INTERNATIONAL CENTRE FOR
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EXECUTIVE SUMMARY
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GAS SEPARATION TECHNOLOGIES FOR ENERGY PRODUCTION

Oxygen is used widely in a range of industrial and power generation applications; key current uses include in chemicals production, glass and ceramics, metals, pulp and paper manufacturing and power generation. Air separation to produce oxygen is a highly energy-intensive process. Any improvements that can be made to enhance the performance of air separation can have a large impact on the introduction of net zero emission technologies in industrial and power generation applications. In the case of cryogenic air separation in an oxyfuel power plant, it represents a significant efficiency penalty, accounting for 10–15% of the plant's gross power output. A review of recent developments in the performance of cryogenic and state-of-the-art air separation technologies which offer potential for step-change improvement in air separation unit (ASU) performance, has therefore been carried out.

COMPARISON OF AIR SEPARATION TECHNOLOGIES

Technology type	Specific power consumption, kWh/t	Technology readiness level (TRL)
Cryogenic	160–225	9
Pressure swing adsorption	525	9
Vacuum swing adsorption	265	9
Ion transport membrane (ITM)	150	6
Electrochemical	1320	4
Chemical looping	30–150	4
Ceramic autothermal	115	6
Vortex	–	4
Magnetic	45	3
MOLTOX® – a molten salt chemical process	100	6

Cryogenic technology – Cryogenic air separation is an established process used to produce high-purity oxygen at large volumes of over 5000 tO_2/d per single unit. It remains the preferred technology for producing very high-purity oxygen and nitrogen and is the most cost-effective technology for high-production rate plants. It is an energy-intensive process where development and optimisation have reduced the energy demand down to around 150–250 kWh/tO_2 in current production plant. As a relatively mature technology, further options for reduction of this energy demand are incremental. They are focused on reducing system exergy losses, both by technological advantages in equipment to reduce pressure drops and enable more efficient heat exchange, and by designing increasingly complex distillation processes which optimise the use of the available exergy.

The most promising approach for efficiency improvement and cost reduction is through heat integration of the ASU plant with the power cycle or industrial process streams. Such reductions are highly case specific. They could include replacing water-cooling in ASU heat exchangers with boiler feedwater and recovering the heat energy as preheating duty. In addition, since applications such as oxyfuel combustion and enriched combustion for industrial processes do not require 99%+ oxygen purity, decreasing the oxygen purity to 95–97% is typically undertaken, which is usually accompanied by an energy consumption reduction of at least 10%.

The target for cryogenic technology integrated in oxyfuel-based systems, set over 10 years ago, is to reduce the energy demand of oxygen production to 120–140 kWh/tO_2. Progress has been made, but based on the available public domain literature, this level of specific energy demand is yet to be achieved. It is noteworthy that despite the relatively mature nature of cryogenic technology, it still appears to account for the majority of patent applications relating to air separation since 2019, accounting for over 60% of patents over this timescale.

An interesting opportunity for cryogenic ASU can be its coupling with low-carbon power plants, to offer flexible operation and energy storage to complement the rapid integration of intermittent renewable sources into electricity grids.

Adsorption and membranes – Adsorption and membrane separation technologies are also available commercially, but typically at an order of magnitude scale below that required for oxyfuel and integrated gasification combined cycle (IGCC) applications. The required oxygen purity level of around 95% can typically be achieved, but scale-up appears to be a key challenge without any obvious solution. This may limit these technologies to smaller-scale industrial oxygen applications. Ion transport membranes (ITM) appeared to be the preferred membrane offering for integration with power plants and was demonstrated at 100 tO_2/d scale around 10 years ago, but further development has been limited, perhaps due to issues of durability and high-temperature sealing.

Chemical looping –Oxygen generated by the chemical looping air separation method could result in significant advantages, with specific power consumption perhaps as low as 30–150 kWh/tO_2 which makes this technique promising for oxyfuel combustion. Improved oxygen carrier mechanical stability and oxygen transfer rates are key development areas and oxygen carriers that are active at lower temperatures would be desirable. Chemical looping-based air separation offers good potential for integration with power and industrial plant.

Electrolysis – Electrochemical oxygen production as a co-product of hydrogen, seems set to become increasingly significant as renewable hydrogen is rolled out globally. The marginal cost of oxygen production on the back of hydrogen production should be relatively low and could provide an additional income stream to help improve the economics of renewable hydrogen. With renewable hydrogen production forecast to be as high as 650 MtH_2/y by 2050, the opportunity for oxygen production is significant. There remain challenges around water electrolysis for hydrogen production in terms of the high electrical energy demand requiring large amounts of renewable electricity, sufficient land to host the wind and/or solar photovoltaic (PV) generation capacity, as well as the large quantities of concrete, glass and steel to build the wind turbines and solar PV systems. However, since specific targets are being set for renewable hydrogen capacity in regions such as Europe, valorisation of the co-produced oxygen seems to be highly likely.

Overall – Cryogenic air separation will continue to be the preferred technology to produce oxygen for large-scale power and industrial applications. Continued incremental improvements and heat integration will reduce the energy of oxygen production and hence cost, but at a reducing rate of return. Adsorption and membrane technologies will find application in industrial oxygen markets where lower quantities of oxygen are acceptable. Chemical looping offers the promise of lower energy of oxygen production, together with good heat integration opportunities, but requires further development to progress towards a commercially ready solution. Electrochemical oxygen as a valorised co-product to renewable hydrogen from water electrolysis seems set to increase significantly in importance through to 2050.

There are also opportunities to combine aspects of air separation technologies themselves to improve oxygen separation efficiency and hence overall cost. For example, electrochemical oxygen could be used to supplement cryogenic oxygen, with the cryogenic oxygen smoothing out electrolyser oxygen output and providing grid balancing and energy storage services.

Compliance with Sustainable Development Goals (SDGs) – Finally, in terms of the wider SDG goals, the production of industrial oxygen and its use in manufacturing and integration within advanced power generation cycles is a key technology contributing in particular to SDG 7 – affordable clean energy for all, SDG 9 – industry innovation & infrastructure and SDG 13 – climate action.

Each executive summary is based on a detailed study which is available separately from: www.sustainable-carbon.org. This is a summary of the report: Gas separation technologies for energy production by Greg Kelsall, ICSC/331, ISBN: 978–92–9029–654–6, 109 pp, June 2024.