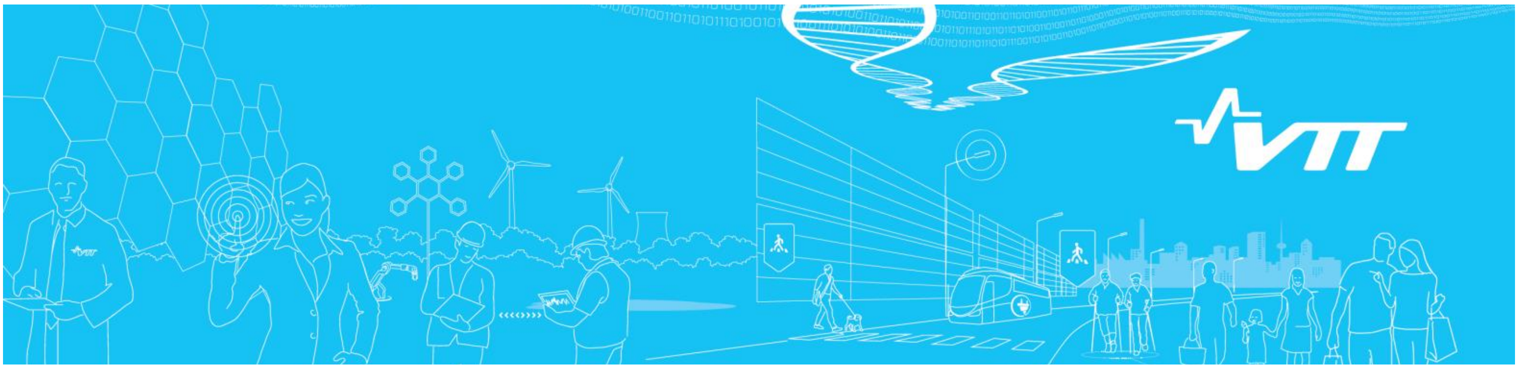
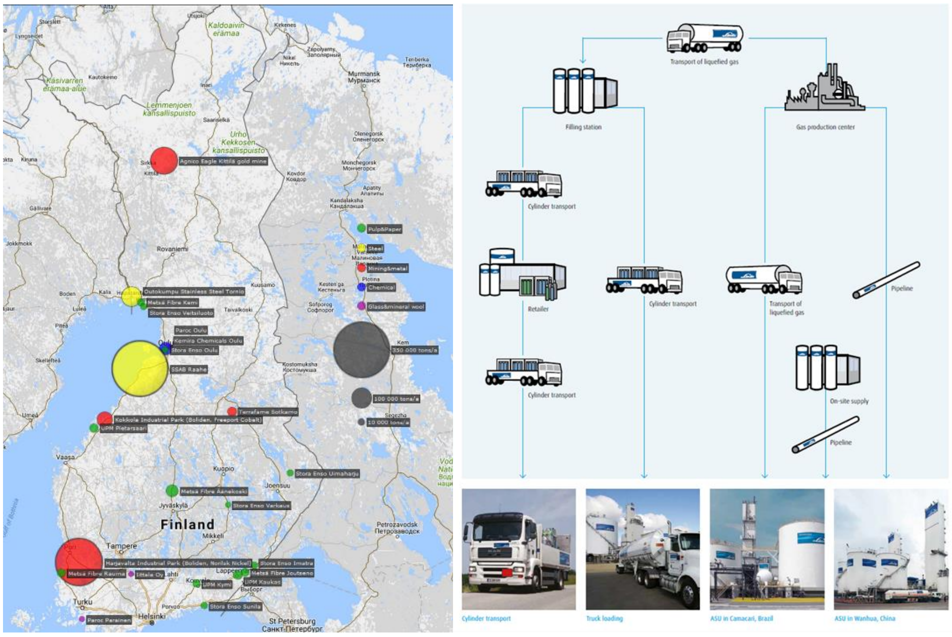


RESEARCH REPORT

VTT-R-06563-17



Industrial oxygen demand in Finland

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Confidentiality: Public

NEO CARBON ENERGY

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Summary

The purpose of this study was to map the main oxygen consumers in Finland and to identify the most promising candidates for utilising electrolytic O_2 which is formed as a by-product in Power-to-X applications.

The estimated total oxygen demand was ~1.3 Mt/a which accounts the amount of oxygen that would be generated in a ~1700 MW_e electrolyser (assuming 62% LHV efficiency and 5000 h/a full load utilisation). Most of the oxygen is used by the steel and mining/metal refining sectors followed by the pulp&paper industry. Data for the oil refining sector (Neste refineries) could not be obtained.

The pulp mills, that currently source their oxygen in liquid form (Uimaharju, Kemi, Kymi, Imatra, Veitsiluoto, Varkaus), were seen as the most promising near-term end-users for the by-product oxygen from Power-to-X processes. The oxygen demands are high enough for on-site multi-MW electrolysers and the value of O_2 should be markedly higher than for plants having on-site oxygen generation. In addition, there are various (biogenic) CO_2 sources available at pulp mills and some of the CO_2 could possibly be separated at low cost via electrically heated pre-calcination concept. However, the lack of heat demand might be a challenge for the total economic feasibility. Furthermore, oxygen supply contracts can be long-term contracts, which can set some constraints for switching to electrolytic O_2.

Confidentiality	Public

Jyväskylä 13.12.2017

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Preface

This report is a part of the Neo-Carbon Energy project (2014–2017) which is Tekes' – the Finnish Funding Agency for Innovation – strategic research openings. The project is carried out in cooperation with Technical Research Centre of Finland VTT Ltd, Lappeenranta University of Technology LUT and Finland Futures Research Centre FFRC at University of Turku. The project involves 15 industrial partners, 3 NGO's and 5 international partners.

Neo-Carbon Energy's solution (www.neocarbonenergy.fi) is an entirely new energy system based on solar and wind alongside other renewables such as hydropower, geothermal and sustainable biomass. The system will produce energy that is emission-free, cost-effective and independent.

This report aims to shed light on the utilisation of industrial oxygen in Finland.

Jyväskylä 20.12.2017

Authors

Contents

1 Goal and methodology

The purpose of this report is to provide data on oxygen consumption (and production) in Finland for the Neo-Carbon Energy project and to identify the most promising end-users for the electrolytic oxygen, which is formed as a by-product in Power-to-X processes involving a water electrolysis step for producing hydrogen.

The identification of oxygen consumers was carried out by mapping first the air gas production plants for which info was readily available. The next step was to find out which companies are operating at the close vicinity and then using the environmental permissions, corporate societal responsibility reports and company websites it was determined how much, if any, oxygen is consumed by each company/process. In addition, some information has been obtained directly from the companies, some has been taken from publications and some has been estimated.

For sectoral distribution, the following classification was used:

- Steel
- Mining and metal refining
- Chemical industry
- Oil refining
- Pulp & paper
- Other (waterworks, glass industry, hospitals)

With the used methodology some of the small (and medium) scale users, to which oxygen is delivered in bottles or as bulk liquid, are left unidentified. For these kinds of users only some already known users such as pulp mills, glass industry, hospitals and drinking water waterworks have been included.

2 Oxygen production and supply

The Finnish air gas market is divided between Air Liquide Finland, Oy AGA Ab (part of Linde Group) and Woikoski Oy, whose production plants together with their main specifications are listed in Table 1. In addition, Terrafame Oy operates a VPSA O_2 unit in their Sotkamo nickel mine.

Table 1. Production units of Air Liquide, AGA and Woikoski

	City	Site/utiliser	Gases	Type	Notes
Air Liquide Finland	Oulu	Kemira, (Stora Enso)	O_2, N_2, argon	Cryogenic	
	Raahe	SSAB	O_2, N_2, argon	4x Cryogenic	
	Kittilä	Agnico-Eagle Gold mine	O_2	Cryogenic	
	Kokkola	Kokkola industrial park	O_2, CO_2	VSA	
	Harjavalta	Harjavalta industrial park	O_2	VSA	
	Joutseno	Metsä Fibre pulp mill	O_2	VSA	
	Äänekoski	Metsä Fibre pulp mill / CP Kelco	O_2, N_2	VPSA (O_2), AMSA^{TM} membrane (N_2)	N_2 is for CP Kelco
	Nokia			Gas bottling	
AGA	Tornio	Röyttä industrial park	O_2, N_2, argon	Cryogenic	
	Harjavalta	Harjavalta industrial park	O_2, N_2, argon, H_2	Cryogenic	H_2 from naphtha (from LNG in future)
	Kilpilahti	Kilpilahti industrial area	O_2, N_2, argon, CO_2, (H_2)	Cryogenic	CO_2 capture from a process, (H_2 reformer from CH_4 in 2016)
	Imatra	Ovako steel mill	O_2, N_2, argon	Cryogenic	
	Pietarsaari	UPM Wisaforest	O_2	Cryogenic	
	Lappeenranta	Kaukas mill	O_2	VPSA	
	Sunila	Stora Enso, Sunila mill	O_2	VPSA	
	Koskenkorva	Altia	CO_2	CO_2 capture	
	Rauma	Metsä Fibre pulp mill / Forchem	O_2, N_2	VSA (O_2)	N_2 to Forchem for tall oil refining
	Riihimäki, Oulu				Gas bottling
	Äänekoski	Metsä Fibre pulp mill / CP Kelco	O_2, N_2	VPSA (O_2), PSA (N_2)	N_2 is for CP Kelco
Woikoski	Mäntyharju, Voikoski	Woikoski	O_2, N_2, argon, (acetylene, N_2O)	Cryogenic	
	Kokkola	Kokkola industrial park	O_2, N_2, argon, (H_2, CO_2)	Cryogenic, (electrolysis, CO_2 capture)	H_2 from water electrolysis (on-site delivery to Freeport Cobalt + bottling)
	Järvenpää, Pirkkala, Kotka, Varkaus, Oulu			Gas bottling	

VSA=Vacuum swing adsorption, PSA=Pressure swing adsorption, VPSA=Vacuum pressure swing adsorption, AMSA^{TM} = Air Liquide's membrane based technology

Vast majority of the oxygen is produced in the large air separation units located near a major consumption site to which oxygen – and possibly also other air gases – are delivered in gaseous form.

The two main technologies used for large-scale oxygen production are cryogenic air separation and vacuum pressure swing adsorption (VPSA). Cryogenic separation units can produce oxygen at purities over 99.5% while in VPSA units the purity is <95%. Cryogenic separation can be scaled to highest capacities while VPSA is best suited to medium-scale applications (Figure 1). VPSA units are highly flexible: they have high turndown ratios and start-up/shutdown can be achieved in a few minutes time. A cryogenic air separation plant can take hours to start-up and is less flexible in terms of output changes and minimum loads. Another difference is that cryogenic units typically produce simultaneously also nitrogen and argon and a small portion of the gases is typically extracted in liquid form to serve as a backup. In addition the liquid products can be delivered to other customers or to bottle filling stations (Figure 2). If the liquid production capacity has been intentionally over-dimensioned, this gives the air gas companies the possibility to optimize the production periods, e.g. produce at times when the cost of electricity is lowest.

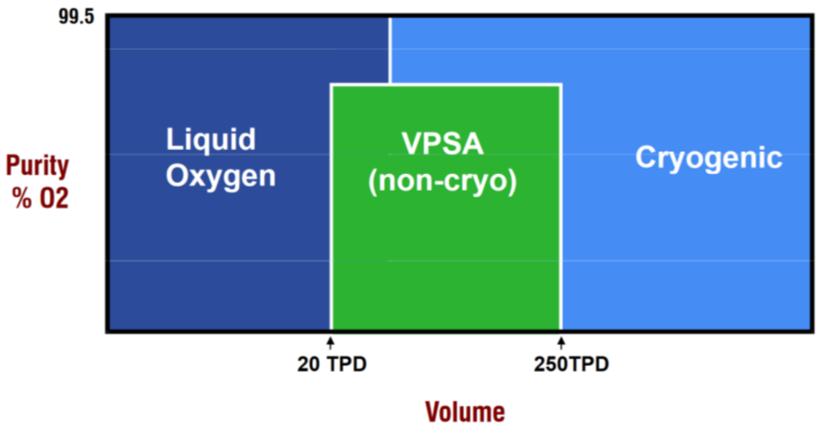

Figure 1. Most suitable technology based on the required purity and demand of oxygen (tonnes per day). Liquid oxygen means delivery by trucks. (Courtesy of Praxair)

The usual commercial arrangement in the industrial gas business is to supply product 'over the fence'. That is, the air gas company will own and operate the plant and insure high reliability by providing liquid backup reserves. Onsite generation contracts typically involve a fixed monthly fee, which includes a capital costs, all maintenance and repair costs, backup systems and a backup supply of liquid. Electricity costs, which are proportional to production rate, are passed through to the customer. (Wilcox 2005) This is likely the case also in Finland although this was not confirmed in this study.

Contracts for the delivery of liquid oxygen are obviously also dependent on the transport distance and might also include e.g. a diesel price as a variable. There is only a very limited information available on transport costs of oxygen but there is a rule of thumb among the industrial gas companies that delivery accounts roughly 40–50% of the total costs (Strahan 2013). This applies to delivery in liquid form and naturally there can be marked deviations from this rule of thumb in practice.

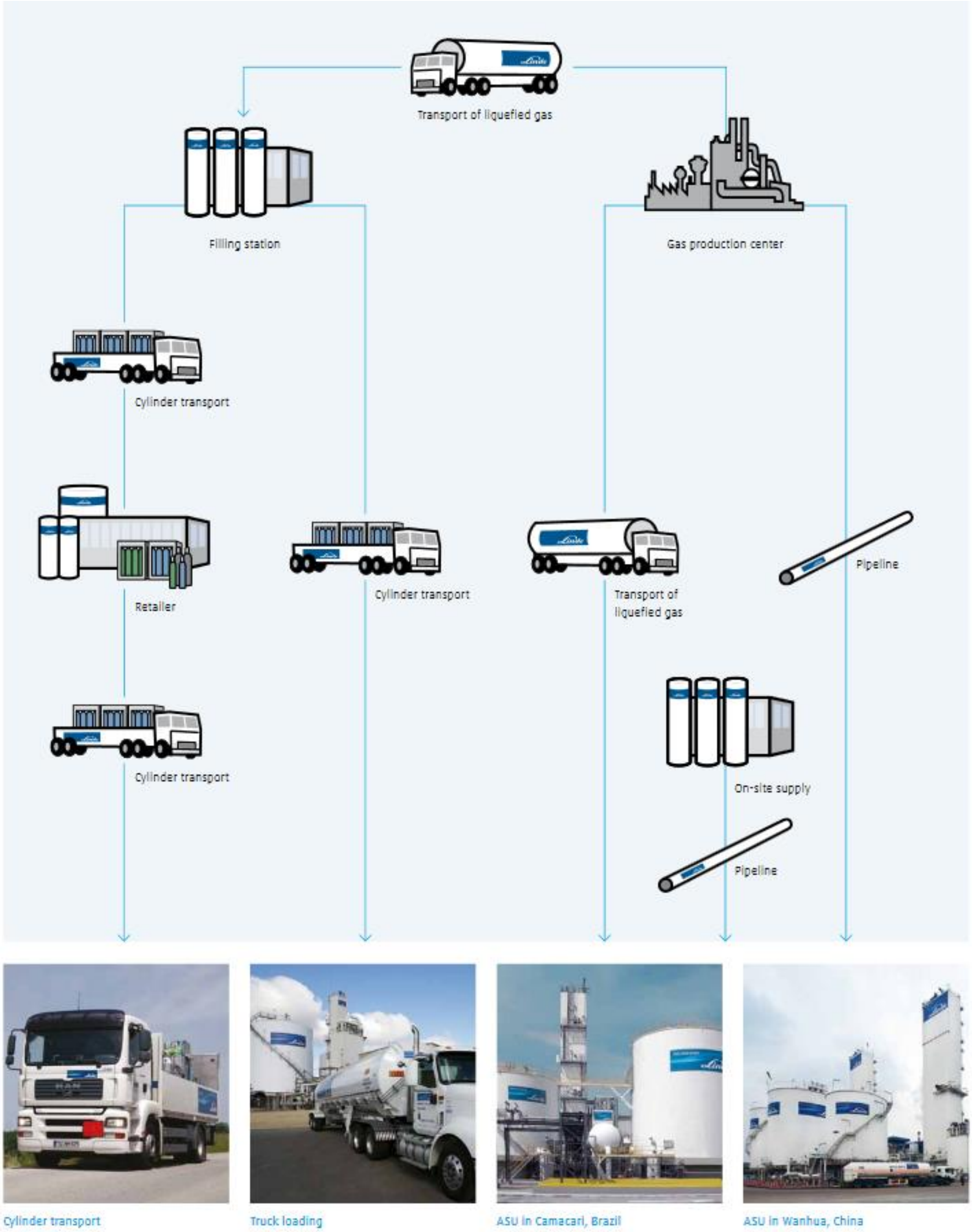

Figure 2. Typical gas distribution chain. (Courtesy of Linde)

3 Results

3.1 Total oxygen utilisation and sectoral distribution

The estimated total oxygen consumption in Finland is ~1.3 Mt/a. According to Official Statistics of Finland (OSF 2016) total volume of traded oxygen was 1.05 Mt in 2014, which is quite close to the estimated total demand. On a side note, the value of oxygen trade in 2014 was ~76 M€ leading to average price of ~73 €/t.

The estimated sectoral distribution of bulk oxygen consumption in Finland is shown in Figure 3. Vast majority of the oxygen is used in steel, mining and pulp industries. Within the chemical industry sector only one site was confirmed to use oxygen which could indicate that the used methodology might have failed to identify all the relevant consumers. In oil refining sector, Neste refineries (Porvoo, Naantali) were confirmed to use oxygen but no data on the amounts could be obtained as this was considered confidential information by Neste. The identified small-scale users were glass industry, hospitals and waterworks for drinking water. Oxygen used for welding, calibration, food industry etc. have been excluded from the analysis as no data was found with the exception of a couple of shipyards. For a snapshot of global oxygen markets see Appendix A.

More detailed look on oxygen utilisation in each of the sectors is given in the following chapters together with potential new users in the near future.

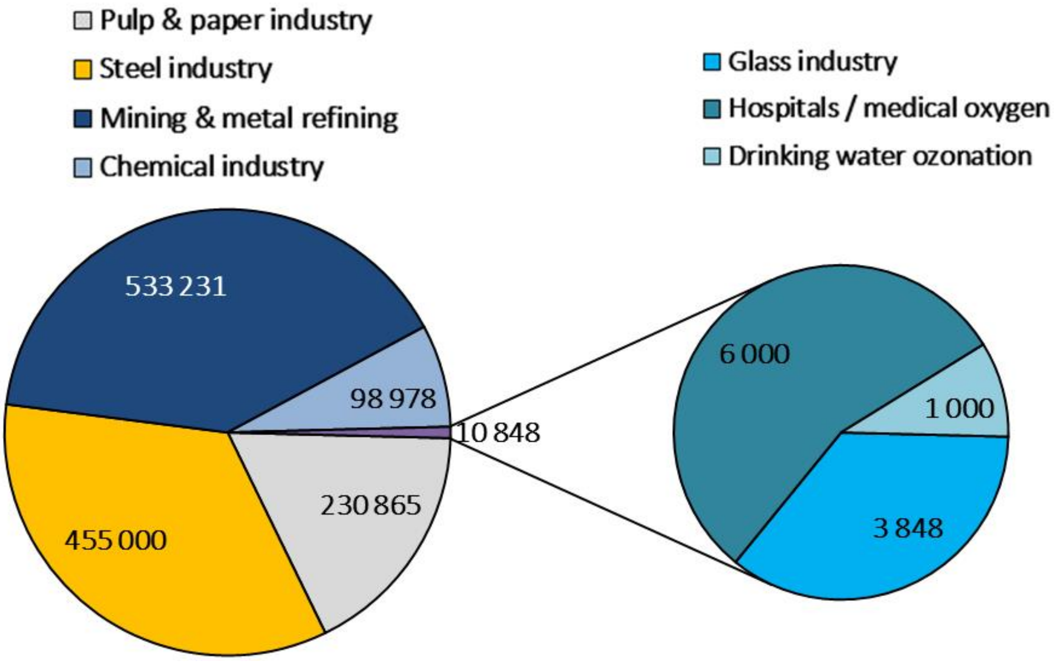

Figure 3. Estimated sectoral distribution of oxygen consumption in Finland (t/a). Note: there is no data on oxygen use in the oil refining sector.

3.2 Pulp and paper industry

Table 2 lists the Finnish pulp mills, their capacities and oxygen consumptions. The main data source was environmental permissions (which for some of the mills were from 2003 so they might be outdated). For plants whose oxygen consumption could not be found, the consumptions were estimated using average specific consumption of other mills producing similar products (28.1 kg of O_2 for a tonne of air-dry pulp).

In pulp mills oxygen is used mainly for delignification and bleaching and it is produced on-site using V(P)SA units (at least Joutseno, Kaukas, Rauma, Sunila, Äänekoski, (Kuopio)) or delivered in liquid form (Uimaharju, Kemi, Kymi, Imatra, Veitsiluoto and Varkaus). Wisaforest Pietarsaari mill has a cryogenic air separation unit and for Stora Enso Oulu, oxygen is delivered from the nearby Kemira site's air separation unit. The on-site units are typically owned by the air gas company and they can also be responsible for operating the plant. Plants with on-site O_2 generation typically have liquid systems for backup purposes.

Table 2. Oxygen consumption in Finnish pulp mills

Pulp & paper industry		*Pulp 1000 adt/a*	*Oxygen t/a*
Uimaharju/Enocell	Stora Enso	450	8 000
Heinola (semi-chemical pulp)	Stora Enso	265	-
Joutseno	Metsä Fibre	690	19 394*
Kaukas (Lappeenranta)	UPM	740	22 000
Imatra (Kaukopää&Tainionkoski)	Stora Enso	1100–1300	10 850
Kemi	Metsä Fibre	650	14 200
Kymi (Kouvola)	UPM	530	14 897*
Oulu	Stora Enso	360	8 000
Rauma	Metsä Fibre	650	20 750
Sunila	Stora Enso	380	10 000
Varkaus	Stora Enso	310	1 600
Veitsiluoto (Kemi)	Stora Enso	375	8 100
Pietarsaari	UPM (Wisaforest)	790	22 204*
Äänekoski (future)	Metsä Fibre	1 300	46 000
Kuopio (planned)	Finnpulp	(1 200)	(43 000)
SUM			205 995**

*estimated using average specific oxygen consumption of other similar mills
**includes Äänekoski but not Kuopio

3.3 Steel industry

Raahe (SSAB) and Tornio (Outokumpu Stainless Steel) are the main oxygen consumers in steel production sector (Table 3). Minor amounts of oxygen is utilised also in Ovako's plant Imatra.

Table 3. Oxygen consumption in steel industry

Steel industry		*Oxygen t/a*
Raahe	SSAB Raahe	350 000
Tornio	Outokumpu Stainless Steel	100 000
Imatra	Ovako	5 000
SUM		455 000

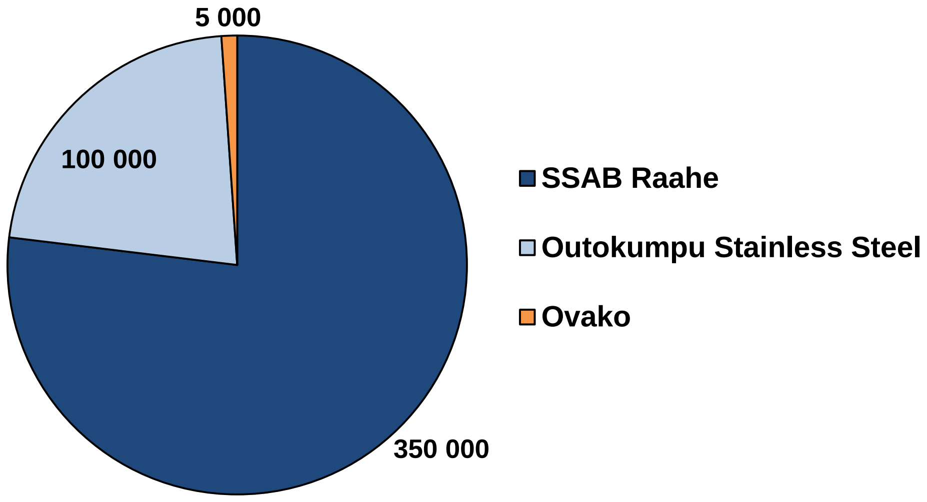

Figure 4. Oxygen utilisation in steel industry (t/a).

Raahe mill produces steel via blast furnace and basic oxygen furnace route (BF + BOF). Oxygen is utilised both in the blast furnace and in the basic oxygen furnace. In the blast furnace iron ore is reduced to iron by injecting coke, pulverised coal, limestone and oxygen enriched air. The carbon-rich molten pig iron exiting the blast furnace is converted into steel in the basic oxygen furnace (BOF) by blowing oxygen to oxidize the carbon. (Arasto 2015)

In 2015, oxygen consumption in iron making (BF) was 148 000 t/a and in steel making (BOF) 203 000 t/a (Kinnunen 2016). Oxygen is produced on-site using cryogenic air separation plants. Should SSAB invest in an oxygen blast furnace, oxygen consumption could triple (Arasto 2015).

Outokumpu's Tornio mill produces stainless steel mostly from recycled metal. The production site includes melt shop, hot rolling mill, cold rolling mill and ferrochrome smelter. Oxygen is produced on-site in an air separation unit which produces also nitrogen and argon. Part of the oxygen and argon is extracted in liquid form for back-up purposes. Around 100 000 tonnes of oxygen is used annually (Kärki 2016).

Ovako Imatra Oy produces specialty low-alloyed steel bars from scrap iron using electric arc and hot rolling. Oy AGA Ab supplies the needed oxygen, nitrogen and argon gases. Oxygen consumption is ~5 000 t/a (ISY-2003-Y-240). Liquid O_2 and N_2 are also stored at the site and transported to other customers.

3.4 Mining and metal refining

The two major oxygen consumers in the mining and metal refining sector are Agnico-Eagle Finland Oy's Kittilä gold mine and Boliden Harjavalta Oy (copper, nickel) (Table 4). Significant amounts of oxygen is used also by Norilsk Nickel Harjavalta, Boliden Kokkola Oy (zinc), Terrafame Oy and probably also by Freeport Cobalt Oy.

Table 4. Oxygen consumption in metal refining sector

Mining & metal refining		*Oxygen t/a*
Kittilä	Agnico-Eagle Finland Oy	150 000
Harjavalta	Boliden Harjavalta Oy	242 749
Harjavalta	Norilsk Nickel Harjavalta Oy	46 000
Kokkola	Boliden Kokkola Oy	50 482
Sotkamo	Terrafame Oy	24 000*
Kokkola	Freeport Cobalt Oy	20 000?
SUM		438 749

*capacity 36 000 t/a but the mine has not yet reached full capacity

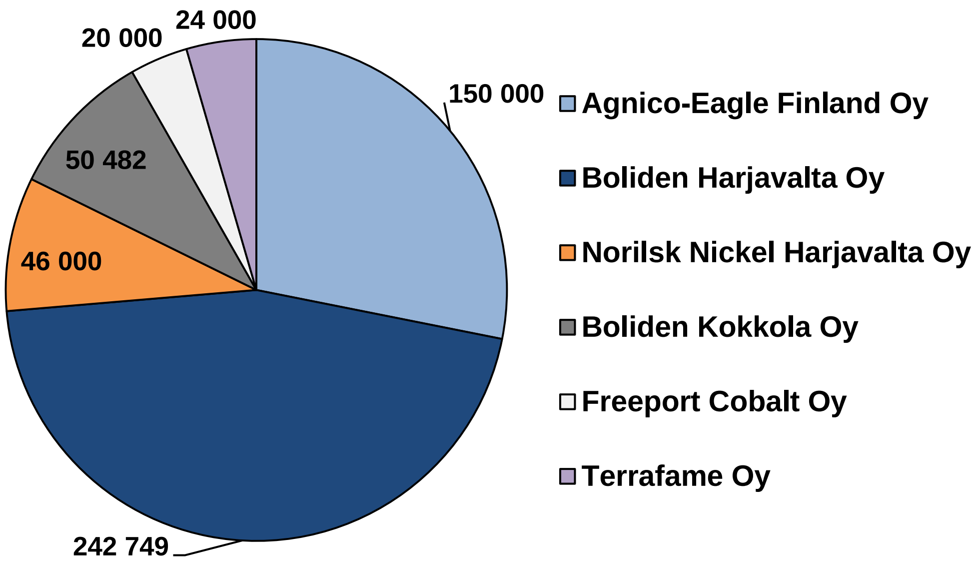

Figure 5. Oxygen utilisation in mining and metal refining industry (t/a).

Agnico-Eagle Finland Oy's Kittilä mine is the largest gold mine in Europe extracting annually about 1.4 million tonnes of ore, yielding about 6 000 kg of gold. The mineral processing comprises crushing, grinding, flotation, pressure oxidisation, dissolution, and electrowinning. Oxygen is needed in the pressure oxidisation process step. (http://www.agnicoeagle.fi/en) Oxygen is produced on-site in AGA's cryogenic air separation plant.

Boliden Harjavalta Oy smelts copper and nickel concentrates and refines copper. The main products are copper cathodes, nickel matte, gold and silver, as well as sulphuric acid as a by-product. (http://www.boliden.fi/Operations/Smelters/Harjavalta/) Oxygen-enriched air is used in the smelters and oxygen is also utilised in the converters. Oxygen is supplied by Air Liquide Finland that operates a VSA unit and AGA Finland which, in addition to oxygen, supplies also nitrogen from its cryogenic air separation plant. AGA also supplies hydrogen (produced from naphtha, in future from LNG) to Norilsk Nickel Harjavalta Oy.

Norilsk Nickel Harjavalta Oy produces metallic nickel to be used as raw material in the manufacturing of stainless steel and various metal alloys and for surface treatment purposes. Composed of several hydrometallurgical subprocesses, the production line processes raw nickel matte, nickel sediments and some secondary raw materials. After grinding, leaching and solution purification phases, the process solution is divided and directed into cathode and briquette production lines. Cathode nickel is made of nickeliferous solution by electrolytic precipitation. Briquettes are made of metal powder obtained by reducing nickel from the solution with hydrogen. (http://www.norilsknickel.fi/en/frontpage/)

Terrafame Oy is a Finnish multi-metal company producing primarily nickel and zinc by bioheapleaching at its mine located in Sotkamo. Oxygen is used for precipitation of iron in the metal recovery process. Oxygen is produced on-site with a VPSA unit. The capacity of the unit is 36 000 t/a but the mine is not yet operating at full capacity. (https://www.terrafame.com/)

Boliden Kokkola Oy, is the second largest zinc producer in Europe (315 000 t/a). The main raw material is zinc sulphide concentrate and the main products are pure zinc and zinc alloys. (http://www.boliden.fi/Operations/Smelters/Kokkola/)

Freeport Cobalt Oy (previously OMG Kokkola Chemicals Oy) produces metallic cobalt and copper, inorganic cobalt-, nickel- and copper-based salts and organic metal carboxylates. Main raw materials are mineral concentrates. Data on oxygen utilisation is not directly available. In 2007 the use of oxidising agents was 22 000 tonnes and this could be mostly oxygen. Woikoski has built an electrolysis unit at the site which delivers at least H_2 to the process. There is no information regarding the utilisation of the high-purity O_2 produced as a by-product.

3.5 Chemical industry

The only chemical industry plant that was confirmed to use oxygen was Kemira's Oulu plant complex, whose main products are formic acid and hydrogen peroxide. Oxygen is used both as a raw material in the production of hydrogen peroxide and as a gasification agent. The formic acid business was acquired by Eastman Chemical Company from Kemira in 2014.

Table 5. Oxygen consumption in chemical industry sector

Chemical industry		*Oxygen t/a*
Oulu	Kemira Chemicals Oy	48 978
Oulu	Eastman Chemical Company	50 000?
SUM		98 978

Hydrogen peroxide is a chemical compound with the formula H_2O_2 and it is used as an oxidizer, bleaching agent and disinfectant. Besides oxygen, Kemira's anthraquinone-based production process needs only hydrogen and water as reactants. In the Oulu plant, hydrogen originates from oxygen-steam gasification of heavy fuel oil (operated by Eastman) and oxygen is produced in Air Liquide's cryogenic air separation unit. The CO from the gasification goes to formic acid production.

The anthraquinone process is a cyclic process based on the use of an organic working fluid. The process steps are: hydrogenation→oxidation→extraction→drying→hydrogenation. There are two production lines for hydrogen peroxide in the Oulu plant. The first one utilises a two-step oxidation in which the air is used in the first step and pure oxygen in the latter one. The other line has one step oxidation with pure oxygen.

In 2015 the utilisation of oxygen in hydrogen peroxide synthesis was ~49 000 tonnes. (Vihelä 2016) The actual oxygen consumption figures for gasification could not be obtained as Eastman considered it confidential information. However, using the total oxygen production of the air separation unit and subtracting the demand of other users, this is estimated to be 45 000–55 000 t/a.

Note: It is possible that there are more chemical plants utilising notable amounts of oxygen but they just have not been identified in this study.

3.6 Oil refining

Neste Oyj's Naantali and Porvoo (Kilpilahti) refineries were confirmed to use oxygen. However, Neste considered the oxygen consumption figures to be confidential so no data could be acquired.

In Naantali refinery oxygen enrichment is used at least in Claus plants which convert hydrogen sulphide to elemental sulphur. Oxygen enrichment was adopted in 2006 to increase the capacity of the Claus plants. The waste-water treatment system is also equipped with oxygen injection systems for occasional high concentrations of harmful components due to process disturbances. (LSY-2004-Y362) Oxygen is also used in Porvoo refinery but the processes are not specified in the environmental permission (LSY-2004-Y120).

3.7 Other users

3.7.1 Glass industry

The confirmed oxygen consumers in the glass industry sector were Iittala Oy's container glass plant in Hämeenlinna and Paroc Oy's rock/mineral wool plants in Parainen and Oulu (Table 6). Paroc's Lappeenranta plant was closed down in April 2016. Also Pilkington's Lahti plant, that produced clear and green float glass for automotive industry and for which it used 4000 t/a oxygen (Ohlström&Savolainen 2005), was shutdown couple of years ago. According to environmental permissions glass wool production plants of Saint Gobain Rakennustuotteet Oy in Hyvinkää and Forssa do not use oxygen.

Table 6. Oxygen consumption in glass industry sector

Glass industry		*Oxygen t/a*
Iittala (Hämeenlinna)	Iittala Oy	1 921
Parainen	Paroc Oy	1 045*
Oulu	Paroc Oy	882*
SUM		3 848

*plants were operating at around half of their maximum capacities

In the glass industry oxygen-enrichment is used in melting furnaces. Paroc's mineral wool production plants have coke-fired cupola furnaces (one production line has electrically heated furnace) for melting rock/minerals while Iittala container glass production uses natural gas to melt the glass. For all of the plants, oxygen is delivered in liquid form. Oxygen consumption in Paroc's plants might increase in future as Lappeenranta unit is no longer in operation.

3.7.2 Hospitals / medical oxygen

Medical oxygen market size (6 000 t/a) was estimated on a rough level using data from Japan indicating that oxygen consumption per capita is around 1.1 kg/a (Kato et al. 2005). In Finland, most of the medical oxygen is delivered in liquid form. Typical limit where the use of liquid oxygen is viable is around 10 000 Nm^3/a (~14 t/a).

The price of medical oxygen is high, especially in Finland. In the public tenders for delivering medical gases for the hospitals of city of Turku for 2012–2014, the price of LOX was ~250 €/t (VAT 0%), when the estimated annual consumption was 200 t. Price of bottled O_2 was markedly higher at 3–7 €/kg not including bottle/bottle rack rental costs.

In Finland air gas companies have allegedly benefitted from a monopoly situation. Only Woikoski Ab and AGA Ab have had the permission to produce and sell medical gases. In 2011 the EU allowed the hospitals to generate their own oxygen on-site using small scale oxygen generators ("oxygen concentrators") but in Finland the first such unit has only very recently got the green light from Fimea (Finnish Medicines Agency). The on-site generators are typically based on PSA technology and they are said to be able to produce oxygen for <100 €/t. In Finland Laser Gas (http://www.lasergas.fi) has been trying to push on-site generators into the markets. On-site generators have been in use in various EU countries and e.g. Canada but they have met opposition from the gas companies. (MOT 2016)

The quality requirements for medical oxygen are listed in Table 7. The limit for oxygen concentration is lower for oxygen generated on-site. Oxygen concentration does not usually have much effect in practice as before giving oxygen to patients, it is typically diluted to 30–60% O_2 content. Breathing air with >80% O_2 content for extended periods can be damaging. (SSTY 2014)

The medical oxygen produced by air gas companies is produced in the same units as industrial oxygen. To avoid contamination medical oxygen must be delivered in vessels which have been dedicated to medical uses and certain quality control measures have to be applied. According to air gas companies, the quality control is the cause of the high price (MOT 2016).

Table 7. Quality requirements for medicinal oxygen (SSTY 2014)

Gas	Oxygen (cryogenic distillation)	Oxygen 93% (on-site generation)
Oxygen, O_2	≥ 99.5%	93% ± 3%
Water vapour, H_2O	≤ 67 ppm	≤ 67 ppm
Oil	–	≤ 0.1 mg/m^3
Carbon monoxide, CO	≤ 5 ppm	≤ 5 ppm
Carbon dioxide, CO_2	≤ 300 ppm	≤ 300 ppm
Nitrogen oxides, NO+NO_2	–	≤ 2 ppm
Sulphur dioxide, SO_2	–	≤ 1 ppm

3.7.3 Drinking water ozonation

Ozone is used for disinfection of drinking water in a few larger waterworks that use surface water as the raw water. The ozone is produced on-site from oxygen which seems to be typically delivered in liquid form. Based on the results from questionnaire to Finnish waterworks (Prizztech 2011), the total use of oxygen was around 1 000 tonnes in 2009.

Two examples of such waterworks are Viitaniemi in Jyväskylä and Kurkelanranta in Oulu. The oxygen consumption in Viitaniemi (which produces around ¼ of household water used in Jyväskylä) is around 120 t/a and the cost is ~235 €/t (Nissinen 2011). In Kurkelanranta ~29 tonnes of oxygen was used in 2015 (Oulun Vesi 2016).

3.7.4 Shipyards

Based on their environmental permissions, the use of oxygen in Rauma and Turku shipyards were 263 and 612 t/a in 2007. In shipyards oxygen is used in welding and cutting and it is delivered as liquid.

3.8 Possible large-scale users in the near future

Kaidi has been planning to build a biorefinery producing biodiesel and gasoline in Kemi. The plant would be based on plasma gasification of woody biomass followed by Fischer-Tropsch synthesis and it would produce 150 000 tonnes of biodiesel and 50 000 tonnes of biogasoline annually. For this two million cubic meters of wood is required.

There is limited amount of data in plasma gasification but assuming that oxygen consumption is similar to oxygen blown CFB gasification considered by Hannula (Hannula 2015), around 300 000–500 000 t/a of oxygen would be required depending on whether oxygen is needed only in gasification step or also in reforming. As an oxygen consumer the Kemi plant would thus be in the same class as Raahe steel mill.

4 Relevance of the results with respect to Neo-Carbon Energy project

First, to put the estimated total oxygen demand of ~1.3 Mt/a into perspective, the needed electrolyser power to meet it would be around 1700 MW_e (assuming 62% LHV efficiency and 5000 h/a full load utilisation). For the largest consumers in the steel and metal refining sectors the electrolyser capacities would be ~70–500 MW_e and for pulp mills ~2–60 MW_e.

The oxygen demand of an ideal consumer should be high enough to make on-site Power-to-X application viable in order to avoid the need to liquefy and transport the oxygen. Furthermore, the ideal consumer would require ultrapure (>99.99%) oxygen. However, these two criteria do not meet in practice. In other words, when ultrapure oxygen is required, the demand in tonnes or kilos is typically low. For the overall Power-to-X feasibility, the site should also have a source of CO_2 (preferably biogenic) and demand for heat.

Further challenge is that especially the cryogenic air separation units are also capable of delivering high purity (~99.5%) oxygen. Thus, the additional benefit from using ultrapure electrolytic O_2 e.g. in steel/metal converters would likely be negligible. In many other industrial processes, such as blast furnaces, smelters and Claus plants, oxygen is used only to enrich the air making the purity pretty much irrelevant. For pulp mills 90–95% purity, achievable with VPSA units, is sufficient.

Large-scale users typically source oxygen from on-site generation systems. In these cases the justifiable value of oxygen from electrolysis for the oxygen consumer is the variable costs of the on-site generation unit (+the margin of the air gas company), at most. The fixed fee (which covers the CAPEX, maintenance, backup systems) needs to be paid to the air gas company regardless of the oxygen use. The variable costs of oxygen generation are mostly electricity costs and modern cryogenic and VPSA plants can produce O_2 for some 250 kWh/t (Hannula 2015, Air Liquide 2017). If the total electricity price is for example 60 €/MWh this is only 15 €/t. For these plants, the electrolytic O_2 (combined with liquid O_2 backup) could become an option, when the current onsite oxygen plant needs to be refurbished. Still the users who have oxygen delivered as liquid seem to be a more attractive option. For these kinds of users the annual oxygen costs are more dependent on the actual use as the fixed costs are a lot lower as plants only need to have oxygen storage tanks and re-gasifiers. Furthermore as producing liquid O_2 requires more energy (although it may be produced at times of low electricity price) and because – according to the rule of thumb within gas companies – transportation can double the product cost, electrolytic oxygen would substitute a more expensive product.

Liquid oxygen is delivered to some waterworks, glass industry, pulp mills, hospitals and shipyards (and engineering works).

In *waterworks* the oxygen demand (for producing ozone) is probably too low for them to be interesting for Power-to-X considerations. For example, a ~150 kW_e electrolyser would be sufficient to cover the annual need of the Viitaniemi waterworks (120 t/a) with 5000 h/a peak load utilisation. Furthermore, the waterworks are not a source of CO_2 although there might be other sources such as heating or CHP plants nearby.

In *glass industry* sites (Paroc's mineral wool plants and Iittala's container glass factory), oxygen demand is a magnitude higher (~1000–2000 t/a). Oxygen-enrichment is used to melt the raw materials in coke or natural gas fired furnaces and thus there is CO_2 available (probably also at elevated concentrations). However, the CO_2 is fossil-based and for decarbonising the process, switching to electrically heated melting might be a more viable option for the mineral wool plants. One of the Paroc's production lines already has an electrically heated furnace so it seems to be mature technology already. The Iittala container glass process might still warrant a closer look, though.

For *medical oxygen* the challenges are the relatively small and dispersed market, legislation and the delivery chain. As medical oxygen is produced in the same units as industrial oxygen, the higher selling price is mostly negated by the required additional quality control measures and logistics costs, especially in case of bottled O_2. Nowadays, the legislation concerning production of medical oxygen recognizes cryogenic separation and on-site generation using PSA based "oxygen concentrators" so electrolysis based generation would likely need an approval first. In future, on-site generation will likely further cut down the market. Thus the medical oxygen market does not seem especially attractive.

On the other hand, the Uimaharju, Kemi, Kymi, Imatra, Veitsiluoto and Varkaus *pulp mills* could be promising candidates. The estimated oxygen demands were 1600 t/a for Varkaus and 8000–15 000 t/a for the others corresponding to ~2 and ~11–20 MW_e electrolysers. Maybe apart from the Varkaus mill, the others would enable relevant scale for Power-to-X process even if not all of the oxygen would be substituted. In addition, there is more than enough biogenic CO_2 available at pulp mills and some of it could possibly be separated at low cost via electrically heated pre-calcination concept (Kouri et al. 2016). The obvious disadvantage of pulp mills on Power-to-X's viewpoint is the lack of heat demand. There is no public information on the price of liquid oxygen for pulp mills but it is likely markedly lower than for example Viitaniemi waterworks (235 €/t, Nissinen 2011) due to economies of scale. Also most of the pulp mills with liquid O_2 delivery are located close to an air separation plant which decreases transport costs.

The highest value for electrolytic O_2 would be in the processes that require ultrapure (>99.99%) oxygen. The markets for the ultrapure oxygen in Finland remain unknown still but it quite safe to assume that the market size (in tonnes) is not very large. Ultrapure oxygen is used for example in analytical laboratories and in semiconductor industry.

5 Summary

The purpose of this study was to map the main oxygen consumers in Finland and to identify the most promising candidates for utilising electrolytic O_2 which is formed as a by-product in Power-to-X applications.

The estimated total oxygen demand was ~1.3 Mt/a which accounts the amount of oxygen that would be generated in a ~1700 MW_e electrolyser (assuming 62% LHV efficiency and 5000 h/a full load utilisation). Most of the oxygen is used by the steel and the mining/metal refining sectors followed by the pulp&paper industry. Table 8 summarises the oxygen consumers identified in this study and Figure 6 shows how the large-scale consumers are distributed geographically. Data for the oil refining sector (Neste refineries) could not be obtained.

The pulp mills, that currently source their oxygen in liquid form (Uimaharju, Kemi, Kymi, Imatra, Veitsiluoto, (Varkaus), Figure 6), were seen as the most promising near-term end-users for the by-product oxygen from Power-to-X processes. The oxygen demands are high enough for on-site multi-MW electrolysers and the value of O_2 should be markedly higher than for plants having on-site oxygen generation. In addition, there are several sources of (biogenic) CO_2 available at pulp mills and some of the CO_2 could possibly be separated at low cost via electrically heated pre-calcination concept (Kouri et al. 2016). However, the lack of heat demand might be a challenge for the total economic feasibility. Furthermore, oxygen supply contracts can be long-term contracts, which can set some constraints for switching to electrolytic O_2.

*Table 8. Summary of major oxygen consumers in Finland (*estimated)*

Pulp & paper industry		Oxygen t/a
Uimaharju/Enocell	Stora Enso	8 000
Heinola (semi-chemical pulp)	Stora Enso	-
Joutseno	Metsä Fibre	19 394*
Kaukas (Lappeenranta)	UPM	22 000
Imatra (Kaukopää & Tainionkoski)	Stora Enso	10 850
Kemi	Metsä Fibre	14 200
Kymi (Kouvola)	UPM	14 897*
Oulu	Stora Enso	8 000
Rauma	Metsä Fibre	20 750
Sunila	Stora Enso	10 000
Varkaus	Stora Enso	1 600
Veitsiluoto (Kemi)	Stora Enso	8 100
Pietarsaari	UPM (Wisaforest)	22 204*
Äänekoski (future)	Metsä Fibre	46 000
Kuopio (planned)	Finnpulp	(43 000)
SUM		**205 995**
Steel industry		**Oxygen t/a**
Raahe	SSAB Raahe	350 000
Tornio	Outokumpu Stainless Steel	100 000
Imatra	Ovako	5 000
SUM		**455 000**
Mining & metal refining		**Oxygen t/a**
Kittilä gold mine	Agnico-Eagle Finland Oy	150 000
Harjavalta	Boliden Harjavalta Oy	242 749
Harjavalta	Norilsk Nickel Harjavalta Oy	46 000
Kokkola	Boliden Kokkola Oy	50 482
Sotkamo	Terrafame Oy	24 000
Kokkola	Freeport Cobalt Oy	20 000*
SUM		**533 231**
Chemical industry		**Oxygen t/a**
Oulu	Kemira Chemicals Oy	48 978
Oulu	Eastman Chemical Company	50 000*
SUM		**98 978**
Oil refining		**Oxygen t/a**
Naantali	Neste Oyj	?
Porvoo (Kilpilahti)	Neste Oyj	?
SUM		**?**
Glass industry		**Oxygen t/a**
Hämeenlinna (Iittala)	Iittala Oy	1921
Parainen	Paroc Oy	1045
Oulu	Paroc Oy	882
SUM		**3848**
Hospitals / medical oxygen		**Oxygen t/a**
SUM		**6 000***
Drinking water ozonation		**Oxygen t/a**
SUM		**1 000***
Shipyards		**Oxygen t/a**
Rauma		263
Turku		612
SUM		**~1 000**
TOTAL OXYGEN DEMAND		1 304 052 t/a

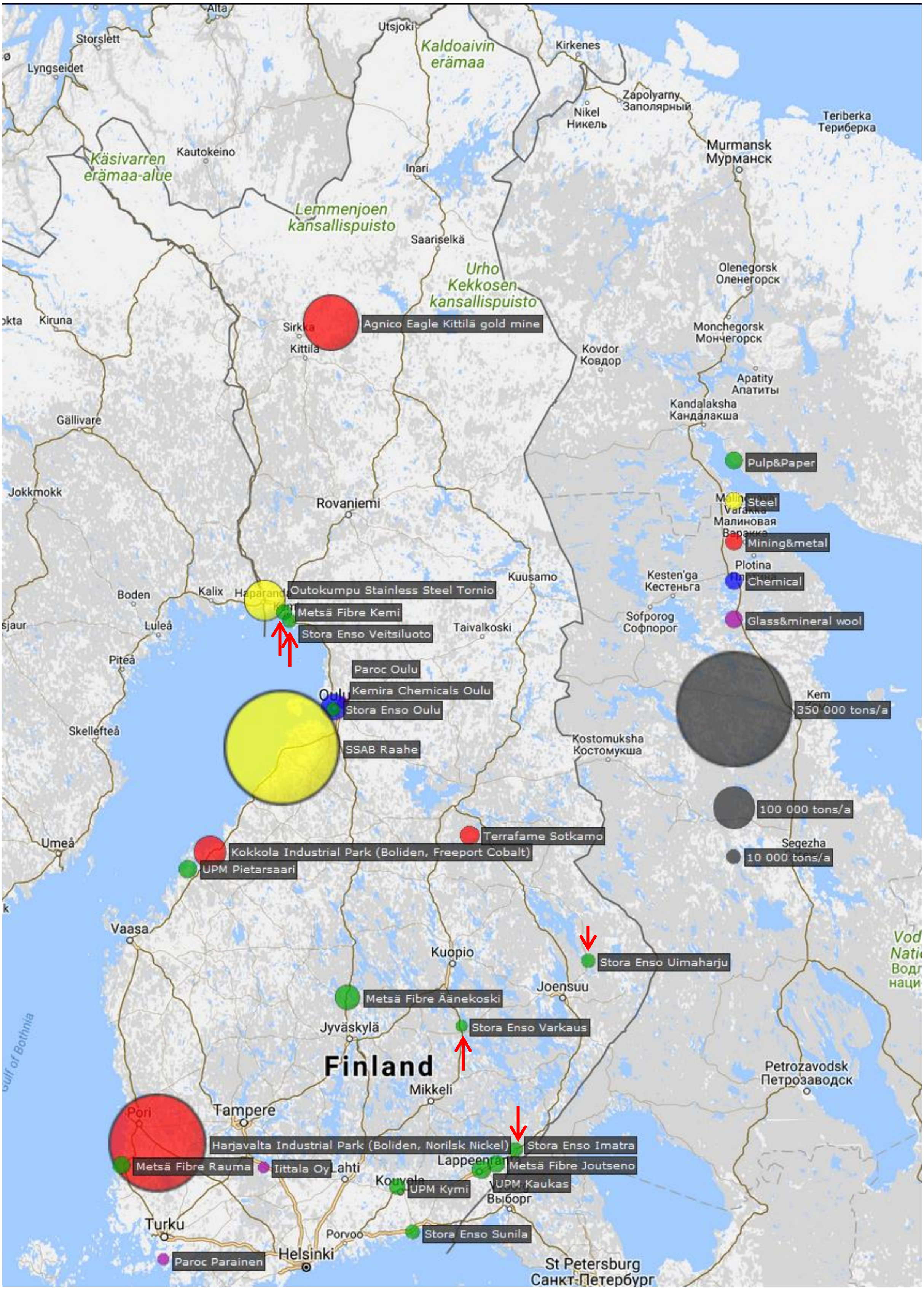

Figure 6. Main oxygen consumers (Note: data on Neste Oyj's refineries is missing). Pulp mills marked with red arrows have liquid O_2 delivery.

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+Various environmental permissions etc.

Appendix A: Global viewpoint

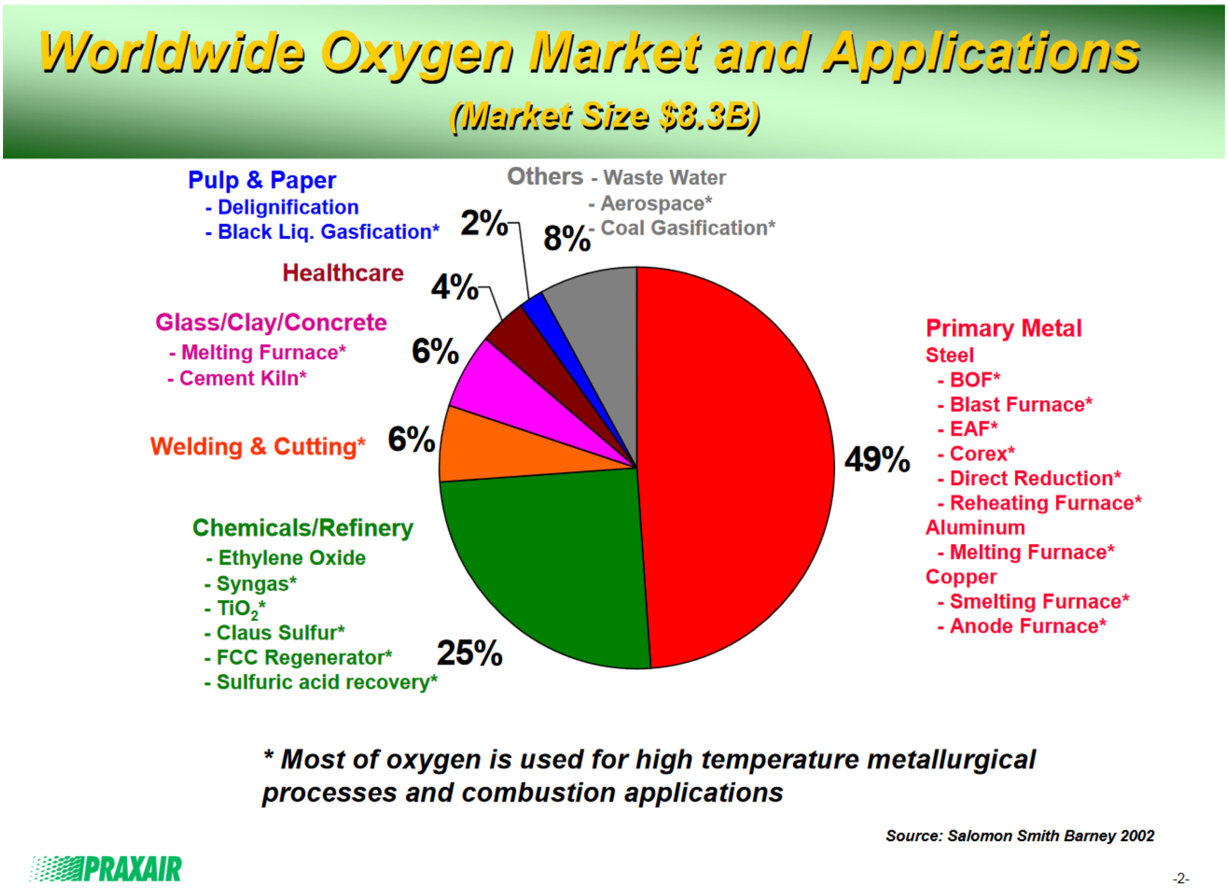

Figure A-1. Global oxygen market ($) and applications (Courtesy of PRAXAIR).

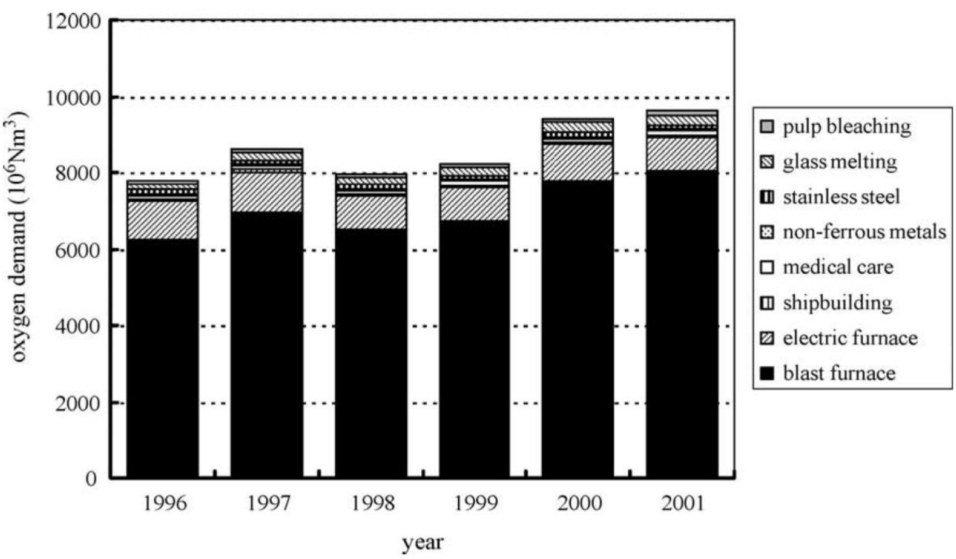

Figure A-2. Country example: oxygen demand in Japan (Kato et al. 2005).

Oxygen global market report

Source: http://www.gasworld.com/oxygen-global-market-report/1277.article

Market growth

"The global oxygen market has maintained a steady 5-6 percent growth over the last ten years. Worldwide oxygen capacity rose from 0.75 to **1.2 million tpd** from 1996 to 2006. The focus of this growth has, however, shifted, with marginal growth in some developed countries balanced by massive growth in developing economies. The oxygen supply in Western Europe, for example, has grown by 46 percent over the last ten years, but grew by less than 1 percent from 2005 to 2006.

Meanwhile, the North Pacific Rim is experiencing significant growth, with a capacity increase of 16 percent over the last year. This demand for oxygen in such places as China is confirmed by the recent trend towards gas companies establishing ASU production facilities in the country together with the high output of plants and equipment by local manufacturers.

Steel

The largest end-user industry using oxygen is the $1 trillion global **steel industry**, which consumes **48 percent** of global oxygen output - approximately 580,000 tpd. Of this usage, 60 percent is captive, that is produced and consumed solely by the end-user. The majority is provided by the industrial gas companies themselves under long-term (usually 15 year) supply contracts. With such high usage, steel demand is clearly the primary driver for oxygen market growth.

Chemical

The second largest end-user industry for oxygen is the chemicals industry, which includes refined products, petrochemicals, agrochemicals, pharmaceuticals, polymers, pigments and oleochemicals. The industry 19 per cent of the worldwide oxygen demand. 40 percent of this is through on-site supply schemes. It manufactures a diverse range of materials and products. The largest sector by turnover is the pharmaceuticals industry, followed by three main groups: chemicals, specialist and products.

Just look at the increase in oxygen capacity that has occurred over the past decade in Saudi Arabia alone - over 8,000 tpd of oxygen is consumed in the petrochemicals sector.

GTL

The largest oxygen consuming site in the world is that at Sasol's coal to liquid facility in Secunda in South Africa. Sasol operates over 35,000 tpd of oxygen capacity to gasify coal and react out the constituents to make clean transport fuels.

At present all the major GTL projects have been sale of plant. Air Products and Linde have shared success among the ASU manufacturers. No GTL projects to date have on-site supply schemes. What is certain is that oxygen demand is going to rise substantially over the next decade."

Chemical industry

Source: den Exter, M. Haije, W. & Vente, J. (2009). Viability of ITM Technology for Oxygen Production and Oxidation Processes: Material, System, and Process Aspects, In: A.C. Bose (ed.), Inorganic Membranes for Energy and Environmental Applications.

“The main use of oxygen in chemical industry is for production of ethylene oxide, ethylene dichloride, propylene oxide, and acetic acid. Notice that the sequence of product production quantities is slightly different since different amounts of oxygen are required for each ton of product. This especially applies for polyethylene, requiring only a small oxygen quantity per ton of product. Most of these production processes are carried out in plants making use of oxygen but sometimes air is used as oxygen source as well. Additionally, many chemical processes are carried out using oxygen in the form of air only. Examples are the production of nitric acid, formaldehyde, terephtalic acid, and carbon black as the main air-consuming production processes. Production of these 4 compounds consumes an additional 106.5 Mton/a of oxygen, 74% of the total oxygen consumption (129.5 Mton/a) of the full range of air consuming production processes.”

“Huge oxygen consumers outside the chemical industry are the steel producers. The oxygen consumption for primary steel production being six times the sum of the major oxygen consuming chemicals mentioned in Table 2.1. The relative contributions to oxygen consumption in the steel industry can be found in blast furnace enrichment (32%), basic oxygen furnaces (43%), electric arc furnaces (19%), and cutting and burning activities (6%).“

Table A-1. World use of gaseous oxygen in bulk production of chemicals and steel in 2004 (den Exter et al 2009)

Product	Production [Mt/a]	O_2 use [Mt/a]	Process Description
Ethylene oxide	15.1	7.2	Oxidation of ethylene. Air is sometimes used but O_2 preferred in new and larger plants.
Ethylene dichloride	49.1	4.0	Oxichlorination of ethylene. Air is sometimes used
Propylene oxide	5.8	2.0	Epoxidation of propylene: PO/TBA-route. Air is sometimes used
Acetic acid	8.1	1.6	Oxidation of naphta/n-butane (35 %) or acetaldehyde (5 %). Air is sometimes used
Titanium oxide	4.3	0.9	From the ore: chlorination (in presence of O_2) to $TiCl_4$, subsequent oxidation to TiO_2
Vinyl acetate	5.0	0.8	From ethylene, acetic acid and O_2.
Acetaldehyde	2.4	0.7	Oxidation of ethylene (Wacker-Hoechst process). The 1-step process uses O_2; the 2-step process uses air
Perchloroethylene	0.7	0.1	Oxychlorination of ethylene dichloride (PPG process)
Acetic anhydride	1.9	0.1	Oxidation of acetaldehyde. Air is sometimes used
Polyethylene (LDPE)	18.7	0.01	Polymerisation of ethylene in a high pressure tubular reactor. Oxygen is used as initiator (radical formation)
Cyclododecanol Cyclododecanone Crotinic acid	0.01	0.02	Oxidation of cyclododecane. Air is sometimes used
Subtotal		17.4	
Steel [14]	1241.0	104.0	
Total		121.4	