atmosphere this shelf life is prolonged to 5-8 days. Oxygen may also be found for other food stuff packaging in combination with other gases, and typically lower (less than 15%) concentrations.

5 Selected case studies of potential use of the resulting oxygen gas

In this chapter further details are given to five different use cases which represent potential uses, but also illustrates some of the range of functions that the oxygen can have and requirements of oxygen. The cases are:

- Oxygen enriched combustion in heat and power production (case 1),
- Oxygen enriched combustion engines (case 2),
- Seabed aeration (case 3),
- Sewage treatment (case 4) and
- Aquaculture (case 5).

5.1 CASE 1: OXYGEN ENRICHED COMBUSTION IN HEAT AND POWER PRODUCTION

Heat and power plants would be an ideal user for oxygen enriched combustion. The production units are large, and the positive effect of enriched combustion makes it an interesting case, especially if production units of hydrogen are present, thus making amounts of produced oxygen available at the site. Technically the add-ons of hydrogen production in combination with carbon capture system to an existing combined heat and power (CHP) plant will lead to several benefits.

5.1.1 Introduction to the case

For this theoretical case two possible boiler systems are discussed. The oxygen enrichment and following flue gas treatment as well as carbon capture systems have the same design regardless of boiler technology, which emphasizes that the new systems are simple add-ons to an existing plant as well as integrated parts in a fresh designed CHP. For robustness reasons the simplest way of adding oxygen was chosen. The injection points have been chosen from the perspective of keeping a high plant availability, low impact on operation and maintenance, and simple systems without extra complexity with I&C systems.

Figure 13 shows a block scheme of an entire CHP process integrated with hydrogen production, CCS and a further use of CO_2 in electro fuel production. The figure shows the possibility to transform traditional combustion technology into a circular and therefore more environmentally feasible production.

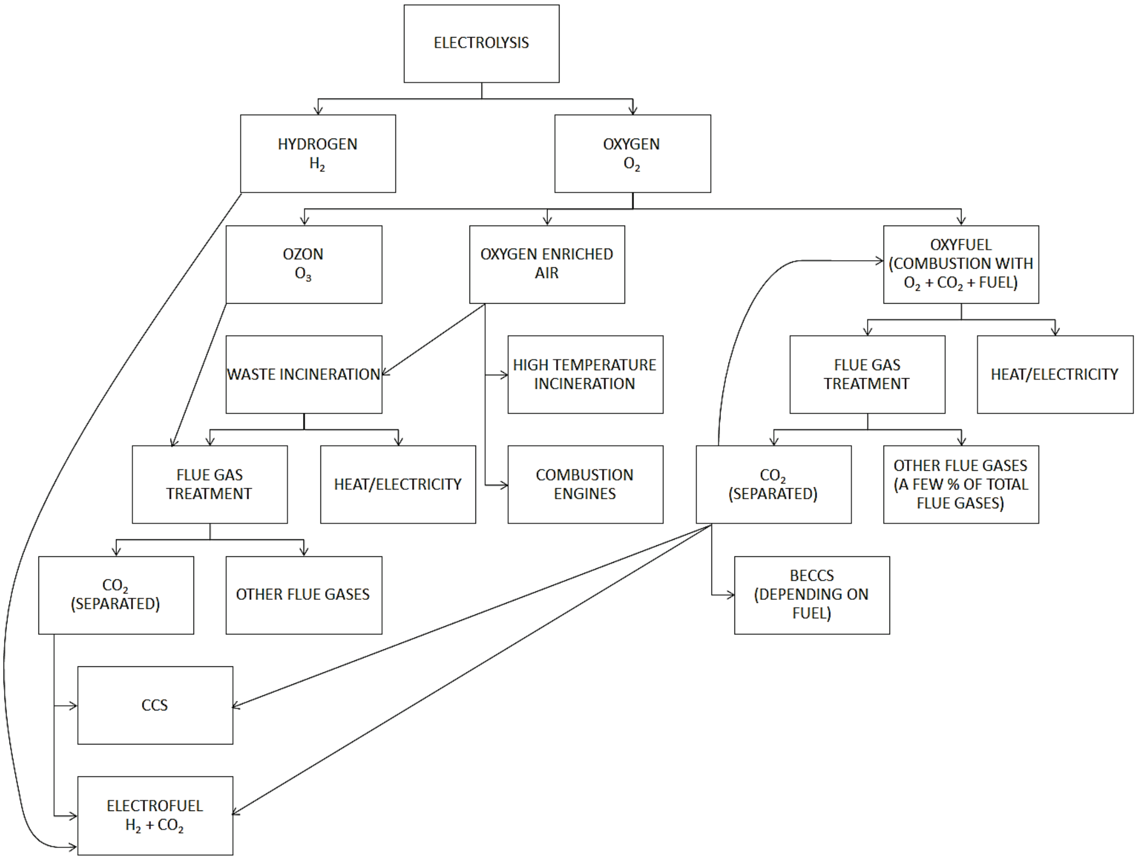

Figure 13: block scheme of an entire CHP process integrated with hydrogen production, CCS and a further use of CO_2 in electro fuel production.

Figure 14 shows a block scheme that highlights certain parts of the process in Figure 13 and combines them in a hypothetical scenario. This figure focuses on the possibility to combine High temperature electrolysis, which operates at around 500-800°C, and combustion with either O_2 enriched air or, if one takes this concept further, oxyfuel combustion.

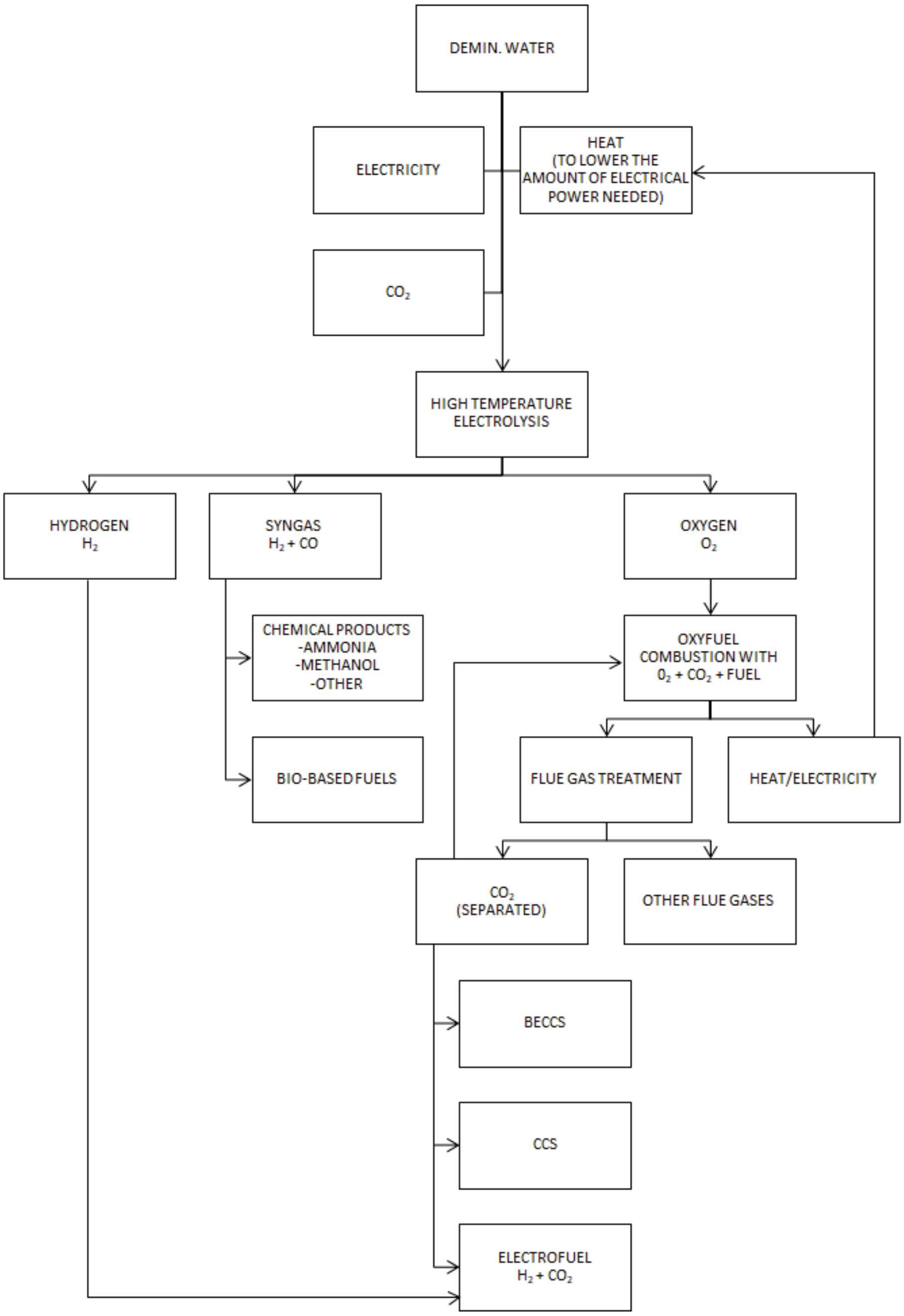

Figure 14: High temperature electrolysis, which operates at around 500-800°C, and combustion with either O2 enriched air or, if one takes this concept further, oxyfuel combustion.

5.1.2 Technical description

Alternative 1. BFB boiler system

A 100 MW BFB boiler system using forest residues as fuel. The plant is equipped with electrical turbine, wet flue gas cleaning with FGC, SCR, flue gas recirculation and carbon capture system.

The fuel delivery, storage and fuel preparation systems are not described. The combustion air distribution to the furnace starts in the fuel shuts leading into the boiler. A smaller amount of combustion air is normally distributed together with the fuel at the end of the fuel shute. This air flow spreads the fuel particles over a larger area and prevents areas in the furnace from having heavy concentrations of fuel and mitigates under stoichiometry conditions at the furnace fuel inlet.

The BFB boiler has the primary (fluidization) air entering underneath the furnace from an array of small air nozzles spread evenly over the furnace area. The fluidization air keeps the sand bed at the furnace bottom floating. In the sand bed, normally kept at about 850°C, the fuel particles dry, gasify and the remaining char particles burn out. Above the sand bed additional combustion air is added for the burning of combustion gas. The air distribution can occur in several stages as secondary-, tertiary- and sometimes quaternary air.

The air stages keep the combustion temperatures under control and enables a good heat transfer from the furnace to the boiler walls and the heat extracting surfaces within the boiler.

The fluidization process is very sensitive to the actual gas flows and high temperatures making the sand bed form into sinter and agglomerate if temperatures are too high, adding oxygen to the fuel shute or fluidization air would be a bad idea. Instead, oxygen is added at the air stages above the bed.

For an existing BFB boiler the amount of oxygen added at the secondary stage could cause some issues with the heat transfer within the furnace. Changes to the automation system to comply with the changes in gas flows, temperatures and pressures need to be undertaken. A new boiler would consider these parameters already in the design and account for the gas flows.

The addition of oxygen to the combustion air system is made directly to the air duct prior to the secondary air fan. The oxygen system is pressurized and inlet to the system is made via nozzles and a motor driven valve connected to a steering loop that controls the O_2 level in the air.

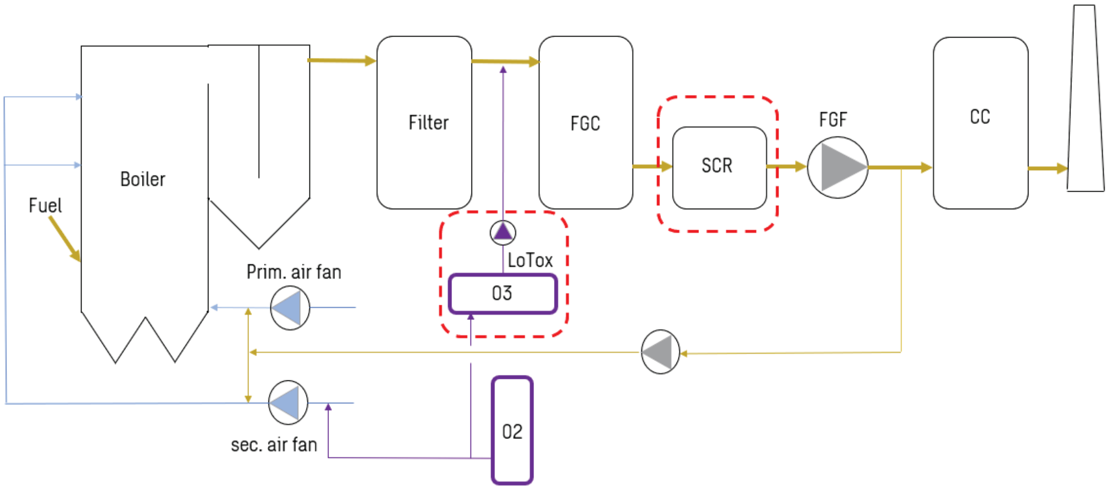

Figure 15: A simplified block schedule showing main components and connections for the example plant with BFB technology.

Figure 15 provides a simplified block schedule showing main components and connections for the example plant with BFB technology. For de-NOx both SCR and LoTox-systems are shown within brackets. This illustrates that either one of the systems is possible to use.

Alternative 2. Waste to energy (WTE), Grate fired boiler

A waste to energy (WTE) 100 MW grate fired boiler system firing municipal waste. The plant is equipped with a turbine for electric production, wet flue gas cleaning with FGC, SCR, flue gas recirculation and a CCS system.

The fuel delivery, storage and fuel preparation systems are not described. The combustion air distribution to the furnace starts in the wind box underneath the grate. Fuel distribution into the furnace is made by hydraulic pushers and then the moving grate transports the fuel as it burns towards a bottom ash chute, normally leading down to a bottom ash quenching system.

The grate is typically divided into 4 or 5 sections with the possibility to adjust air flow to the different sections. The purpose of the first section is to heat up the fuel and evaporate the water content within the fuel. The fuel will burn out at the following combustion sections. At the last section the fuel will have burned out and only the remaining ash/slag will be left.

The grate fired boiler will also have staged combustion air inlets, typically with secondary air inlets just above the grate and tertiary air higher up in the furnace. Air fan set up is similar to a BFB and the addition of oxygen can be injected into the air duct in same manner as the BFB.

A grate fired boiler gives different combustion challenges compared to a BFB-boiler. The grate holds a large amount of fuel burning which means that the combustion process is more difficult to adjust. More fuel leads to a slower change rate than the BFB that holds very limited amounts of fuel within the furnace.

Adding oxygen to the primary air underneath the grate leads to faster burn out rate and higher temperatures on the grate. This is possible to handle, but for an existing grate fired boiler this gives challenges keeping the fuel bed thickness and thermal ware low for the grate elements. Higher combustion temperatures on the grate also leads to more ash deposits and melts clogging the small holes for primary air inlet through the grate elements. This is a normal occurrence but will increase and therefore can risk more unavailability due to combustion problems. To control the issue with high temperatures and too fast burn out rates, flue gas recirculation to the primary air duct would be used to balance the oxygen enrichment. This would in theory give a "normal" combustion with normal flue gas flows within the process. The benefit is the lower flue gas flow exiting the smokestack and therefore lowering the flue gas thermal loss.

These issues can lead to heavily increased maintenance costs why the oxygen addition, in this case, is proposed to be added to the secondary air system as in the case with the BFB-boiler. Flue gas recirculation is used to control the oxygen enrichment and the combustion as suggested above. The upside is that the grate and fuel bed will be kept at the same conditions as it is designed for, eliminating any effects from the oxygen enrichment.

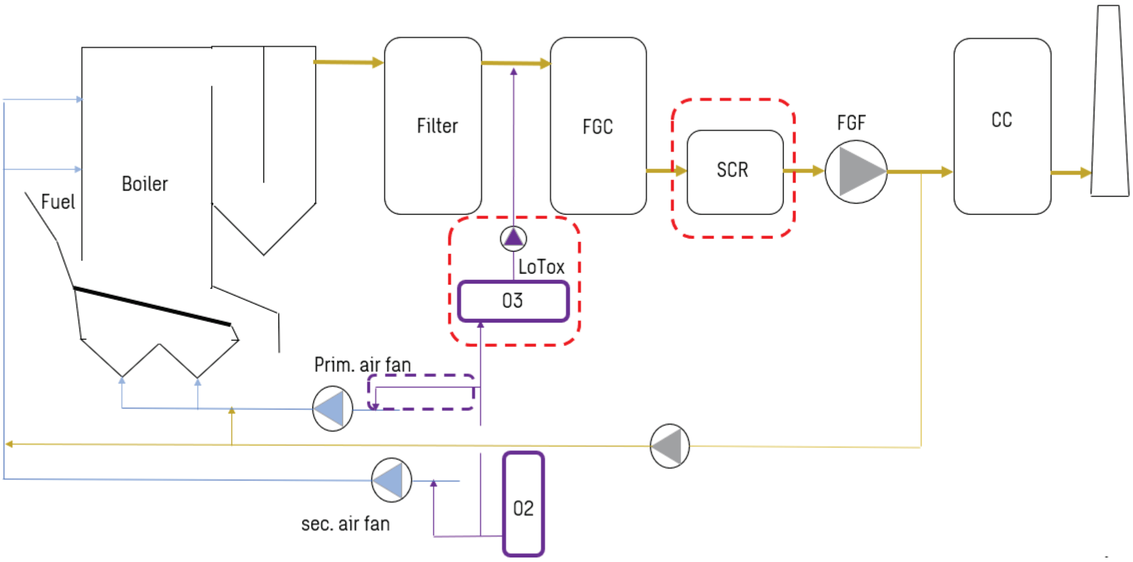

Figure 16: A simplified block schedule showing main components and connections for the example WTE plant with a grate fired boiler

Figure 16 shows a simplified block schedule showing main components and connections for the example WTE plant with a grate fired boiler. For de-NOx both SCR and LoTox-systems are shown within red brackets. This illustrates that either one of the systems is possible to use. Figure 16 illustrate (within purple brackets) the possible connection for Oxygen enrichment to the primary air system.

Flue gas cleaning systems

Oxygen enrichment will not affect the flue gas treatment system after the boiler, with an increase of circulated flue gas. Gas flows can be upheld or slightly decreased giving only a change in flue gas composition, with more carbon dioxide and less nitrogen (Figure 17).

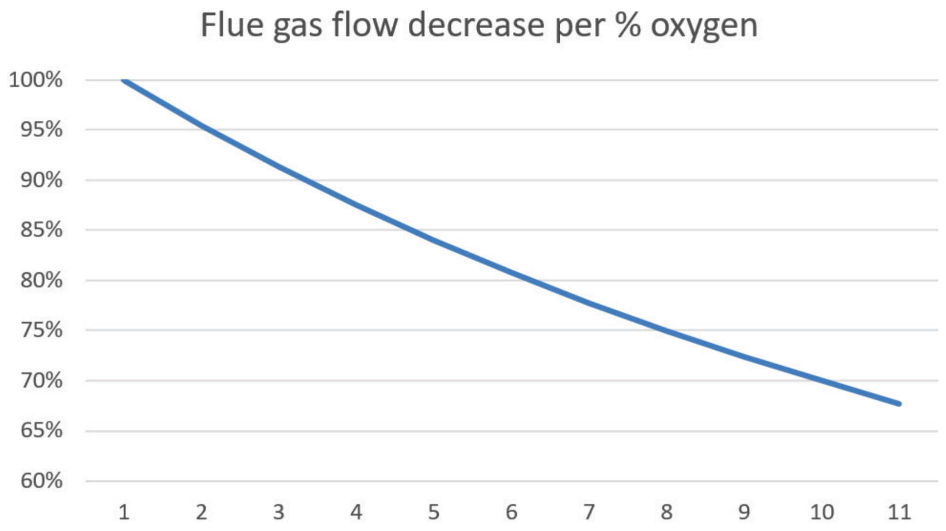

Figure 17: Potential decrease of flue gas flow when adding oxygen to the combustion air

Flue gas flow 100% corresponds to ambient air containing 20,95% O_2 (normal combustion). Each percent added oxygen decreases the N_2 content and therefore the total flue gas flow. To maintain a normal flue gas volume, flue gas recirculation will be used within the process.

The changes needed for the oxygen enrichment is the addition of:

- A flue gas recirculation system (including recirculation fan, ducting, necessary, control and instrumentation equipment). An existing flue gas recirculation system is likely to be under dimensioned and the control loops need more accuracy. The flue gas recirculation fan is connected after the flue gas cleaning prior to the existing ID-fan.
- NO_x-reduction system SCR/LoTOx. Flue gas recirculation will lower the NO_x-formation that the oxygen enrichment increases. The temperatures and flow balance can be upheld for the ordinary NO_X-reduction system (SNCR) to work properly for an existing plant. A new plant design can either focus on keeping a high gas recirculation – similar to existing plant designs, or a compact plant design accepting higher combustion temperatures and lower gas flows. The latter design will mean an increase in the formation of thermal NO_x and probably a need for an SCR system for the NO_x reduction. As mentioned earlier in section 4.5.2 a LoTOx-system with ozone injection and NOx capture in the wet flue gas cleaning can be an alternative since oxygen is easily accessible at the site in the case with hydrogen production.

The technical readiness level is high for all systems included in the scope. The issue is the adaptation of existing plant technology to the concept with oxygen enrichment. From this point of view, it’s more an issue of the risk acceptance level for a potential customer and plant manufacturer. The former Vattenfall oxyfuel pilot at Schwartze Pumpe showed that the system works and therefore a technology readiness level (TRL) 7 is at least achieved. If considering the flue gas recirculation combined with oxygen enrichment – the technology step is much smaller and should therefore not present risk levels that stops further development.

5.1.3 Requirements on oxygen quantity, quality and stability of supply

A 100 MW boiler needs an oxygen quantity of approximately 40,000 kg/h for an arbitrary forest fuel with 5% O_2 in the flue gas post combustion. Depending on the degree of oxygen enrichment (23-35% of combustion air) the oxygen amount needed from the oxygen enrichment system is 3,5-16 tons/h. The exact numbers will vary a little between different fuels and O_2 levels.

The quality of O_2 is not an issue for a large-scale combustion plant. The only aspect identified that could cause problems is moisture content. Depending on where the oxygen injection to the combustion air takes place it could give corrosion problems in the duct near to the injection point. The potential issue is only a theoretical problem, since addition of oxygen would be made after combustion air preheating thus only lowering the temperatures marginally.

An existing plant already designed for use of ambient air for combustion will not encounter problems if the oxygen supply is cut off. In this case the plant would return to normal operation with ambient air as the oxygen provider. The DCS-system will of course need to have a sudden oxygen cut-off regulated in the control systems to prevent a plant- or system trip. The oxygen system will keep pressure above a set pressure level. When low pressure occurs, due to low levels of oxygen the control system will close the oxygen injection in a controlled manner, keeping the process running smoothly.

5.1.4 Economic assessment -investments and operational costs

For an add on oxygen enrichment system consisting of:

1. oxygen tank with necessary piping, valves, nozzles
2. Flue gas recirculating system with necessary ducting, dampers, recirculation fan
3. I&C equipment and connection to the plant DCS and programming
4. Safety equipment, modifications/adaptations on the existing plant

The investment cost is estimated to be less than 50 MSEK, including all aspects such as project costs, erection and necessary adjustments and modifications, possible replacements of existing ID- and combustion air fans. The cost estimate shall be considered strictly as an indication of a maximum investment cost.

The system add-on will increase operation- and maintenance costs marginally and is expected to be 0,5% of the investment cost, or 250,000 SEK annually.

5.1.5 Environmental and socio-economic aspects – benefits and trade-offs

The Oxygen enrichment improves combustion and decreases the fuel consumption by reducing the flue gas loss. All emissions decrease except for NO_x which increases. Laughing gas levels (N_2O) are generally low, but the increase of oxygen will further reduce the small amounts existing.

Lower amounts of nitrogen push the concentrations of CO_2 in the flue gas up making a carbon capture system simpler.

The higher NO_x emissions will push the NO_x reduction systems from ammonia injection in the furnace (SNCR) towards catalytical NO_x reduction (SCR). An SCR-system has higher efficiency in reducing NO_x than SNCR with less ammonia injection. The investment cost for an SCR-system is much greater than SNCR-systems which, if needed, will double the investment cost. SCR systems for forest residues need to be placed as a tail-end solution since deactivation of the catalytic mass otherwise will be high due to alkaline and sulphur in the flue gas flow.

5.1.6 Concluding remarks from the case - synergies and added values

Real applications of oxygen enrichment in CHP-plants have not been relevant from a historical perspective, the costs for oxygen transports have never been economically feasible. With hydrogen production nearby, enabling oxygen streams for the possible utilization in the combustion process, the economic aspects are less likely an issue. From the technical perspective oxygen enrichment and effects on combustion and flue gas cleaning processes are not controversial to handle.

Some uncertainties and problems will need to be overcome, but process issues arising already have working technical solutions to solve them.

The positive effects of better fuel utilization, lower flue gas flows and emissions give good economic potential for investments but are of course closely linked to the hydrogen production system and where it is placed.

Calculating economic feasibility is somewhat complex since three different areas intertwine: Hydrogen production, oxygen enrichment and a possible CCS-plant.

5.2 CASE 2: OXYGEN ENRICHED COMBUSTION ENGINES

5.2.1 Introduction to the case

While case 1 describes the use of oxygen enriched combustion air in combined heat and power (CHP) plants, an alternative is to use oxygen for combustion air enrichment in other combustion applications such as combustion engines. Oxygen enrichment can be applied to existing engines/generators with only minor alterations or additions in equipment, but still generate significant benefits. One application where this can be of interest is within the maritime industry where the larger engines allow for economies of scale and where there might be logistical synergies with ports – especially since ports are often seen as favourable spots for hydrogen hubs. While oxygen enriched engines for maritime applications have not been tested before, more general studies of oxygen enriched combustion have indicated that it might allow for improved efficiency and decreased emissions of unburnt matter, as hydrocarbons, carbon monoxide and soot, and a possible increase in emissions of NO_x (Baskar & Senthilkumar, 2016; Distaso et al., 2019;

Gong et al., 2019; Karimi et al., 2022; Nidhi, 2019; Senthil Kumar et al., 2019; Serrano et al., 2021; Shi et al., 2020; Zhang et al., 2022; Zou et al., 2022).

5.2.2 Technical description

A system example would basically be composed as follows:

Oxygen storage tank, or tanks, equipped with valves and filling system with necessary piping and if needed particle filter or similar. The filling coupling will use a standardized filling nozzle. If different filling nozzle types are used from different oxygen delivery systems (for example in different ports in different countries) the tank can be equipped with one or more coupling types.

The pressurized storage tank is equipped with the necessary instrumentation regarding pressure, temperature, flow etc. Placement of the tank(s) will be ideal up on the ship deck, where easy access for external filling and space for the tank(s) is not a limitation. This can off course be different for each individual vessel. Ideally the tank placement would be in the near vicinity of the combustion engine thus making the oxygen system as compact as possible. However, this does not take safety aspects into account, which could volume, placement and manner of oxygen handling onboard.

Smaller pressure tanks for oxygen placed nearby the engine are connected to the main tank via pipes and valves for possibility to isolate the tanks and parts of the pipe connections, if leakages occur.

From the smaller oxygen tanks, connections to the engine air supply pipe with proper injection nozzles are placed. The oxygen tanks are pressurized, and the continuous injection of oxygen will decrease the tank pressure. With two, or more smaller tanks, refilling from the main tank can be done without interfering the combustion process. A three-way valve will shift oxygen tanks when the pressure in the used tank falls below a set pressure value. For this case a system with the "maximum amount" of components is proposed since a real case is dependent on the actual area available and the physical size of a system, however in an actual case the small oxygen tank(s) might be possible to discard thus making the system less area demanding.

The tank provides a set pressure to the combustion air inlet duct, and the combustion process automation system is integrated with the injection nozzle valve.

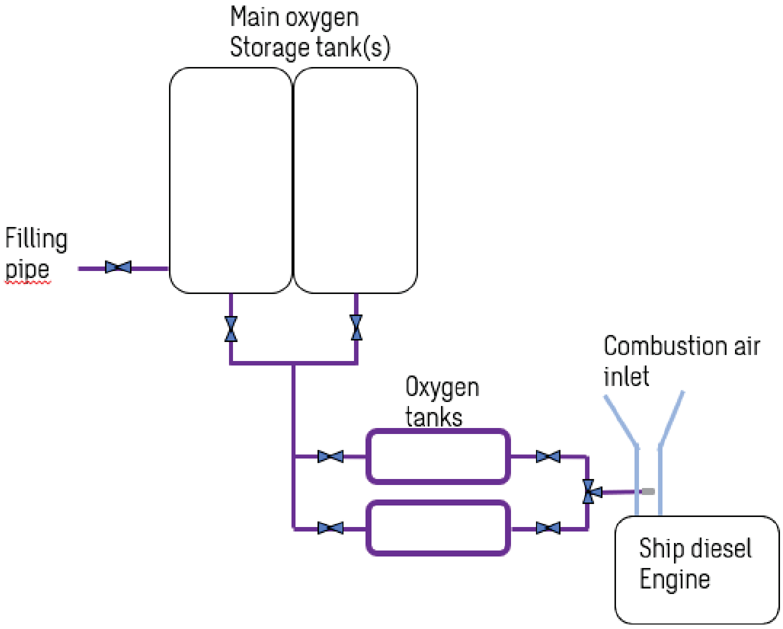

Figure 18: Simplified block diagram of a possible oxygen enrichment system.

The combustion process adjusts the oxygen injection to the engine based on an optimum set point value. The engine will work as a separate unit and using oxygen for the process without any manual work needed.

Flue gas from the combustion will because of the decreased volume of nitrogen be more CO_2 enriched, making it easier and cheaper to separate CO_2 from the flue gas in a CCS-system.

For an oxygen enrichment system proposed the TRL-levels are high. Technology for filling, storing and transporting of oxygen already exists as well as proven technology for gas injection systems for combustion engines.

5.2.3 Requirements on oxygen quantity, quality and stability of supply

While several studies have investigated the use of oxygen to increase efficiency and decrease emissions of engines (Baskar & Senthilkumar, 2016; Distaso et al., 2019; Gong et al., 2019; Karimi et al., 2022; Nidhi, 2019; Senthil Kumar et al., 2019; Serrano et al., 2021; Shi et al., 2020; Zhang et al., 2022; Zou et al., 2022), no studies have been found that study this in a maritime application. This means that no reported numbers of required oxygen quantity, quality or supply are available. However, these questions can be answered in other ways. Regarding quality requirements, the oxygen should preferably be free from particles and moisture. However, the combustion engine can handle impurities and small amounts of moisture without any disturbances to the process. Since a combustion engine normally only have a coarse air filter, smaller contaminants in the added oxygen are not expected to give any negative effects at all. Stability of supply is not likely to be an issue, since oxygen will in most cases be produced in electrolysers onshore, meaning that onboard oxygen storage sufficient to cover consumption between bunkering locations (ports) should be enough to meet possible requirements for stability of supply. One possible issue could be the engine's behaviour in cases where oxygen is no longer added to the combustion air (technical issues or used-up storage), This should however be a minor technical obstacle since an engine for robustness and redundancy reasons should be designed for using a span from zero up to an arbitrary percentage of oxygen addition.

The required oxygen quantity for a vessel can be estimated based on engine size/fuel consumption and oxygen blending level.

5.2.4 Environmental and socio-economic aspects – benefits and trade-offs

In general, the injection of oxygen into combustion engines is expected to influence engine efficiency and emissions of unburnt hydrocarbons, soot, carbon monoxide and NOx. Several studies – both experimental and simulation based – have investigated these effects, and a compilation of the results is presented in the following subsections.

Increased engine efficiency

The Specific braking fuel consumption is the ratio of fuel consumption to the braking produced, an important parameter that reflects how well the engine is performing. At a fixed hydrogen to carbon (H/C) molar ratio, the stoichiometric air-fuel ratio decreases as the oxygen concentration in the combustion air increases. So less burning air is required for complete fuel burning. At a constant air mass flow rate, additional oxygen was used to burn the diesel fuel and improve combustion. The specific fuel consumption decreases by about 5-12 percent when the oxygen concentration increases from 21 to 27 percent. (Baskar & Senthilkumar, 2016)

The intake air oxygen enrichment increased the brake thermal efficiency (BTE) at all loads. The BTE increased to a level of 36.2%, 28.4%, and 23.6% respectively at 100%, 80% and 60% loads. The increase in BTE with oxygen enrichment can be attributed to the complete combustion of the low and high reactivity fuels present in the combustion chamber as a result of greater oxygen availability and improved mixing of combustible materials with oxygen. BTE increased with growing oxygen concentration and reached its maximum rate at 23% oxygen in the intake air. It should be noted that BTE is even greater at 40% load and oxygen enrichment. It was mentioned as 16.1% with electronic fuel injection (EFI) of ethanol and increased to 17.4% with 23% of oxygen enrichment. (Senthil Kumar et al., 2019)

Decreased emissions of unburnt hydrocarbons

Six main mechanisms are believed to be responsible for hydrocarbon emissions: cracks, oil layers, deposits, fuel oil, flame arrester, and exhaust valve leakage. When combustibles do not find enough oxygen to react, hydrocarbons do not decompose when exhausted. Since oxygen enrichment provides additional oxygen within the combustion chamber, more complete combustion is achieved and therefore the level of hydrocarbons in the exhaust gases, including carbon monoxide, is reduced. Oxygen enrichment can reduce the extinguishing distance of the mixture, as it has been found to be a decreasing function of the flame temperature. It is well known that the flame temperature increases in the case of oxygen enrichment and this allows the flame to propagate much closer to the cylinder wall and reduce HC emissions. The hydrocarbon emissions were reduced to a minimum of 10% at 23% oxygen to a maximum of 40% at 27% oxygen enrichment levels principle. (Baskar & Senthilkumar, 2016)

However extreme decrease in HC emission was reached in oxygen improvement technique. At 100% load the HC emission was noted as 168 ppm with 23% of oxygen enrichment. Comparable decrease was noted at all power outputs with oxygen enrichment. The decrease in HC emissions is explained by the availability of more oxygen in the combustion chamber, which contributed mainly to the complete combustion of the primary fuel and a decrease in the formation of HC. (Senthil Kumar et al., 2019)

Decreased emissions of carbon monoxide

The mechanism of CO formation is well established, and this is mainly due to the lack of sufficient oxygen for the complete oxidation of HC. The CO concentration drops from 15% at full load to 55% at idle and 27% oxygen enrichment. The additional oxygen present in the mixture plays an important role in lowering the CO values. Combustion efficiency is higher when combusted with oxygen than when combusted in ambient air, and this is thought to play a role in reducing HC and CO emissions as well as improving thermal efficiency. (Baskar & Senthilkumar, 2016)

With oxygen enrichment, there was a significant reduction in CO emissions across all power outputs. It decreased to a minimum of 0.2%, 0.25%, 0.16%, and 0.16%, respectively, at 100%, 80%, 60%, and 40% loads at the best efficiency points for an oxygen concentration of 23%. The reduction in CO emissions from oxygen enrichment can very well be explained by the presence of oxygen in the combustion chamber, which contributed to the complete oxidation of the carbon in the fuel. It should be noted that even at 40% load there was a significant reduction in CO emissions. (Senthil Kumar et al., 2019)

Decreased emissions of soot

One of the promising results of oxygen enrichment is a significant reduction in exhaust smoke density. The agglomeration of soot particles in diesel engine exhaust gases is the main source of soot formation in a diesel engine. It is formed mainly due to the incomplete combustion of fuel hydrocarbons with some contribution from lubricating oil. Soot formation is highly dependent on stoichiometry, temperature, pressure and agitation. The main effect of oxygen enrichment is to rise the ratio of oxygen to fuel, which in turn provides better mixing and improves fuel oxidation and therefore suppresses soot formation. Oxygen enrichment also decreases ignition delay, which means quicker burning rates and burning times, further reducing soot formation. The minimum smoke reduction at oxygen enrichment is 15% at full load at 27% oxygen enrichment, the maximum reduction is 60% at idle at 27% oxygen enrichment. The level of smoke transparency is consistently reduced at all loads and levels of oxygen concentration. (Baskar & Senthilkumar, 2016)

Unburned matter emissions were further reduced for all oxygen concentrations at all loads by combining oxygen enrichment with reactivity controlled compression ignition (RCCI) mode. The main reason for the reduction in smoke emission during oxygen enrichment can be explained by the improved mixture preparation of the injected highly reactive fuel, which reduced the local areas of fuel enrichment present in the combustion chamber. Due to the additional oxygen, burning was complete and hence no smoke emission happened. (Senthil Kumar et al., 2019)

Possibly increased emissions of NOx, but also possibly a decrease

Thermal NOx is the main component of NO_x in diesel engines and is the reaction product of nitrogen from high temperature combustion air and oxygen enrichment at the same time. The two main NO_x generation mechanisms are thermal and fuel NO_x. The third mechanism, called prompt NO_x, dominates only in fuel rich systems and is not the main source of NOx for diesel engines. Only thermal NOx based on Zeldovich's mechanism is main and it is basic shown as:

$O + N2 \leftrightarrow NO + N, N + O2 \leftrightarrow NO + O, N + OH \leftrightarrow NO + H.$

Higher post-flame temperatures and higher oxygen concentrations during combustion result in a high rate of thermal NO_x formation. When the oxygen level rises to 27%, the NO_x level increases to three times the ambient air. This is the main disadvantage of combustion with oxygen enrichment; however, this can be controlled and maintained within reasonable limits by adjusting fuel injection timing and applying exhaust gas treatment techniques. (Baskar & Senthilkumar, 2016).

NO emissions were shown to be 255 ppm and 353 ppm respectively for neutralized waste cooking oil (NWCO) and ND at 100% load. It was noted as 196 ppm, 169 ppm and 100 ppm respectively at 80%, 60% and 40% loads with NWCO a fuel. The introduction of ethanol by EF injection in RCCI engine mode significantly reduced NO emissions at all ethanol energy fractions at all powers. The high latent heat of evaporation lowered the cycle temperature and reduced NO emissions to a minimum of 170 ppm at 25 percent ethanol energy at 100 percent load. The reduction was 166 ppm and 160 ppm at 80% and 60% loads, respectively, at the points of maximum efficiency. A similar decrease in NO emission was noted at 40% load with all energy fractions of ethanol. However, oxygen enrichment increased the NO emissions. (Senthil Kumar et al., 2019)

5.2.5 Concluding remarks from the case - synergies and added values

While the application of oxygen in oxygen enriched maritime engines is not a currently ongoing activity, it does have promising potential. With ports turning into hydrogen hubs, oxygen will already be close to the end-user, allowing for synergies in logistics. While uncertainties remain over the effect on NO_x emissions, other environmental aspects are more clearly positive, such as the decrease in fuel consumption as well as the positive effect on emissions of hydrocarbons, carbon monoxide and soot. Lastly, the application also holds promising commercial potential, as ports and hydrogen producers could add value through the handling and offsetting of biproduct oxygen, and for shipping companies that could possibly save fuel costs and thus benefit from better profitability. The larger uncertainties that remain are whether this is practically implementable in ports and at ships, if the possible cost savings can compensate for the added costs from oxygen handling, if increases in NO_x emissions can be avoided or even reversed and if safety issues of storing oxygen onboard can be overcome.

5.3 CASE 3: SEABED AERATION

The case of seabed aeration is based on a production case with a large wind farm (12 TWh/year). The resulting hydrogen production is about half of the production case that is presented as the steel production case, and 10 times the size of the industrial case. The defining variable in this case has been the wind farm rather than a considered hydrogen demand in a specific industry.

5.3.1 Introduction to the case

The oxygen conditions along the deeper bottoms in the central parts of the Baltic Sea proper have been strained for decades. They show no signs of improving, quite the opposite (Figure 19). The Baltic Sea is naturally sensitive to oxygen deficiency because a salinity stratification separates the bottom water from the less salty surface water. The layering means that new oxygen only gets to the bottom water under exceptional weather conditions that allow salt water from the Kattegat to flow into the Baltic Proper. This happens irregularly, often at intervals of several years. In addition, the anthropogenic supply of nutrients from land, and the resulting stimulated production of organic material, especially phytoplankton, is believed to have increased the spread of oxygen-free bottoms in the Baltic Sea over many years.

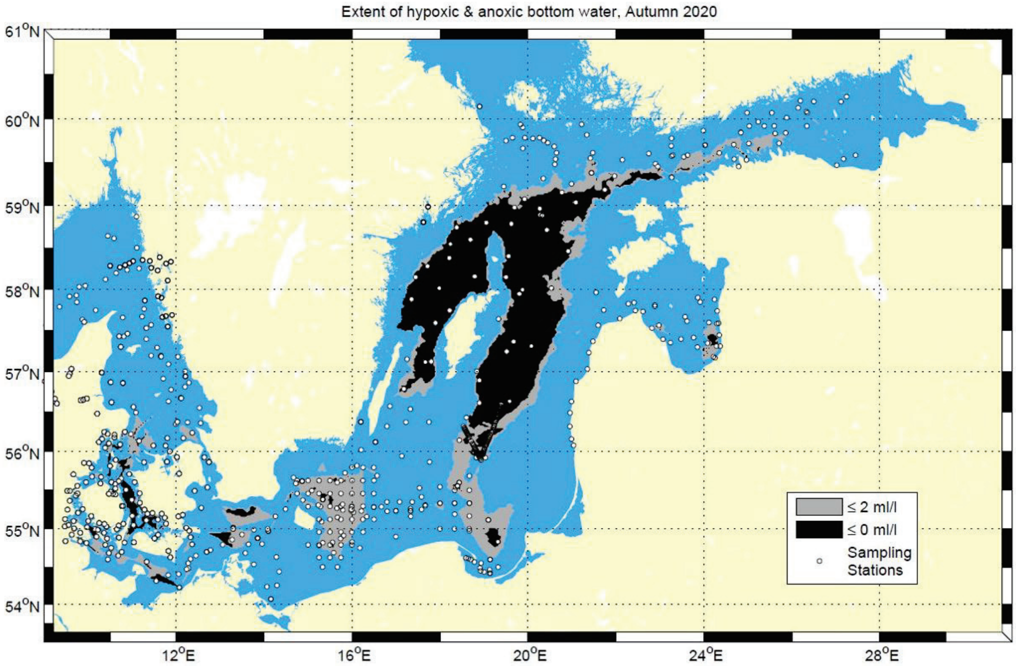

Figure 19: The distribution of bottoms with oxygen-stressed (grey, ≤2 ml/l) and oxygen-free (black, ≤0 ml/l) conditions in the Baltic Proper. From SMHI (www.smhi.se/nyhetsarkiv/den-extrema-syrebristen-i-ostersjon-fortsatter-1.169650).

When microorganisms break down the organic material, oxygen is consumed, which depletes the oxygen supply in the bottom water if no new oxygen is added. When oxygen concentrations drop below 2 ml/l (≈ 2.7 mg/l), the conditions for higher animal life cease, and laminated sediments spread (Figure 20). This is because the mixing of the sediment layers by the bottom-dwelling animals (bioturbation) ceases.

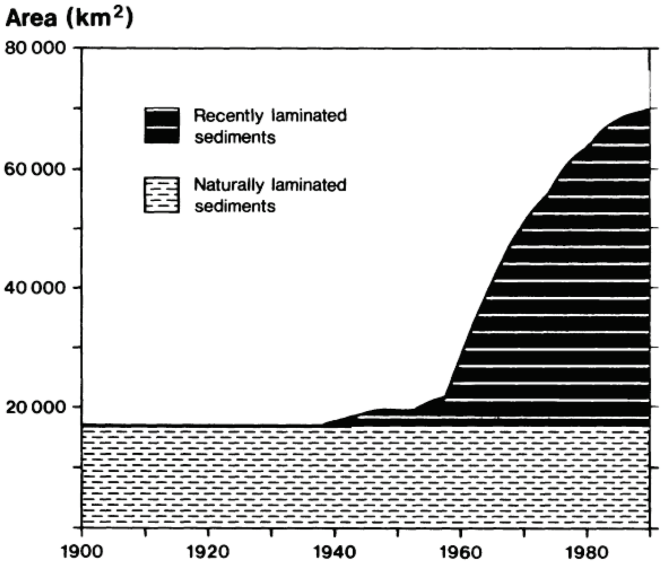

Figure 20: Schematic illustration of the expansion of laminated sediments in the Baltic Proper during the 20th century. From Jonsson et al., 1990.

Several wind farm developers plan to establish offshore wind farms in the Baltic Sea. Limitations in the grid capacity for electricity transmission mean that part of the generated power from the wind farms will likely be used to produce hydrogen gas on site (Figure 21). The oxygen gas obtained as a by-product could be used for the oxygenation of dead bottoms. To have a lasting effect, oxygen must be continuously brought down to a depth of 80-100 meters to basins in the Baltic Proper, where there is a more or less permanent lack of oxygen.

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Figure 21: Electrolyser for production of hydrogen in connection with offshore wind farms. Photo montage: Vattenfall.

5.3.2 Technical description

The Western Gotland Basin was chosen as the study site for the case study (Figure 22, Table 2).

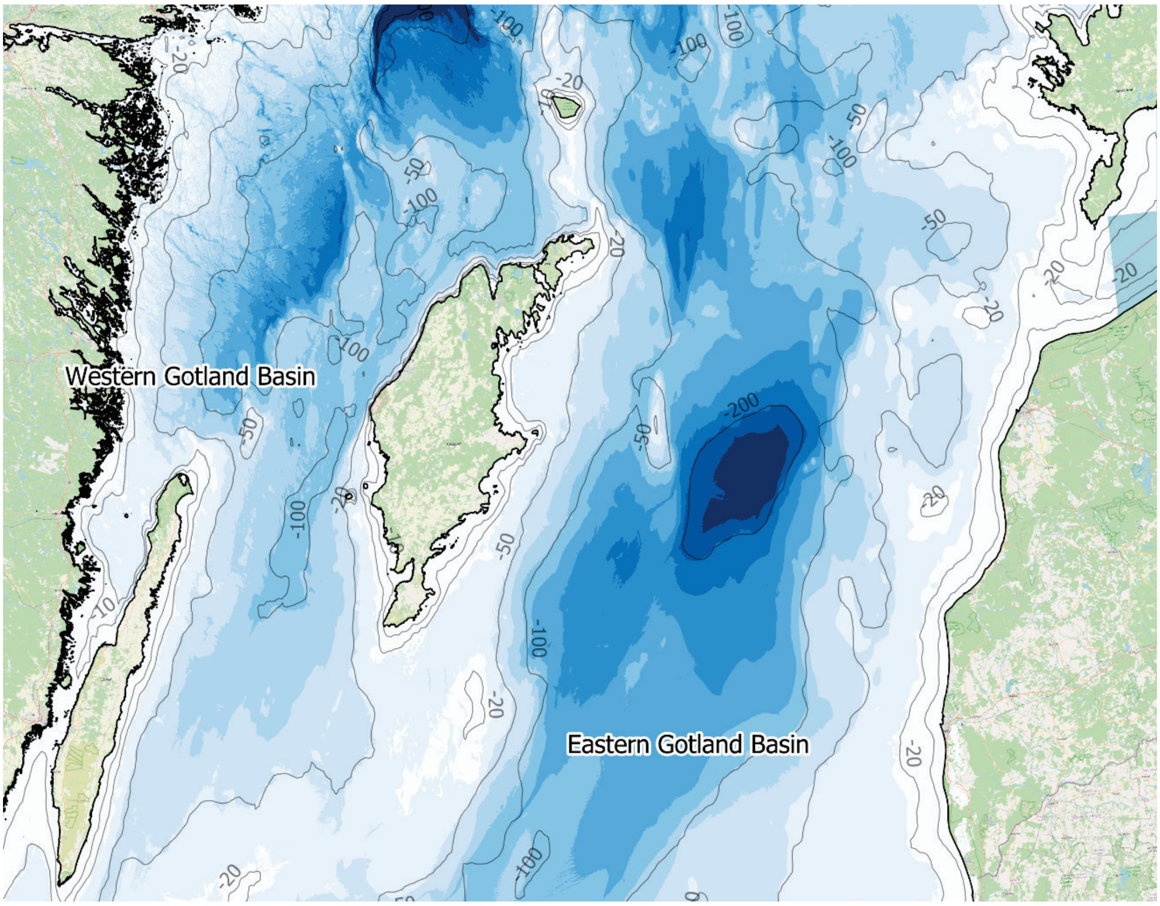

Figure 22: Map of Central Baltic Proper. Western Gotland Basin was chosen for the oxygenation study. Map source: www.emodnet-seabedhabitats.eu

Table 2: Morphometric characteristics of the Western Gotland Basin

Parameter	**Value**
Average depth (m)	89
Maximum depth (m)	450
Area (km2)	26,000
Deep bottom area* (km2)	10,400
Water volume (km3)	2,330
Deep Bottom water volume**(km3)	655

*area below 75 m water depth, **water volume below 75 m depth

The basin has, for many years, suffered from oxygen depletion. In 1993-1994, a significant saltwater intrusion into the Baltic Sea temporarily raised the oxygen levels to 4 mg/l (Figure 23). However, this oxygen impulse was limited. The saltwater intrusions that subsequently occurred have not been able to raise the oxygen concentration above the critical level of 2 mg/l (Figure 23).

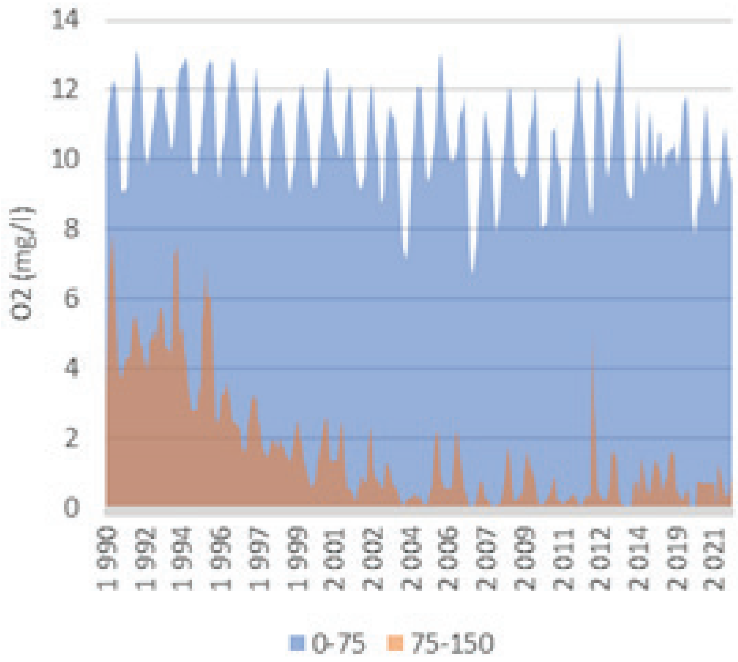

Figure 23: Time trend 1990-2021 oxygen concentrations (mg/l) in surface (0-75 m) and deep water (75-150) in the Western Gotland Basin. Data from SMHI.

For the case study, we assumed a wind farm with the characteristics in Table 3.

Table 3: Technical parameters for assumed sea-based wind farm

Parameter	Value
Total electricity production	12 TWh/yr
Hydrogen gas production	140,000 ton/yr
Oxygen gas production	1,100,000 ton/yr
Oxygen gas flux at the surface	85,000 m^3/h
Energy demand compressors for oxygenation of deep water	75 GWh/yr

5.3.3 Requirements on oxygen quantity, quality, and stability of supply

To assess what possible effects the supply of oxygen from the wind farm to the bottom water in the western Gotland basin could have, a simple process-based mass balance model for oxygen turnover Figure 24 was developed. The target variable was the oxygen concentration in the bottom water. It is affected by different flows, advection (horizontal inflow and outflow), vertical mixing in the jump layer (halocline) between surface and bottom water, oxygen consumption (decomposition of organic material in water and sediment), and oxygen supply from the wind farm.

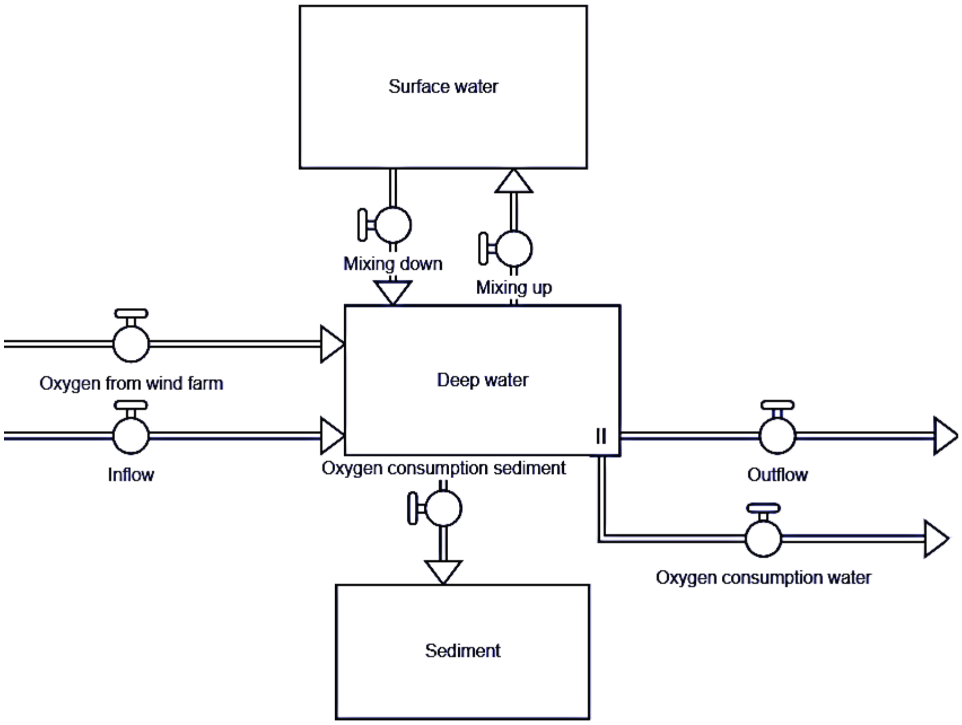

Figure 24: Block sketch of mass balance model for oxygen turnover

Figure 24 shows simulated oxygen gas concentrations over time in the Western Gotland Basin deep water, given that the wind farm supplies oxygen. The results show that the oxygen addition from the wind farm has the potential to more or less maintain oxygen concentrations over time in the bottom water after a saltwater intrusion. The Oxygen Transfer Efficiency (OTE) is allowed to vary between 0.4 and 0.8 (40-80%). With an OTE of 60 %, the oxygen concentration stabilizes above the critical level of 2 mg/l.

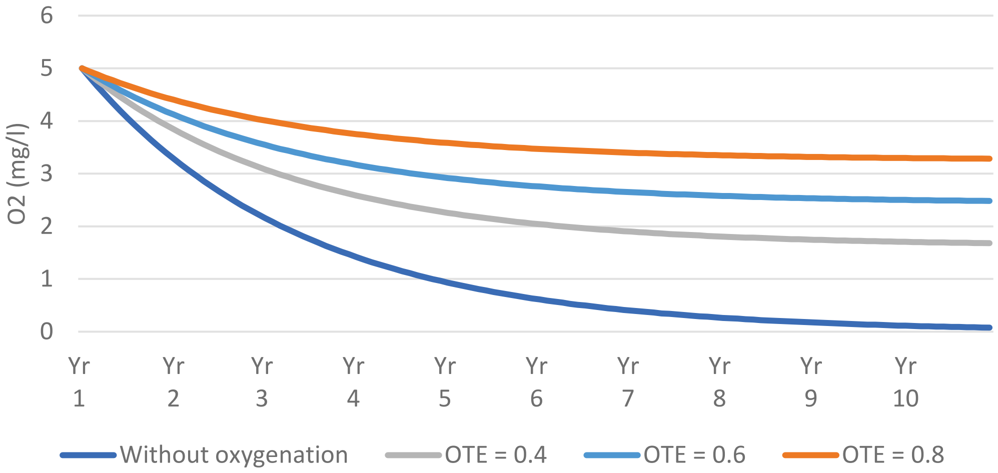

Figure 25: Simulated oxygen concentrations in the deep water of the western Gotland Basin (>75 m depth) for ten years after a saltwater intrusion given different degrees of Oxygen Transfer Efficiency (OTE).

5.3.4 Economic assessment -investments and operational costs

Under the assumption that the electricity price is SEK 1/kWh, the annual operating cost to run the compressors (75 GWh/yr) can be estimated at SEK 75 million. If one succeeds in maintaining oxidized conditions in the sediments, their ability to permanently bury phosphorus (P) increases by an order of 0.5 mg P/g dw. In the Western Gotland Basin, with bottoms below 75 meters depth of just over 10,000 km^2, the annual phosphorus burial, thanks to the oxygenation, can be estimated at approximately 3,000 tons P/ year, which gives a cost efficiency of SEK 25/kg P. In Table 4 the cost-effectiveness of oxygenation is compared with other measures against eutrophication. The table shows that the cost-effectiveness of an oxygenation step should be extremely high if the methodology works. However, at this stage, it has not been able to calculate the costs for investments and running costs for the equipment to transfer and spread oxygen to the deep water.

Table 4: Cost-effectiveness of various measures to reduce phosphorus concentrations. Examples from Lake Hjälmaren (Karlsson et al., 2019) compared to oxygenation in the study case

Method	Cost SEK/kg reduced phosphorus
Aluminium treatment sediment	400-700
Reduction fishery	750 -1,500
Dredging	1,000
Oxygenation	25

5.3.5 Environmental and socio-economic aspects – benefits and trade-offs

The environmental cost in terms of carbon dioxide emissions from the oxygenation can be estimated from the associated carbon emissions from the wind-generated power, which has been suggested to average 12.8 g CO_2-eqv./kWh (Vattenfall 2022). With an energy demand of 75 GWh, it would mean yearly CO_2-emissions around 100 tons. That would be a deficient number compared to other measures proposed to combat eutrophication (Karlsson et al., 2019).

Other potential drawbacks that need to be addressed in a risk-benefit analysis are:

Gas bladder disease, a gas oversaturation, prevails when the gas content of the water exceeds the amount that can dissolve in the water at the respective pressure and temperature. Gas supersaturation can occur when air is introduced into water under pressure. Gas bladder disease occurs when a gas oversaturation leads to the formation of gas bubbles in the fish's blood and tissues. The disease state can be compared to diving sickness in humans

Release of environmentally hazardous substances, one of the concerns directed against large-scale oxygenation is that this would lead to increased levels of environmentally hazardous substances in water and biota through, for example, redox-sensitive metals going into solution in oxidized conditions or increased sediment mixing (bioturbation) by benthic animals can lead to a release of organic substances (Granberg et al., 2008; Josefsson et al., 2010).

Erosion of water layers, depending on which technical design is chosen for an oxygenation step, more or less strong turbulence is created in the water mass, which can lead to a weakening of the stratification between surface and bottom water. This is not desirable because it can lead to nutrients from the deeper aquifers being transported up to the surface water and contributing to primary production (Cooke et al., 2016). The technical design of an oxygenation step is thus essential.

5.3.6 Concluding remarks from the case - synergies and added values

Seabed aeration is a realistic case for use of the oxygen from electrolysers. The potential demand can be quite high. The location of the demand is fairly well defined, and this will represent substantial challenges in terms of transportation costs. In the case the electrolysers are found on long distances away from these sites the transport costs will be substantial.

This use does not represent a monetary value in terms of the product. The support to establish functional and resilient ecosystems will create several benefits in terms of ecosystem services such as improved fish stocks. The initial studies show that the alternative actions for improving the seabed will have higher costs. The opportunity here is strong in terms of improving the environmental profile of the hydrogen value chain.

5.4 CASE 4: SEWAGE TREATMENT

5.4.1 Introduction to the case

In water treatment, oxygen is important for the biological processes. Even chemical-physical processes depend on oxygen. Here, we have chosen to focus on the water treatment processes found at wastewater treatment plants (WWTPs). At WWTPs, aerobic (oxygen-requiring) biological processes are operated to convert and remove nitrogen compounds or break down (oxidize) organic matter. The separation of nitrogen takes place in several steps, where the first steps are aerobic processes where ammonium is oxidized to nitrite and further to nitrate. This process is called nitrification. For both reactions (i.e. oxidation of ammonium and organic matter), oxygen is acting as an electron acceptor.

The chemical and physical processes that can be based on oxygen are e.g. ozone, which is generated and created from either liquid oxygen (LOX), or fed with oxygen gas (a so-called pressure-swing adsorption (PSA) system). Oxidation using ozone is an example of a water treatment method that possibly will be introduced as an additional treatment step at WWTPs soon. The purpose of an additional treatment step (a so-called advanced treatment) is to also include treatment of organic micropollutants (e.g., drug residues, antibiotics and hormone-disrupting substances) that are not removed in the conventional treatment present at WWTPs.

To better understand how oxygen affects and controls the aerobic biological processes, the specific processes and how they are affected by oxygen are described in more detail below. After these sections, there is one paragraph explaining how ozone can be produced and generated at WWTPs.

5.4.2 Technical description

Oxygen for an activated sludge process

At the majority of WWTPs in Sweden, there is an activated sludge (AS) process, which is a water treatment process that can be equated with a suspension of microorganisms and internal material being aerated. The AS process is the most common type of biological process in sewage treatment plants. AS mainly aims to break down organic matter, but nitrification can also be achieved. The AS process requires the microorganisms to have access to dissolved oxygen (DO) so that they can grow and be maintained in the process. At the end of the purification step, the active sludge is then separated by sedimentation or with a membrane. A biological process that uses membranes is also called an MBR process and separates the sludge very efficiently.

The efficiency of the purification in the AS process is controlled by the availability of DO in the water. In the vast majority of facilities, oxygen is supplied to the bottom of the pool through pressurized air. The air is pressurized using compressors/blowers that take air from the atmosphere without further pre-treatment. The processes are usually controlled by a desired concentration of oxygen in the activated sludge basin. A low DO concentration leads to a lower quality (low degree of degradation) in the treated outlet water. The AS process supplied with pressurized oxygen (PO) is called POAS. The AS process is a process that is well suited when water with lower organic content and lower mixed liquid suspended solids (MLSS) content is to be treated (Skouteris, Rodriguez-Garcia et al. 2020). In this case, oxygen supply through air is completely sufficient. However, there is a limitation regarding treating water with a higher organic content, as it implies a higher demand on oxygen and the rate of the oxygen transfer. To overcome this, the supply of oxygen with a higher degree of purification (e.g., PO) is required. The essential difference between the addition of air compared to PO is that air is a gas mixture that contains 21% oxygen and 78% nitrogen gas, while PO from e.g. hydrogen production has a high degree of purity (99.99%). Pressurized oxygen generally means that a higher amount of oxygen is added per unit of time because the partial pressure is higher than for air (Skouteris, Rodriguez-Garcia et al. 2020).

In a recently published review article by Skouteris et al. (2020), the potential of PO for aerobic wastewater processes is summarized. Here, it is highlighted which parameters are directly affected when air is replaced with PO.

Table 5 summarizes the main points for when AS is compared with POAS. POAS is in the cited work summarized as a simple and compact system, which is among other things, shown by a lower sludge production, reduced odor and reduced emissions of volatile hydrocarbons (VOC).

Table 5: Comparison between addition of air and pressurized oxygen for the activated sludge process, including possible consequences. Summarized from (Skouteris, Rodriguez-Garcia et al. 2020)

Description	Air	Pressurized oxygen (PO)	Comment
Oxygen concentration	Aeration needs to achieve an oxygen concentration of > 1,1 mg O2/L	A larger amount of oxygen can be added to the process per time unit	When the DO concentration falls below the requirement, the growth of filamentous bacteria increase, and the risk of foam formation and sludge formation increases
Oxygen transfer rate	Limited and directly linked to the oxygen concentration in air	Can increase and reach higher capacity due to the purity of the oxygen in the gas at low flow rates.	
Kinetics for microorganisms	Limited	Can increase	Increased kinetics for PAOS implies that a higher load of organics can be treated (see below) at a maintained sludge age
MLSS	The process has an upper limit which is directly linked to the amount of oxygen	An increased MLSS concentration can be treated	
Removal efficiency		The ability to oxidize a higher variety of organic pollutants (and a higher amount) increases with an increased DO at low OTR	
Degradation of phenols and micropollutants	Limited	Increased ability (e.g. antibiotics, hormone-disruptive compounds)	The ability of degradation is dependent on the time for the treatment process (operating time)
pH	pH seldom affects the output of the treatment process as it is run at an open atmosphere.	POAS-systems are sensitive to pH, especially the nitrification process	If generated CO2 is not removed from POAS, pH will decrease and affect the nitrification

For the AS process, which is a treatment process that is run at relatively long retention times below 24 hours, PO can lead to direct positive effects in the form of a reduced risk for the growth of filamentous bacteria. For example. Martins et al. (2003) showed that when the DO was below 1.1 mg O_2/L, sludge formation properties were negatively affected and the formation of filamentous bacteria increased rapidly (Martins, Heijnen et al. 2003). In addition, and as filamentous bacteria can contribute to foam formation, PO implies that foam formation can be better controlled (Skouteris, Rodriguez-Garcia et al. 2020). In some cases, the oxygen demand in the AS process means that a large amount of air needs to be added, which leads to foaming. Here, temperature has a large impact, both for PO and air, because the oxygen concentration increases at low temperatures.

Increased oxygen supply also allows the kinetics of degradation to increase, which is particularly appropriate for the treatment processes that can be run at shorter treatment periods (Skouteris, Rodriguez-Garcia et al. 2020, Mohammadpour, Cord-Ruwish et al. 2021).

For the AS process, which is dependent on a high sludge age, the treatment process cannot be run too fast without affecting the sludge age. In contrast, POAS enables treatment of water with a higher concentration of suspended particles, so-called MLSS, as compared to the AS process which otherwise has an upper limit regarding MLSS concentrations (Rodríguez, Leyva-Díaz et al. 2013). On the negative side, an increased enzymatic kinetics (from PO supply) can quickly consume the added oxygen and thereby lead to an oxygen deficiency in the effluent water, which results in a deteriorated sludge formation. However, PO makes it possible for more organic substances to be broken down or for the extent of the decomposition to increase. To demonstrate this more closely, it can be mentioned that in a study by Batt *et al*. (2007), carried out on the wastewater of four full-scale treatment plants, it was shown that the degradation of four different antibiotics (sulfamethoxazole, ciprofloxacin, tetracycline and trimethoprim) was enhanced and degraded from 37 to 70% when supplied with PO and for a residence time of one hour, which is 10-20 times faster than what the AS process normally is run at(Batt, Kim et al. 2007).

POAS systems are mainly operated to break down organic carbon and can therefore be operated at low sludge ages and short residence times. However, the same flexibility does not exist for nitrification, where a higher sludge age is needed for the nitrifying, slow-growing organisms to benefit and oxidize ammonium. For this reason, POAS systems tend to be used primarily for waters where the MLSS concentration is high and where nitrification is not required to the same extent. Another aspect that affects how well nitrification can work in POAS is that the CO_2 formed during the process cannot be easily driven off. One consequence is that the pH drops in the process, which prevents nitrification from working optimally. A better way to use oxygen for nitrification is if it is supplied to processes that take place at a lower temperature, where the kinetics are otherwise too slow for a successful nitrification when aeration with blowers is used. These processes are more described here below.

Oxygen for nitrification

In addition to organic material being broken down during the purification process at a WWTPs, nitrogen also needs to be removed before the treated water reaches the recipient. For Sweden's WWTPs, there is a requirement for nitrogen separation of at least 70% for all WWTPs that connect more than 10,000 people and that release water to the coast between Norrtälje and Strömstad in the south of Sweden (Naturvårdsverket 2016). However, today, there is an ongoing discussion to also include nitrogen removal at WWTPs north of Norrtälje. The reason behind the change of the above-mentioned regulation set by Swedish Environmental Protection Agency (SEPA), is that the Gulf of Bothnia could be at environmental risk by a warmer climate as a result of climate change. Expected effects are, e.g., that the oxygen presence in the Gulf of Bothnia deteriorates, in parallel with the fact that the Gulf of Bothnia is affected by heavy inflows of nitrogen-rich and phosphorus-limited river water occurring during the spring periods when the snow melts (HaV 2022). This said, it may become relevant to supplement treatment plants in northern Sweden with a treatment step removing nitrogen. The nitrogen removal needs to work at low temperatures as the WWTPs are situated in the north of Sweden where climate is colder.

Nitrogen, in the form of ammonium is directly linked to both eutrophication and lack of oxygen in aquatic environments, it is also known that the aquatic environment becomes toxic to living organisms when the ammonium content is too high. The biological process that results in nitrogen removal occurs in two steps, i) nitrification followed by ii) denitrification (Ergas and Aponte-Morales 2014). During nitrification, ammonium is oxidized to nitrate. This reaction, in turn, occurs in two separate steps. Step 1 means that ammonium is oxidized to nitrite, after which nitrite is oxidized to nitrate during step 2. The nitrification is an oxygen-dependent process in which nitrifying microorganisms work. During denitrification, nitrate is reduced to nitrogen gas and nitrogen is thus separated from the water phase (Ergas and Aponte-Morales 2014, Skouteris, Rodriguez-Garcia et al. 2020). Denitrification is dependent on an external carbon source.

For this case study, it is the oxygen-dependent phase (phase 1), nitrification, that we choose to focus on. The process intended for nitrification is a moving bed biofilm reactor (MBBR) using carriers, where both nitrification and denitrification can be carried out in two separate contact tanks with and without oxygen present.

Process-wise, it is important that the DO content is controlled in the MBBR process. If the DO content is too low, it can lead to an imbalance between the nitrifying bacteria that work in phase 1 and phase 2. However, it is known that if the DO is kept at about 4 mg O_2/L, the two phases can be balanced and there is no risk of the nitrifying bacteria out-competing each other (Skouteris, Rodriguez-Garcia et al. 2020). It is of particular importance that sufficient supply of DO occurs when the ammonium content is high (more ammonium needs to be oxidized) and/or when the temperature is low (biological activity is low) (Skouteris, Rodriguez-Garcia et al. 2020). Studies have shown that in comparison to air, the rate of nitrification is higher with the addition of PO (Skouteris, Rodriguez-Garcia et al. 2020). Rodriguez et al. (2012) showed that when treating incoming wastewater, and for two different residence times (12 and 18 hours respectively), nitrification could increase by 8 and 13.5% respectively, with the addition of PO. However, this was demonstrated for a membrane bioreactor (MBR) process that we described above (Rodríguez, Reboleiro-Rivas et al. 2012) (Rodríguez, Reboleiro-Rivas, González-López, & Hontoria, 2012). However, we have not identified in the literature how the effect will be in an MBBR process, where both nitrification and denitrification are carried out. There is also a lack of studies that evaluate the extent of nitrification when the DO content varies, or when air is replaced with pure oxygen at e.g., lower temperatures. There is thus a potential knowledge gap regarding how nitrification can be performed at lower temperatures with oxygen, where the rate at a lower temperature (<10 degrees) can be expected to be similar to that achieved for air at a higher temperature (≥10 degrees).

Oxygen gas to generate ozone

Ozone is one of the strongest oxidizing agents available and can be used for disinfection and to reduce the odour and colour of water (von Sonntag and von Gunten 2012). The use of ozone is mainly known in drinking water treatment, but today ozonation is also discussed as a suitable treatment process for WWTPs in Sweden and in Europe (von Sonntag and von Gunten 2012, Eggen, Hollender et al. 2014, Baresel, Ek et al. 2017, Cimbritz and Mattson 2017). At WWTPs, ozone will be implemented as a tertiary treatment step after the biological processes and in order to oxidize micropollutants. In this case, ozone is generated on site at the treatment plant and is led into a contact tank as ozone gas. Ozone is here allowed to react with the micropollutants over a certain period of time, in order for the organic micropollutants to oxidize and break down into smaller components.

The generation of ozone can in principle take place with two different systems; 1. Ozone can be generated from liquid oxygen or oxygen gas, 2. Ozone can be generated from ambient air in a so-called PSA system where oxygen is formed (Sweco 2020). For this case study, we have chosen to further investigate the possibility of generating ozone from liquified oxygen (1) obtained from hydrogen production.

5.4.3 Energy use at wastewater treatment plants – what does it look like?

The energy consumption of a treatment plant has been estimated in several different studies. For example, it is mentioned in Skouteris et al. (2020) and references therein, that 50 to 90% of all energy used at a treatment plant is the electricity that must be supplied to blowers for aeration. In the same study, it is mentioned that the total energy consumption varies from 0.18 to 0.8 kWh per treated cubic meter of wastewater. Energy consumption also affects the costs, which correspond to a large part of the total cost. In other words, there are good incentives to change this, and here the use of oxygen can play an important role.

In a relatively recently published report for the Swedish Water Development Fund (in Swedish *Svenskt Vatten*), knowledge about blowers and their energy use for wastewater treatment in Sweden is summarized (Bengtsson, Fujii et al. 2019). An important conclusion for this work is that even though the Swedish treatment plants are well optimized regarding energy, a lot of work remains. It is mentioned that the work should focus on the biological treatment where the dominant part of the oxygen consumption is taking place. For example. it is mentioned that approx. 30 to 50% of the treatment plants' total energy is used for blowers (Bengtsson, Fujii et al. 2019), a range that is somewhat lower than what Skouteris and colleagues (2012) report on. For the Swedish context, it should be mentioned that Balmér and Hellström (2011) estimated the energy use at Swedish treatment plants at 67 kWh/pe, year and slightly lower, 59 kWh/pe, year when inlet and outlet pumps were excluded in the calculation (Balmér and Hellström 2011).

5.4.4 Case study investigation

Based on the sections described above, we have found two main areas where the use of oxygen in wastewater treatment at Swedish WWTPs will be most relevant.

The goal of this case study is thus to make an assessment of oxygen use at WWTPs. It becomes of particular importance to assess the scope of the areas with regards to energy gains, and to some extent assess the amount of oxygen that the WWTPs will be in need of. The assessment is based on the following questions:

1. How are degradation rates for the biological treatment processes affected by supply of PO and what are the consequences for a WWTPs regarding nitrogen purification?
2. How can oxygen be used for ozonation?
3. What is the oxygen and energy requirement for nitrification in cold climates?
4. How can oxygen technically be included in a WWTP for ozonation and nitrogen removal?

The purpose of the assessment is to see if the results from this can show that any particular sub-area needs additional focus for further investigation or studies.

Case study method

In order to carry out the assessment, we have chosen to make certain boundaries. In this chapter, we present them and the chosen method for each sub-area.

Nitrification north of Norrtälje

PO input for nitrification in an MBBR process means that the rate increases. As the sludge age needs to be maintained and not become too low, it is mainly the use of PO supply at low temperatures that is interesting to study, especially as there is a parallel discussion about introducing nitrogen purification in colder climates, at treatment plants north of Norrtälje.

Nitrification at low temperature is not well studied. We have, for instance, not been able to identify how the nitrification rate changes at a lower temperature when oxygen is added. We believe that lab or pilot scale trials are needed to determine the relationship between temperature, nitrification and oxygen. As previously pointed out, there is a study by Rodriguez et al. (2012) regarding the MBR process, where nitrification increased by 8 and 13.5% respectively when supplying oxygen and for 12 and 18h respectively as residence time. However, we have not been able to identify similar data for the MBBR process.

Ozonation from oxygen – how extensive is the use?

The feasibility assessment for how extensive the oxygen use will be from ozonation of wastewater has been made by studying the amount of water that must be ozonated in total if the ten largest WWTPs are taken into account. Table 6 shows which these treatment plants are and how much water needs to be ozonated in this case when we assume that 90% of outgoing water must be ozonated.

For the majority of organic micropollutants to be oxidized, it is required that the ozone dose ranges from 0.6 g ozone/g DOC to about 1.0 g ozone/g DOC (von Sonntag and von Gunten 2012). Assuming an average concentration of DOC at 10 mg C/L at Swedish treatment plants, the ozone content in water needs to be from 6 – 10 mg O_3/L. From ozone generated from oxygen gas, the obtained ozone concentration corresponds to 5 to 20% of the oxygen concentration by weight, depending on the type of ozone generator used (Liquide 2022). We have chosen to calculate the ozone gas concentration based on 10% according to formula (I):

Oxygen, O_2 (g) = 0,1 * O_3 (g)

Table 6: The ten largest treatment plants in Sweden, total amount of outgoing wastewater and total amount of water that potentially needs to be oxidized in an advanced treatment step with ozone. Quantity is presented in 1,000 m^3/year, shown with two significant

Name of treatment plant	Total volume [1,000 m^3/year]	Total volume of effluent wastewater for ozonation [1,000 m^3/year][2]
Gryaab AB Ryaverket	130,000	120,000
Henriksdals treatment plant	100,000	90,000
Käppalaverket	55,000	50,000
Bromma treatment plant	48,000	43,000
Himmerfjärdsverket	40,000	36,000
Sjölunda WWTP	39,000	35,000
Öresundsverket	19,000	17,000
Uppsala WWTP	18,000	16,000
Kungsängens reningsverk	17,000	15,000
Eskilstuna WWTP	17,000	15,000

Oxygen and energy requirements during nitrification in cold climates

In order to assess the oxygen and energy demand for nitrification in cold climates, we have chosen to summarize all treatment plants (> 10,000 pe) that are located north of Norrtälje with their effluent wastewater into the Bothnian Sea and the Gulf of Bothnia. The summary is shown in Table 7 and shows that in one year it is a total of $1.2*10^8$ m^3 of wastewater. We have then calculated the oxygen demand required to oxidize this water, which rests on certain assumptions.

Incoming water summarized in Table 7 is assumed to contain 50 mg N/L. All this water must be nitrified. Nitrification requires 4.60 g O_2/g N and through denitrification 2.86 g O_2/g N is reused, resulting in a net consumption of 1.74 g O_2/g N.

The need for energy to oxygenate water with air depends on many factors such as type of aerator system and water depth. A so-called fine blown aerator system has an energy requirement from 2.6 to 7.1 kg O_2/kWh (Bengtsson, Fujii et al. 2019) and references therein), which reflects an energy consumption at standard conditions (1 atm, 20°C, 0 mg O_2/L). For this case study, we choose to do our calculation with this assumption.

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[2] The total amount of wastewater to undergo ozonation is set to 90% of the effluent wastewater.

Table 7: Sewage treatment plant (WWTP) > 10,000 pe (person equivalents) north of Norrtälje with the Gulf of Bothnia and the Bothnian Sea as recipient.

Wastewater treatment plant (WWTP)	City	Annual water flow [1,000 m^3/year]
Svedjans WWTP	Boden	4,400
Bollnäs WWTP	Bollnäs	2,000
Borlänge WWTP (former Fagersta WWTP)	Borlänge	4,700
Främby WWTP	Falun	6,300
Kavaheden avr	Gällivare	2,700
Duvbackens WWTP	Gävle	13,000
Haparanda/Torneå, WWTP Sundholmen	Haparanda	4,000
Brunna WWTP	Hedemora	1,100
Sandholmen WWTP	Hortlax	4,000
Hudiksvalls WWTP	Hudiksvall	3,000
Kattastrands WWTP	Härnösand	3,300
Kiruna WWTP	Kiruna	4,900
Krylbo WWTP	Krylbo	2,500
Uddebo WWTP	Luleå	11,000
Solvikens WWTP	Mora	2,300
Hedåsens WWTP	Sandviken	4,400
Tuvans WWTP	Skellefteå	6,400
Fillanverket	Sundsvall	4,300
Tivoliverket	Sundsvall	8,500
Granskärs WWTP	Söderhamn	2,300
Öns WWTP	Umeå	14,000
Åredalens WWTP	Åre	1,100
Gövikens WWTP	Östersund	6,900
Annual water flow to the Bothnian Sea and the Gulf of Bothnia		120,000

5.4.5 Environmental and socio-economic aspects – benefits and trade-offs

Effect on nitrification rate

The literature shows that aerobic processes benefit from oxygen supply in the form of kinetics, increased separation of organic substances, better ability to break down water with a high content of MLSS, etc. In addition, the literature review has clearly shown that it is primarily the sludge age that limits the extent to which increased kinetics can be used in POAS on wastewater with lower MLSS. Our recommendation is therefore that PO supply is focused on nitrification at low temperature, where the kinetics at low temperature with PO can probably be compared to that obtained, for example, when supplying air at 10°C.

We can thus expect that nitrification can occur with similar efficiency at temperatures lower than 10°C when PO is added, but the extent of it and at what temperature it is obtained is not established in the literature. It is particularly the extent of nitrification for an MBBR process oxygenated with pure oxygen that is interesting to study further. Suitable temperatures to test would be from 2°C to5 °C.

Ozonation from oxygen – how extensive us the use?

The total amount of water to be ozonated when ozonating 90% of effluent wastewater is shown in Table 8. The calculated amount of oxygen at low and high ozone doses is also shown for each treatment plant and as a total amount. Our calculations show that the oxygen demand for an ozone process in the future will vary from approx. 30,000 – 50,000 tons per year, when all ten largest treatment plants are taken into account. The amount today corresponds to a market value of SEK 440 to 730 million at a unit price of SEK 15,000/ton.

Based on ongoing feasibility studies regarding advanced purification of micro pollution and which VA companies around Sweden are conducting, it can be mentioned that ozone is one of two main technology options for the advanced purification. Activated carbon is the other option. To adjust the potential extent of oxygen used for ozone we therefore assume that half of the WWTPs will choose to use ozone as an advanced treatment step. The need for oxygen in the future can therefore be estimated to be from 15,000 – 25,000 tons per year, which corresponds to a market value of from SEK 220 – 365 million

Table 8: Estimated amount of oxygen that is potentially needed for the 10 largest treatment plants in Sweden during ozonation when 90% of effluent wastewater is ozonated with a low (0.6 g ozone/g DOC) or high (1.0 g ozone/g DOC) ozone dose respectively.

Wastewater treatment plant /WWTP)	**Water volume that will undergo ozonation [1,000 m^3/year]**	**Total amount oxygen at low ozone dose [tons/year]**	**Total amount oxygen at high ozone dose [tons/year]**
Gryaab AB WWTP	120,000	8,100	13,000
Henriksdals WWTP	90,000	6,000	10,000
Käppala WWTP	50,000	3,300	5,500
Bromma WWTP	43,000	2,800	4,800
Himmerfjärd WWTP	36,000	2,400	4,000
Sjölunda WWTP	35,000	2,300	3,900
Öresunds WWTP	17,000	1,200	1,900
Uppsala WWTP	16,000	1,100	1,800
Kungsängens WWTP	15,000	1,000	1,700
Eskilstuna WWTP	15,000	1,000	1,700
Sum of total oxygen need, tons/year		30,000	50,000

Oxygen and energy requirements during nitrification in cold climates

When all treatment plants > 10,000 pe (person equivalents) are to introduce nitrification, the oxygen demand will be 10,440 tons of O_2 per year, corresponding to ca. 10 MW of electrolyser running at 6,000 hours/year. When this oxygen demand is supplied by aeration, the energy demand can vary from 1.5 to 4 GWh per year when we assume an energy consumption of 2.6 – 7.1 kg O_2/kWh.

5.4.6 Concluding remarks from the case - synergies and added values

Under the right conditions and by comparing with air supply using blower systems, supplying pure oxygen shows great potential for aerobic water treatment processes.

There is a limitation with the supply of oxygen to the activated sludge process, which is linked to the fact that the sludge age needs to be maintained and that the MLSS content should not be too low.

Carrying out nitrification at low temperature with oxygen can overcome difficulties in nitrifying wastewater north of Norrtälje. Experiments that show the extent of nitrification, suitable temperatures, and oxygen consumption for an MBBR process with pure oxygen supply have not been identified. It would be particularly valuable if the experiments were compared with an identical process in which air is supplied instead of oxygen.

Ozonation can be expected to be implemented at more and more WWTPs. By calculating the total volume of effluent wastewater of the 10 largest treatment plants in Sweden, assuming that 50% of them will implement ozonation, we have estimated the total use of oxygen to be from 15,000 - 25,000 tons per year, which corresponds to a market value from 220 - SEK 365 million when a unit price of 15,000 SEK/ton is considered.

From a rough calculation for nitrification at treatment plants (> 10,000 pe) north of Norrtälje, the annual oxygen demand is summed up to approx. 10,500 tons of O_2, which corresponds to an energy demand of 1.5 to 4 GWh when aerating with blowers.

Oxygen gas for ozonation is supplied through an ozone generator, after which the produced ozone gas is supplied to the water in a contact tank through nozzles in the bottom of the tank. For oxygen supply to the nitrification, oxygen gas can be led down to the wastewater through pipes and finally through a membrane.

In addition to the potential areas for oxygen use in water treatment mentioned above, there may be potential for oxygenation by oxygen to aerobic processes of process water with high organic content, provided those other operating parameters are controlled such as the removal of formed carbon dioxide which may otherwise affect the pH of the water to be treated.

5.5 CASE 5: AQUACULTURE

5.5.1 Introduction to the case

One option for using oxygen as a hydrogen production by-product is in aquaculture. Fish cultivation in semi-closed as well as closed aquaculture facilities requires both of the by-products from hydrogen production, oxygen and heat, which needs to be supplied in controlled forms to achieve successful farming (Tibbelin et al., 2022).

It is therefore assumed that it is to these facilities that the potential for delivering hydrogen by-product oxygen lie. The total volume of (closed) recirculating aquaculture systems (RAS) in Sweden amounted to approximately 5,000 m^3 in 2021 (Jordbruksverket, 2021). The semi-open aquaculture facilities are more common and well-established than RAS, but no total volume has been identified. A typical aquaculture system in tropical areas can have a volume of around 50,000 m^3, producing e.g. 1,000 tonnes of shrimp per year (M. Djurstedt, personal communication, 2022).

Fish farms have high demands of oxygen in the water to maximize the productivity of the farm. Large amounts of oxygen can be utilized in fish farms since there are no problems with too much oxygen in the water. A 100% oxygen saturation rate is often required and is usually obtained with oxygen cones (Oliviusson, 2022). The oxygen cones supplies and mixes oxygen into the water (Oxywise, 2022). As fish need oxygen for breathing and their metabolism it is vital to maintain a constant access of oxygen in fish tanks. In most farms the oxygen level is continuously controlled with a supply of oxygen when it is needed. For most species the optimum amount of dissolved oxygen is between 4 and 6 O_2 mg/L. In commercial applications with intensive farming, it is common to supply with pure oxygen since it is usually not sufficient to utilize air (Eriksson et al., 2018).

The amount of oxygen that can dissolve in the water depends on the density, the temperature, and the salinity of the water. Low salinity and cold water contain more oxygen at full saturation compared to warm water with higher salinity. In freshwater with atmospheric pressure, the fully saturated water with a temperature of 10°C contains 11.3 mg/L of oxygen while water with 20°C contain 9.1 mg/L. The fishes' demand for oxygen generally increases with higher temperatures. Consequently, fish cultivation of species that require higher temperature also results in more rigorous oxygen supplies (Eriksson et al., 2018). This corresponds to land based closed aquaculture where the parameters are under control and differs from the environment in open fish culture in Sweden. Therefore, closed aquaculture might be a suitable application for oxygen from hydrogen production.

Aquaponics is one example of closed aquaculture, a farming technology where plants are growing in the water meanwhile utilizing the water as a habitat for cultivating fish. This sustainable farming method is described in 4.1.2. Further discussions were held with Björn Oliviusson, a scientist within aquaponics. His scientific work is held at The Royal Institute of Technology's greenhouse south of Stockholm, and he is also conducting a private company in aquaponics (Svensk Aquaponik, 2022). Heat is a vital ingredient when growing plants. By holding a minimum temperature of 6°C Mediterranean plants can grow. With a temperature of 10°C, avocados and mango grows. Hence, aquaponic farms use a lot of heat. Oxygen is needed for the fish cultivation in aquaponic farms. However, one synergetic effect about growing plants in aquaponic farms is that the plants are oxidizing the water. The need for extra oxygen is therefore often low. Usually only

15-20% of the farm consists of fish, resulting in a low oxygen need. Consequently, the oxygenation is often done with air in aquaponics in Sweden as of today (Oliviusson, 2022).

5.5.2 Technical description

The technology to dissolve oxygen in aquaculture is definitively mature as it has been implemented in commercial scale. It can be conducted by bubbling air, the use of oxygen cones or inserting pure oxygen gas into the water and let it dissolve (Hansen, 2021). The new aspect in this report is to utilize the pure oxygen from an electrolyser if they are built close to each other, which is rather easily set up with gas pipes, tubes and a compressor if needed.

5.5.3 Requirements on oxygen quantity, quality and stability of supply

The oxygen demand is according to (Hansen, 2021) 100 mg O_2 per hour per kg of salmon and according to (Royer et al., 2021) 101,5 mg O_2 per hour per kg of rainbow trout. With the RAS system, there is a need of up to 1 g oxygen per m^3 per day (M. Djurstedt, personal communication, 2022). As previously mentioned, a typical aquaculture system in tropical areas can have a volume of around 50,000 m^3. This is a very large system – compared to the total volume of RAS in Sweden of approximately 5,000 m^3, see 5.5.1. With the total water volume of 50,000 m^3 the oxygen needs per cubic meter equals to a total need of 50 kg oxygen per day – which is approximately 10% of the produced oxygen in the micro production case (576 kg per day). Hence, the oxygen need for fish farming is low, and it's probably relevant for the *micro production case* or for small parts of the oxygen for the *larger production cases*. There is of course also a possibility to scale up the fish farms.

The requirements on oxygen quality in aquaculture are low. Regarding the high purity from electrolysers, the oxygen purity is undoubtedly qualified for being utilized in fish farms. In some farms air is used for the water oxygenation, but pure oxygen could be beneficial in farming with high fish densities and with fish species having high oxygen demands (Eriksson et al., 2018).

The required oxygen purity for aquaculture is not very specified. Since air is the other option for water aeration, a high oxygen purity might not be needed. However, for the intensive farms where air is not sufficient, the substantially higher oxygen content is beneficial for the growth. No studies have been performed regarding how fish farms would react to hydrogen being dissolved in the water. The other substances than pure oxygen in the by-product stream should be studied before implementing in the farm, such as alkaline residuals.

It is extremely important to ensure a stable supply of oxygen to aquaculture facilities, in particular for shrimps and salmon (M. Djurstedt, personal communication, 2022). Some fish species tolerates lower oxygen levels, often warm water species such as tilapia, but all species need constant access to oxygen (Susanne Eriksson, et al., 2019).

5.5.4 Economic assessment -investments and operational costs

When comparing the cost of hydrogen-related oxygen to "conventional" oxygen, it is important to compare the total delivered cost, i.e., the cost of both producing as well as transporting the oxygen to the end customer. The cost should also be compared to oxygenation of water by air pumps, which entails investment in one or several pumps as well as electricity for operating the instalment, but also limits the potential fish production – more on this below.

To ensure secure oxygen transfer from the hydrogen production facility to the receiving aquaculture user – to the right quality, quantity, and stability of supply – new infrastructure investments are needed. For compressed oxygen, there is a need to invest in drying-, compressor-, filling- and potentially also gas cleaning equipment. The cleaning equipment can be needed for e.g. alkaline residual. A number of cylinders at both the producing and receiving facility are needed. A pipeline adds to the total capital expenditures, if required. As for operational expenditures, there is a need to continually fill the cylinders/tanks and deliver them by car or trailer.

For liquid oxygen, investment in a liquefier and dedicated trucks are needed. The liquefaction process requires substantial amounts of electricity, which affect the operational expenditures.

One aspect that could affect the potential profitability of the case is that oxygenation with pure oxygen could lead to increased yield per unit of water volume, which can decrease the need for land usage. The two factors limiting the potential fish volume per water volume are oxygen content (to a certain limit) and water purification speed, and by oxygenating the water with pure oxygen instead of pumped air, the oxygen content can be increased (M. Djurstedt, personal communication, 2022). As land cost is high in Sweden, and often a crucial factor for the economic feasibility of a RAS facility, this aspect could positively influence the case.

All things considered, the economic viability of using oxygen from hydrogen production in Swedish aquaculture systems is highly facility dependent and will need to be analysed for each individual case.

5.5.5 Environmental and socio-economic aspects – benefits and trade-offs

Closed and semi-closed aquaculture facilities are easier to control compared to open systems in regard to both the system internal environment and what is released from the system. In semi-closed facilities, the water is filtered before passed out into the surrounding environment. (Jordbruksverket, 2021)

Closed, land-based, aquaculture and aquaponics, are associated with environmental and socio-economic benefits compared to both open fish farming, but also to large scale open sea fishing operations.

The recirculating, aquaculture practice frequently entails farming tropical fish or shrimps, which are typically grown in distant locations and often associated with negative environmental impact. The tropical species are also often imported with large costs – both economic and environmental – as a result. On a national level, local farming is assumed to increase domestic self-sufficiency, a topic that has been discussed thoroughly since the draught of 2018 and the Covid pandemic (Miljö- och jordbruksutskottet, 2020).

In some recirculating aquaculture applications, the system is completely closed, with no spill or emissions. As an example, the method Bio-RAS uses organic waste from the farm to feed algae and bacteria, which in their turn feed the shrimps and/or fish (M. Djurstedt, personal communication, 2022). The oxygen added to the system is also used to increase decomposition of the waste. Other methods of aquaponic farming uses the organic waste to produce plants.

Benefits of specifically adding oxygen from hydrogen production sites to aquaculture systems, instead of oxygenating the water by pumping air, are not perceived to be extensive. There is a potential benefit in using less electricity by decreasing the need to use pumping systems.

5.5.6 Concluding remarks from the case - synergies and added values

While not being vital in aquaculture, oxygen has a positive impact in many aquacultural applications. Especially for applications with intensive fish farming which has a high demand for dissolved oxygen in the water. A higher productivity can be achieved with oxygen instead of utilizing air.

Some fish farms utilize oxygen cones to achieve a sufficient level of dissolved oxygen. Other use air that is pumped to the water. With an electrolyser available close to the farm there are some potential synergetic effects. Both the oxygen for oxygenation, but also the waste heat from the electrolyser. Temperature is very important for aquaculture, and usually the heat demand is high. Furthermore, fish living in water with higher temperatures also has a higher demand for oxygen. Hence, the combination of hydrogen production and aquaculture might lead to possibilities of breeding fish species that are not common in Sweden.

The oxygen demand for fish farms is very low compared to the amounts of oxygen available from the hydrogen production cases. Only 10 % of the oxygen by-product from the *micro production case* would be necessary for a large aquaculture system with a volume of 50,000 m^3. Consequently, aquaculture applications are only reasonable for small hydrogen production units.

6 Discussion

Oxygen today is a product that is purchased or produced at site for specific purposes. The big change to this market as presented in this report is that oxygen will be a by-product from the hydrogen production and on a scale that will be many times today's demand in Sweden. The production today is 1 billion Nm³ per year. The resulting oxygen from the hydrogen production in 2030 is estimated to about 5 times this present production. In many of the electrolysers found in Sweden today, the resulting oxygen is vented to the atmosphere as cost and required equipment to bring the oxygen to the market is too high.

With the introduction of these new volumes of oxygen there is strong motivation to find use of this resource for productive purposes. There are several opportunities as seen in this report and possibly more to come as this opportunity to access oxygen arise. There are some of the opportunities that could have high demand, such as oxygen enriched combustion and sewage treatment, while other opportunities are not that common at the moment but may become more common in the future. Examples here are food production such as aquaculture, but also other protein production and environmental actions such as seabed aeration.

Based on the analysis of the production cases there are some aspects that will define what is feasible or not. The identified aspects for consideration are:

- Size of production of oxygen and variability in the production
- Transport and storage requirements
- Need for treatment of the raw-oxygen from the electrolyser to receive oxygen of a useable/saleable quality
- Willingness to pay of the final user considering the changed market

Size of the production of hydrogen and subsequently the resulting oxygen will vary greatly between the different cases that are discussed in Sweden at present. With smaller oxygen volumes the potential uses will have to be similarly smaller in size and there are also needs to consider the cost for equipment in low production cases when it comes for upgrading, storage and transports – typically at a larger site it would be easier to motivate the investment than in a smaller site. In the larger cases the potential use will have to allow for potential volumes. Already one of the larger production sites for hydrogen for the steel sectors (a number of large electrolysers with combined capacity to 2,000 MW) will result in more than twice the volumes of raw oxygen production as present production of oxygen in whole of Sweden. The scale might be one of the most challenging aspects in the more large-scale applications. But there are potential uses including sewage treatment, oxygen enriched combustion, seabed aeration with large demands and also potential uses.

Combining actions on initiatives on carbon capture with potential oxygen enriched combustion could a be a potential combination where additional 'climate action' co-benefits could indirectly be associated with the value chain where the hydrogen is used. This could be of special interest in industrial and steel production cases but will require further consideration of the position of the power production facility as another variable for consideration is the transport of the oxygen.

Transport of oxygen produced will be a limiting factor. The transport cost will limit potential uses. Pipelines, transport on road or more local uses are all options for consideration. Oxygen will, for certain uses, be used in bulk and the price is relatively low, requiring consideration of keeping any additional costs as low as possible, which will include the transport costs. In present applications it is not uncommon that large users of oxygen have a production facility on their premisses. By position the production site for the oxygen close to the use point transports can be kept to a minimum. For oxygen produced from electrolysers the transport will become an additional cost that may define whether the potential use is economically feasible or not. It may be considered for cases where the hydrogen use allows, that position the hydrolyser in a site where there is an oxygen demand, and then transport the hydrogen, rather than the opposite.

An additional aspect for consideration in selecting or identifying the potential uses for the oxygen is whether there are special conditions set for the oxygen required in the considered application. The raw oxygen that will be produced in the electrolyser might require further treatment to reach certain qualities. This treatment may create a higher value product, but also be necessary in order for use of the gas. The required treatment will be defined by the hydrolyser set-up and the proposed end-use. There are some premium qualities of oxygen such as the medical oxygen that have a verified level of purity and is safe for use for breathing, while this is not the case of industrial oxygen. Creating combinations of cost-effective solutions of production site, end-use and necessary treatment and ensuring transport solution will thus be required in order to find solutions.

In any hydrogen project the producer will be asked how the oxygen will be managed. The solution to let the oxygen out in the atmosphere may be attractive but does not acknowledge the potential added benefits that can be the result for use of the gas in different processes or purposes. The driving force is from efficient resource use, and potential co-benefits, while the challenge is found in additional costs for collecting, treating and transporting the oxygen to a potential user. The willingness to pay for the oxygen is also unknown in this new production scenario. Oxygen has, until now, been a gas that is purposely produced for an end-use market. With the potential expansion of hydrolyser and subsequent hydrogen production the potential volume of oxygen will be many times the present oxygen production in Sweden.

For the economic evaluation there are two challenges that the cases represent; i) oxygen use in for example wastewater treatment or aquaculture represent a saving of costs and ii) the benefits/services provided are not monetized and thus economic motivation for using the oxygen is weaker seen in for example aeration of the seabed, or actions for carbon capture in bioenergy applications i.e negative emissions.

In the case of actions where costs are saved there is strong motivations to ensure that demonstration and also proof of concepts are provided before these applications will be more widespread. Even though the economic feasibility may be there the applications are untested in full-scale. An additional aspect here is also that the by-product is not the result from the own organisation and thus requiring additional actions on what price will be put on the oxygen and volatility of this price, security of supply issues and requirement of changes in the existing process and required knowledge and additional parameters on operation[3]. Demonstrations and also proof of concept can provide more information on the benefits, costs and challenges in these applications. Support on research and development on the hydrogen production and applications are now found. As the applications on productive uses of oxygen is partly outside the direct hydrogen sector, the challenges to identify sources for funding to demonstrate these applications may be challenging.

In several applications the outcome of the oxygen use is not directly monetized today. The case of the seabed aeration is a good example where the cost for aeration with oxygenation as compared to other alternatives shows a lower cost. The financing of these actions will have to be external. There are added values linked to branding and additional actions on supporting environmental targets (*Swedish miljökvalitetsmål*) and the Sustainable Development Goals. The potentials in improving and restoring the ecosystems in marine environments are priorities for the society but are difficult to monetize. In the case of negative emissions there is a similar situation at the moment but there are ongoing actions to establish systems to create trading on these negative emissions which would create a monetized support for these actions.

The scale of market may bring additional opportunities in productive uses of the oxygen and with an increased market for oxygen from electrolysers an increased understanding of the required treatment as well as suitable transportation options. The proper use and management of the oxygen is a hygiene factor for the hydrogen production. Consideration to the full range of by-products, including the heat, can further strengthen the sustainability profile of the hydrogen produced and, in the end, also the final products or energy services considered where the hydrogen is used.

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[3] In analogue the use of excess heat from processes can be illustrative. Even though excess heat is available it is not always used for productive uses in other sectors like district heating or similar. The reasons are often complex and not singled out on the economic dimension.

7 Conclusions

The increased attention given to hydrogen production in electrolysers also puts the focus on whether there are any productive uses of the oxygen resulting from splitting water molecules. With the expansion of hydrogen production foreseen in Sweden, and in many other countries, there will be an increased attention also to how the resulting oxygen is handled. Presently oxygen from hydrolysers is often ventilated away as collection, treatment and transports of the oxygen to any productive use is too costly or represents too many unknown factors and added risks to the primary production process.

At the same time the by-product from hydrogen production in an electrolyser is quite well-known and questions on potential uses will arise as part of the process to establish the investment, but also as part of environmental and operational permits. There is also an added aspect as a hygiene factor linked to the primary production. An efficient management of both by-products, oxygen gas and heat, would be expected (by an outside onlooker) from a green and sustainable hydrogen production, if this is not the case, or if there is not good explanation why not this is the case, the primary product can suffer. The present expansion of electrolyser capacity and associated hydrogen production provides a whole new setting. In Sweden the foreseen oxygen by-product from hydrolysers alone is about 7 times higher than the present total national oxygen production. Identifying productive uses will thus require thinking outside the box and acknowledge challenges in terms of economic, technical and operational parameters.

This report has provided an introduction to a selected cases of potential uses, associated benefits and markets for the industrial oxygen resulting from the foreseen expansion of hydrogen production in Sweden. The presentation shows that there are several potential uses including industrial uses, supporting ecosystem recoveries and food production but at the same time there are several dimensions, including technical, economical and geographical, that define what these potential uses could be in each specific case. The first aspect that is defined via the ***hydrogen production*** considered provides the scale of operation, variation in operation and also the location of the electrolyser. The two other dimensions are the ***technical dimension*** for recovering the oxygen, potential treatment for making it useful and transport requirements and secondly the ***market*** dimension that relates to the economic value and willingness to pay for the gas, proposed business model.

At this point of the development of the hydrogen production capacity there has not been any universal productive use of the oxygen identified. It will depend on the production, technical and market dimensions. The opportunities to use oxygen to improve different combustion process provides an opportunity with potentially high demand. Presently the combustion system will have to be adapted to work with higher oxygen content in the combustion. Sewage treatment is another potentially attractive solution where economic motivation is not far away. Oxygen can also be used in food production where aquaculture is a good example. Action for seabed aeration is also promising. The case provided illustrates the challenge of source the funding where alternative actions to receive same impacts is more costly. Using the three dimensions above relevant questions on efficient location of electrolysers, consideration of whether certain production that can benefit from the oxygen can be localised at the electrolyser to reduce transport costs etc. There is also need for innovation and creation of business models that allows for the oxygen to be an attractive commodity to be sold, bought and used.

In order for productive uses for the oxygen to be established there is motivation for further support for especially pilots and demonstration. Establishing demonstration cases would provide important experiences and also show case the opportunities. Even though the technologies might be known, the situation of an extremely much higher production of oxygen from the electrolysers than what is presently seen in Sweden will require actions to think outside the box and come up with new solutions. There are already initiatives on-going but there is need to further pursue this. This could be a special section linked to support for hydrogen investment programs for example.

This introductory study also identifies a number of areas where additional research and studies are needed. These areas include especially the technical dimension where the operators of the electrolysers are seeking information on:

- Technical solutions and requirements for treatment of the raw oxygen from the electrolyser.
- Technical solutions for the management of the oxygen, including collection from the electrolyser, and also storage and transport requirements.

In both the cases above, the costs (capital and operational costs) of the collection, treatment and transport of the gas is relevant and, in many cases, a relatively unknown factor. There are assumptions based on present cost of these solutions, but in most cases the oxygen is then a *primary* product and not as in this case a by-product.

The interest to utilise the oxygen from the electrolysers is high, and as shown in this report there are several potential uses. There is however need for demonstration and collection of knowledge of technical, operational, safety and economic parameters linked to the utilisation. Adding productive use of the oxygen will further strengthen the case of the transformative pathways associated with the establishment of hydrogen production capacity in Sweden.

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POTENTIAL USE AND MARKET OF OXYGEN AS A BY-PRODUCT FROM HYDROGEN PRODUCTION

There are high expectations in Sweden to make transitional changes in industry, transport, and energy sectors utilising hydrogen to cut green-house gas emissions. The hydrogen considered will be based on hydrolysis of water where hydrogen gas (H2) will be the main product, but in the process oxygen (O2) is also an output along with some heat. This report focuses the opportunities for using the oxygen resulting as a by-product from the electrolysers as part of the new hydrogen investments done in Sweden.

The total oxygen production in Sweden in 2020 was about 1.4 million tonnes. The volumes of oxygen produced as a by-product from the electrolysers in the Swedish hydrogen scenarios is about 7.5 million tonnes of oxygen in 2030 and almost 19 million tonnes of oxygen in 2045.

This report looks at opportunities for productive uses for the oxygen and highlights some of the challenges and gaps of knowledge.

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