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Effective utilization of by-product oxygen from electrolysis hydrogen production

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Abstract

To avoid fossil-fuel consumption and greenhouse-gas emissions, hydrogen should be produced by renewable energy resources. Water electrolysis using proton exchange membrane (PEM) is considered a promising hydrogen-production method, although the cost of the hydrogen from PEM would be very high compared with that from other mature technologies, such as steam methane reforming (SMR). In this study, we focus on the effective utilization of by-product oxygen from electrolysis hydrogen production and discuss the potential demand for it, as well as evaluating its contribution to improving process efficiency. Taking as an example the utilization of by-product oxygen for medical use, we compare the relative costs of hydrogen production by means of PEM electrolysis and SMR.

1. Introduction

Hydrogen is one of the most promising energy carriers for future energy systems; it can be used (in gas or liquid form) to store and transmit energy, and can be supplied to fuel-cell vehicles (FCVs) as well as to fuel-cell power-generation systems. Hydrogen, used as the main energy carrier, could offer an answer to the threat of global climate change and help avoid the undesirable effects of the use of fossil fuels [1]. Although it is estimated that hydrogen is more expensive than fossil fuels, hydrogen from renewable energy resources is a virtually inexhaustible, environmentally benign, final energy carrier that could meet most of our future energy needs while avoiding the environmental costs and health problems associated with fossil fuels.

Hydrogen is a long-term option. Its production, storage, and distribution facilities must be improved and developed. In the short term, hydrogen will be produced from fossil fuels, such as natural gas, by

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steam methane reforming (SMR), which is a very mature existing technology. In the long run, however, hydrogen must be produced by renewable energy resources to avoid fossil-fuel consumption and greenhouse-gas emissions. In other words, hydrogen has a considerable potential for overcoming the limitations of intermittently renewable energy resources and can therefore benefit their development. For example, in the long run, water electrolysis by proton exchange membrane (PEM) is considered to be a promising method of producing hydrogen through renewable energy resources such as wind and photovoltaic power, because of its high efficiency. Currently, even in the case of well-established alkaline water electrolysis, the hydrogen production cost is high in comparison with fossil-fueled hydrogen-production technologies such as SMR because of the high investment cost of the former and the high electricity cost involved. Technological improvements, both in electrolysis technologies and electricity-production technologies from renewable-energy resources, however, could make the production of hydrogen by electrolysis very attractive for the future. Thus, as a long-term option, hydrogen production by PEM water electrolysis would also contribute to the introduction of future renewable electricity. Furthermore, the introduction of distributed hydrogen production, based on PEM water electrolysis utilizing renewable electricity, would be enhanced.

When hydrogen is produced by the water electrolysis process, half the number of moles of oxygen is produced simultaneously as a by-product of hydrogen. If large quantities of hydrogen need to be produced from renewable resources via the electrolysis process, by-product oxygen will also be produced on a large scale. In this situation, the by-product oxygen should be fully utilized, as oxygen is an important industrial gas used in many processes such as combustion, semiconductor production, and wastewater treatment. The effective utilization of oxygen would improve the energy efficiency of some industrial processes [2]. While by-product oxygen from electrolysis hydrogen production can be harmlessly vented, it seems more prudent to explore its possible large-scale utilization.

Fig. 1 shows the conceptual diagram of the simultaneous utilization of hydrogen and by-product oxygen. The use of oxygen-enriched combustion air in a number of energy-intensive industrial applications has the potential to reduce the amount of heat lost to the atmosphere by about two-thirds. As concern for the global environment rises, demand for oxygen is expanding in such areas as electric

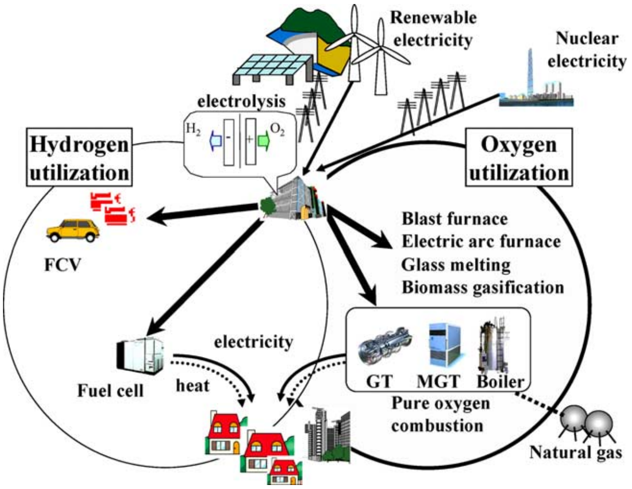


Fig. 1. Conceptual diagram of simultaneous utilization of hydrogen and by-product oxygen.

furnaces and glass melting, as well as in the treatment of municipal solid waste (MSW) and wastewater. Moreover, the utilization of by-product oxygen could contribute to reducing the large amount of electricity consumed in oxygen production by air-separation technologies, such as cryogenic air separation and pressure swing absorption (PSA). If by-product oxygen is to be fully utilized, the balance between by-product oxygen and oxygen demand is very important. If oxygen demand is not very large relative to the potential supply of by-product oxygen from water electrolysis hydrogen production, then large quantities of by-product oxygen will be wasted.

In this paper, we discuss the possible demand for by-product oxygen and its potential contribution to energy saving. First, we present a brief introduction to oxygen- and hydrogen-production technologies. Second, we show current and future oxygen demand and the potential for improving energy efficiency by utilizing by-product oxygen in industry. We then compare oxygen demand with the potential supply of by-product oxygen from hydrogen production by electrolysis. Finally, we evaluate how economical it is to utilize by-product oxygen for medical purposes.

2. Oxygen-production technologies

An air-separation unit using a conventional, multicolumn cryogenic distillation process produces oxygen from compressed air at high recovery and purity. Cryogenic air separation is currently the most efficient and cost-effective technology for producing large quantities of oxygen, nitrogen, and argon as gaseous or liquid products. The energy requirement of the latest technology is about 0.5 kW h/Nm^3 -O$_2$. Oxygen purity of cryogenic process can be higher than 99 vol%. Because of the high purity requirement, oxygen for medical use is normally produced by the cryogenic process. No technology, except electrolysis, is expected to challenge cryogenic air separation for the production of large quantities of oxygen, especially at high purity. In Japan, oxygen demand was 9615×10^6 Nm^3 in 2001 [3,4], and oxygen was produced mainly by the cryogenic process. Because cryogenic air separation consists of five major processes: air compression, air pretreatment, heat exchange, cryogenic separation and oxygen compression, it is utilized for large-scale production in excess of 8000 Nm^3/h and is not suitable for small-scale, on-site oxygen production.

The adsorption process is based on the ability of some natural and synthetic materials, such as zeolites, to preferentially adsorb nitrogen. The regeneration of the adsorbent is necessary and can be accomplished by heating the bed of zeolitic material (temperature-swing adsorption (TSA)) or reducing pressure in the bed (pressure-swing adsorption (PSA)). Because of the faster cycle time and simplified operation, PSA is usually used. The oxygen purity of adsorption process is typically 93–95 vol%. The required energy in the adsorption process is also about 0.5 kW h/Nm^3 -O$_2$. In contrast to the cryogenic process, the adsorption process is used for smaller applications.

Some noncryogenic processes, for example, chemical air-separation process, membrane process and ion-transport membrane, are also available.

3. Hydrogen production by electrolysis

Hydrogen can be produced from a variety of fossil and nonfossil resources by using energy such as heat or electricity. The major processes for hydrogen production include SMR, catalytic decomposition of natural gas, partial oxidation of heavy oil, coal gasification, water electrolysis, thermochemical water decomposition, and photochemical, photoelectrochemical and photobiological processes. SMR, coal gasification, and water electrolysis are the most important industrial processes for hydrogen production today.

SMR is a well-established, commercialized process, and the most common method of producing large quantities of hydrogen. Currently, about 99% of world hydrogen is produced from fossil fuels, primarily natural gas [5]. Hydrogen production efficiencies of SMR with a capacity of over one million Nm^3 -H_2/day are in the range of 63–85% (based on the higher heating value (HHV) of hydrogen), and the investment costs range from 270 to 500 US$/kW [6–9]. At a capacity of over one million Nm^3 -H_2/day, SMR technology has the least-expensive investment cost in comparison with other fossil-fueled hydrogen-production methods. This process also produces carbon dioxide, one of the main greenhouse gases, which is unwanted. To obtain pure hydrogen, purification steps in the downstream of the SMR plant are necessary to remove undesired compounds of this nature.

Water electrolysis is also a well-established technology and the most widely used method of producing high-purity hydrogen. Several processes are available for water electrolysis, ranging from established alkaline systems to developing, advanced methods, such as PEM. The conventional electrolytic methods are known as alkaline water electrolysis, which has been a mature technology for decades, with efficiencies of around 70–80% (HHV). Efforts are being made to enhance the efficiency of alkaline water electrolysis by increasing the operating temperature or electrolyzing under pressurization. The current investment cost of alkaline electrolysis is approximately 500 US$/kW [6,8,10,11]. The investment cost of hydrogen production is higher for alkaline electrolysis than for SMR, but their efficiencies are comparable. PEM, rather than an alkaline aqueous solution, is used as the electrolyte and is considered a promising method because of the extreme volume reduction it involves. Currently, the investment cost for PEM electrolysis is over 1000 US$/kW [11,12]; the high cost of the components is the main drawback of this technology. In addition to the high investment cost, the major cost factor of electrolysis is the electricity, making water electrolysis the most expensive method among the current commercial processes. Thus, electrolysis is used mainly in small plants.

Renewable energy resources, for example, wind, photovoltaic (PV), solar thermal and hydropower, are all efficient sources of the electricity required for water electrolysis. Although the hydrogen produced by renewable-resource-based electricity is very expensive in most cases, it is attractive because it is a very pure and clean energy carrier. In the long run, hydrogen should be produced by renewable energy resources to avoid fossil-fuel consumption and greenhouse-gas emissions.

Water electrolysis powered by renewable energy resources would produce only hydrogen and oxygen, avoiding the emission of CO_2. When large quantities of hydrogen are produced from renewable resources by the water-electrolysis process in the future, by-product oxygen will also be produced on a large scale. When DC electricity is passed between two electrodes (anode and cathode) immersed in water, hydrogen collects at the negatively charged cathode and oxygen collects at the positively charged anode. The main chemical reactions occurring at the two electrodes are:

$$*\text{Anode}: 2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

$$*\text{Cathode}: 4H^+ + 4e^- \rightarrow 2H_2$$

$$*\text{Global reaction}: 2H_2O \rightarrow 2H_2 + O_2$$

For example, when electrolysis efficiency is 71%, 5000 kW h of electricity would produce 1000 Nm^3 of hydrogen and 500 Nm^3 of oxygen. As 250 kW h of electricity is required for oxygen production of 500 Nm^3 by cryogenic air separation, the full utilization of by-product oxygen corresponds to the reduction of electricity consumption to 4750 kW h with electrolysis, raising the electrolysis efficiency to 76%. Electrolysis itself is not attractive for producing oxygen and cannot compete with the other technology. The by-product oxygen might, however, be useful for making the PEM electrolysis hydrogen production attractive.

In this case, the balance between by-product oxygen and oxygen demand is very important. In hydrogen production by water electrolysis, if the oxygen demand is not too large relative to the possible supply of by-product oxygen, large quantities of by-product oxygen must be wasted. Oxygen itself is an important industrial gas used in many industries such as blast furnaces, electric furnaces and glass melting. The by-product oxygen can thus be sold to these industries, reducing the nominal cost for producing hydrogen by PEM electrolysis. On the other hand, if a large oxygen consumer produces oxygen by PEM electrolysis, it can put the hydrogen on the market. In this study, therefore, we discuss the potential demand for oxygen on the basis of a survey conducted both on current oxygen demand and on new technologies utilizing oxygen for improving energy efficiency.

4. Oxygen demand

Fig. 2 shows the oxygen demand in Japan. Total oxygen demand was about 9615×10^6 Nm^3 in 2001. There are a number of new applications utilizing oxygen to improve the energy efficiency of industrial processes. Following are details of some types of industrial oxygen demand.

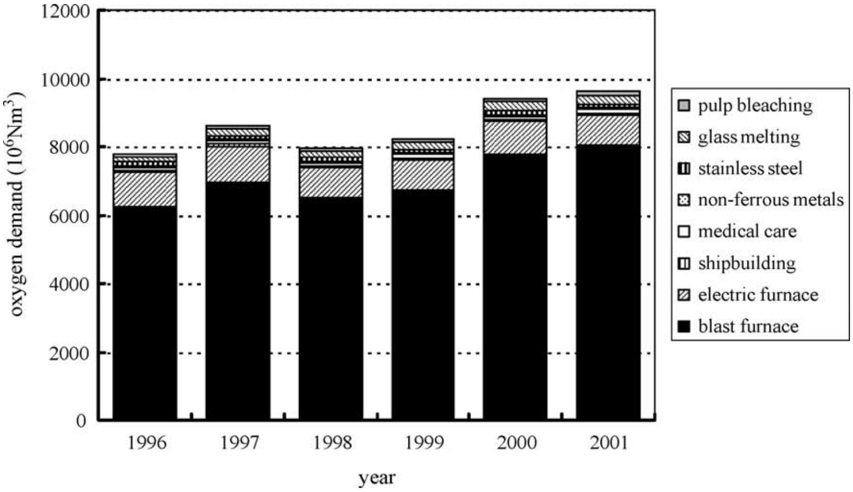


Fig. 2. Oxygen demand in Japan.

4.1. Blast furnaces

The blast furnace process involved in steel making is industry's largest oxygen consumer. In the very latest blast furnace process, oxygen is highly utilized to improve productivity. In Japan, blast furnaces consumed oxygen of 8037×10^6 Nm^3 in 2001, corresponding to 84% of the total oxygen demand. Oxygen for blast furnaces is normally produced on site because of the large demand for it and, normally, the cryogenic air-separation process is utilized. In Japan, almost 70% of cryogenic air separation is used for supplying oxygen to blast furnaces, but as 75% of these systems were built before 1980, the existing systems are going to be replaced with new oxygen-production systems in the near future. At that time, if the hydrogen demand for FCVs is large enough and some of the hydrogen is produced by renewable electricity, an electrolysis hydrogen production system for supplying hydrogen and by-product oxygen to FCVs and blast furnaces, respectively, would be a good option.

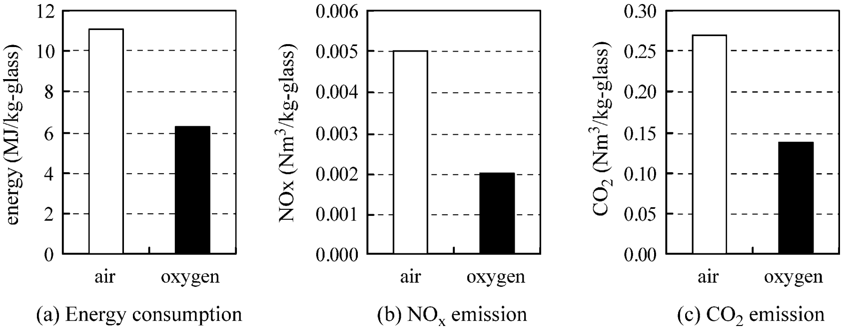
4.2. Electric arc furnaces

With large quantities of the oxygen used in blast furnaces being produced and consumed on site, the largest commercial consumer of oxygen is the electric arc furnace. In 2001, the oxygen demand for electric arc furnaces was about 888×10^6 Nm^3, corresponding to 9.2% of the total oxygen demand in Japan with the adsorption process for producing oxygen being the main one utilized. In the electric arc furnace process, production efficiency has been improved by increasing the amount of oxygen. In the conventional electric arc furnace process, the electricity consumption rate/t of steel production was about 380 kW h/t, with 33 Nm^3/t of oxygen being consumed. Recently, the innovative electric furnace developed by NKK of Japan, has been shown to improve heat efficiency remarkably [13]. This newly developed electric arc furnace process is a fully closed melting-shaft furnace, into which scrap is continuously loaded from the top of the shaft. As the scrap falls into the furnace, it mixes with molten steel and melts rapidly. Because of the furnace structure, which enables scrap to be fed nonstop into molten steel, heat loss on the water-cooled panels and fingers is effectively prevented thereby maintaining the scrap-preheating temperature at around 1000 °C and resulting in lower electricity consumption. In the new electric arc furnace, the consumption of electricity is only 150 kW h/t with oxygen consumption of 45 Nm^3/t. To produce 1 t of steel, therefore, the electricity input is 230 kW h lower in the new electric arc furnace, requiring an additional 12 Nm^3 of oxygen. As a result, the reduction of electricity consumption per unit of oxygen use is 19 kW h/Nm^3 -O_2, which corresponds to a reduction in primary energy of 182 MJ/Nm^3 -O_2 where the efficiency of electric power generation (η_e) is 38%.

In Japan annually, 29×10^6 t of steel are produced by electric arc furnace according to Fig. 2. If all existing electric arc furnaces are replaced with newly developed electric arc furnaces, there would be a reduction of 6634 GW h/yr of electricity (or 62,849 TeJ/yr with $\eta_e=38\%$), plus an additional oxygen demand of 346×10^6 Nm^3/yr, increasing total oxygen demand for electric arc furnaces to some 1300×10^6 Nm^3/yr.

4.3. Glass melting

Glass manufacture is a high-temperature, energy-intensive process. The majority of large glass tank furnaces incorporate regenerative heat-recovery systems. As structural heat losses from such furnaces



(a) Energy consumption (b) NO_x emission (c) CO_2 emission

Fig. 3. Comparison between air-blown combustion and oxygen-blown combustion in glass melting.

typically account for some 40% of total heat input, improving efficiency can lead to significant reductions in energy consumption. In a conventional air-blown combustion melting process, the energy requirement is approximately 11 MJ/kg -glass [14]. Overall efficiency can be improved by rebuilding the furnace to incorporate a number of energy-saving features, namely electric boost and supplementary oxygen-blown combustion. Fig. 3 shows the comparison of energy consumption, NO_x emission and CO_2 emission between a conventional air-blown combustion furnace and a new oxygen-blown combustion furnace. By utilizing oxygen, energy efficiency can be improved by 40%. NO_x and CO_2 emissions can also be reduced outstandingly. In the oxygen combustion furnace, the ideal oxygen requirement is about 0.3 Nm^3/kg -glass. Taking into account energy consumption per unit of production shown in Fig. 3, the reduction of primary consumption per unit of oxygen use is 16 MJ/Nm^3 -O_2.

For cost reasons, the oxygen-blown combustion furnace is not used very much except in electric glass production where the price of the glass product is relatively high compared with other glass products in general. Therefore, if fossil fuel prices increase, the shift to the oxygen combustion furnace would be accelerated. In Japan, the annual production of glass products including sheet glass, glass fiber wool products, glass fiber continuous textiles, glass foundation products and glass containers was approximately 4.4×10^6 t glass in the last 3 years. If these glass products were produced using the oxygen-blown combustion furnace, the estimated oxygen requirement would be approximately 1313×10^6 Nm^3/yr. This would reduce the annual energy consumption of the glass-melting process by 20,951 TJ/yr.

4.4. Electric power plant

An electric power plant has the potential to be one of the largest consumer of by-product oxygen. We are working on the development of a pure oxygen combustion burner for power-generation systems [15]. Based on the development of this, we have proposed a new concept for a power generation system with a pure-oxygen/blown-natural-gas combined cycle (NGCC). Fig. 4 shows the schematic flow diagram of our proposed system in which 85% of the exhaust is recycled as a working medium for the gas turbine. One of the most important features of our proposed system is the exhaust component, consisting of only CO_2, H_2O, and O_2. After the condensation of H_2O, CO_2 can easily be captured without the CO_2 separation unit. This feature could be an advantage over a conventional NGCC with air-blown combustion, which is currently the cheapest option for electricity production. At present, electric power plants with a CO_2 -capture unit attract widespread attention as being environmentally benign

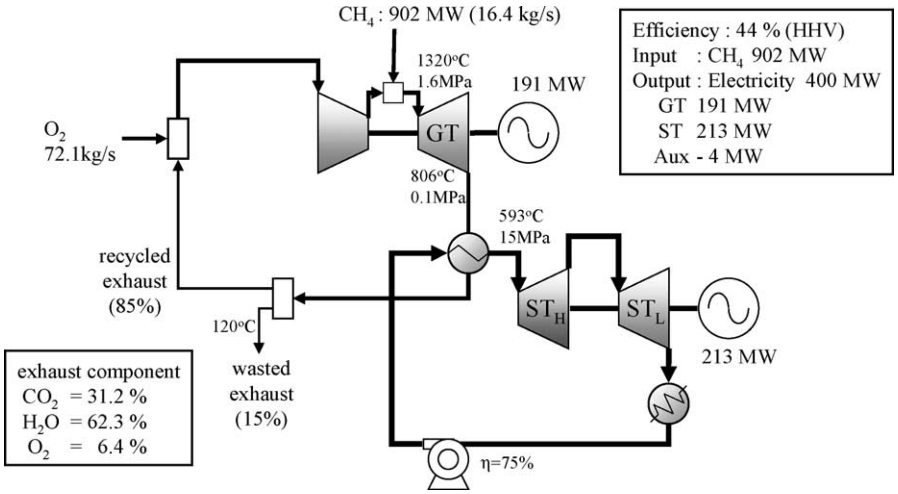


Fig. 4. Oxygen combustion natural gas combined cycle power plant.

installations. Although the capital cost of a conventional NGCC is lower than that of power plants using other fossil fuels, the capital cost, including CO_2 -capture unit, is estimated at about 1000 US$/kW, two to three times higher than without CO_2 capture [16–19]. The total thermal efficiency is around 45% instead of the 53% with conventional NGCC without CO_2 capture, as CO_2 separation from flue gas requires a large amount of power. As our proposed system does not need to have a CO_2 separation unit, it could be as cost-effective an option as a CO_2 -capture power plant fueled with natural gas. The economic assessment of our proposed system is not performed in this paper, but will be carried out as a future study.

As shown in Fig. 4, the oxygen requirement of our proposed system is 72 kg/s (50 Nm^3/s) for producing 400 MW of electricity at the sending end. If this system is operated with a load factor (LF) of 80%, the annual oxygen requirement is 1273×10^6 Nm^3/yr, corresponding to 13% of the current total oxygen demand in Japan.

4.5. Gasification

A gasification process converts any carbon-containing material into a synthesis gas or syngas composed primarily of carbon monoxide and hydrogen, which can be used as a fuel to generate electricity or steam, or as a basic chemical building block for a large number of uses in the petrochemical and refining industries. Typical raw materials used in gasification are coal, petroleum-based materials (crude oil, high-sulfur fuel oil, petroleum coke, and other refinery residuals), gases, or materials that would otherwise be disposed of as waste, for instance, MSW. If the syngas is to be utilized to produce electricity, it is typically used as a fuel in an integrated gasification combined cycle (IGCC) power-generation configuration. The syngas can also be processed using commercially available technologies to produce a wide range of products, fuels, chemicals, fertilizer, or industrial gases.

Gasification is an endothermic chemical reaction, so heat has to be supplied externally or by partial combustion. In the case of partial combustion, the oxidant for the gasification process can be either atmospheric air or pure oxygen. In the simplest gasification system with a partial combustion process, air

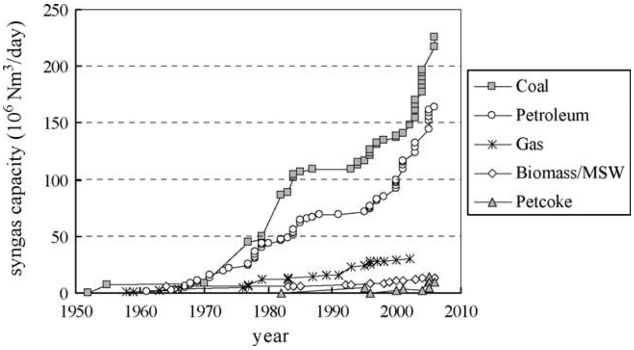


Fig. 5. Cumulative capacity of commercial gasification projects in the world [19].

is used. Although air gasification itself is relatively cheap, downstream gas cleaning is expensive because of the large volumes that need to be handled. On the other hand, oxygen-blown gasifiers offer a higher-heating-value gas and faster reaction rates than air-blown systems, but have the disadvantage of additional capital costs associated with the oxygen plant. The use of by-product oxygen for gasification might solve the economic problem inherent in using oxygen.

Based on the gasification plant survey, there are 163 commercial gasification projects consisting of a total of 468 gasifiers [20]. Fig. 5 shows the cumulative capacity of gasification projects. The capacity is large in coal and petroleum gasification and increases rapidly. Currently, gasification is not commonly used for household waste. Nevertheless, the most significant growth in the market for waste-management systems in the near future is likely to be for the treatment of MSW [21]. The requirement of oxygen depends on the feedstock to be gasified. For example, the Api Energia IGCC plant being built at Falconara Marittima on Italy's Adriatic coast requires 62 t/h of oxygen to gasify 59.2 t/h of high-sulfur heavy oil produced by the Falconara refinery, convert it to syngas, and use the gas to generate 280 MW of electricity, plus steam and other gases for use in the refinery [22]. When this plant is operated with the annual LF of 80%, the annual requirement of oxygen is 304×10^6 Nm^3/yr.

4.6. Medical care

Because oxygen gas used for medical care is categorized as a medical supply, it is produced and delivered within a highly controlled environment. Pure and clean oxygen produced by electrolysis is thus suitable for medical use. The oxygen demand for medical use was about 105×10^6 Nm^3 in 2001 in Japan, which is only 1.1% of the total oxygen demand, including the oxygen produced on site for blast furnaces, however, oxygen for medical use is the third largest sector for oxygen demand in Japan. Utilizing oxygen for medical purposes is not related to the improvement of the energy system, but because of the very high price of medical oxygen, the effective utilization of by-product oxygen might decrease the high cost of electrolysis hydrogen production, especially electrolysis using PEM. We surveyed the retail price of oxygen for medical use at 877 hospitals in Japan, as shown in Fig. 6. Depending on total oxygen demand, the oxygen price is basically very high, ranging from 60 yen/Nm^3 (0.82 US\$/Nm^3) to 10,000 yen/Nm^3 (35 US\$/Nm^3). These prices almost correspond to the fuel price on an Nm^3 basis.

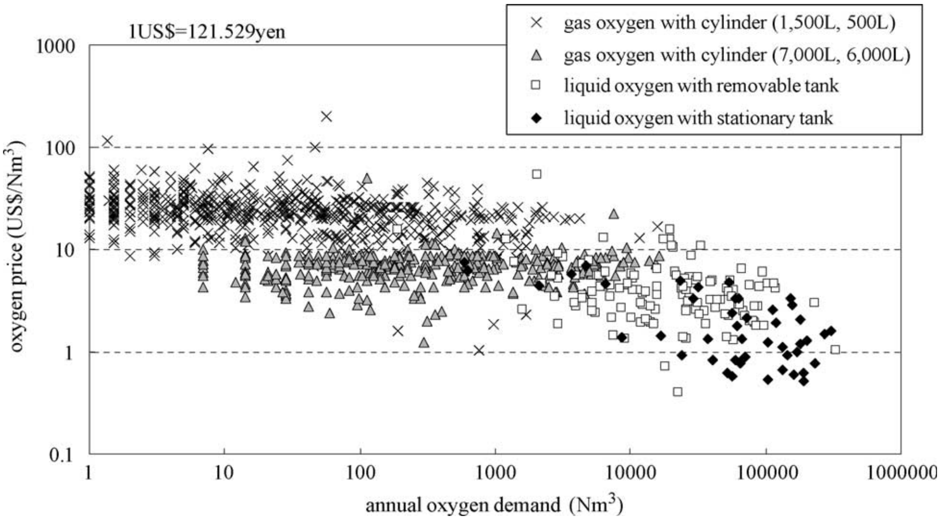


Fig. 6. Retail price of oxygen for medical use in Japan.

In Section 6, we discuss how economical it is to use by-product oxygen from electrolysis hydrogen production for medical purposes based on a survey of oxygen demand and pricing in hospitals.

5. Potential for consumption of by-product oxygen

Hydrogen demand in Japan is estimated to be approximately 15,000–20,000 × 10^6 Nm^3/yr. As most hydrogen for chemical and steel plants, for instance, is produced and consumed on site, the hydrogen demand in the market place is only about 150 × 10^6 Nm^3, in other words less than 1% of actual consumption. Fig. 7 shows hydrogen and oxygen demand in the last 5 years in the market place in Japan,

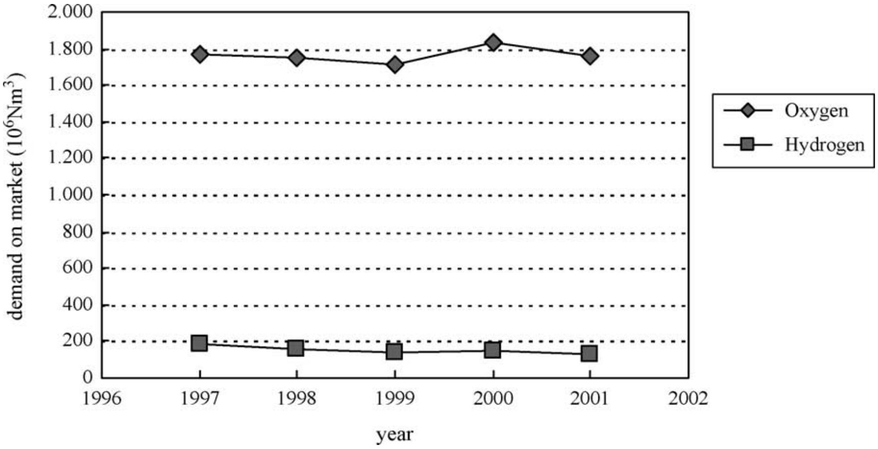


Fig. 7. Hydrogen and oxygen demand on Japanese market.

with oxygen demand being about nine times greater than hydrogen demand, although large quantities of oxygen are also produced and consumed on site.

In the future, there will be new demands for hydrogen. Replacement of fossil fuels by hydrogen in vehicles throughout the world is predicted to occur over the next 50 years as mass production of FCVs accelerates. For example, Japan's target for installing FCVs is 50,000 vehicles in 2010 and 5,000,000 vehicles in 2020, with an estimated hydrogen demand of 160×10^6 Nm^3 in 2010 and 4250×10^6 Nm^3 in 2020, respectively [23]. In the case of southern California, the projected hydrogen demand is 630×10^6 Nm^3 in 2020, assuming cumulative numbers of FCVs of 350,000 for passenger cars, 150,000 for light trucks and 330 buses [24]. Fuel-cell technology for stationary use will also consume large quantities of hydrogen.

The new hydrogen demand must be met by a hydrogen production system in addition to existing systems. If part of the incremental hydrogen requirement is met by the water electrolysis process, half the number of moles of oxygen will be produced simultaneously as a by-product of hydrogen production. In this study, assuming that the estimated hydrogen demand for vehicle use in 2020 in Japan is met by water electrolysis, we compared the amount of by-product oxygen supply and potential demand for oxygen mentioned above. When all hydrogen for vehicle use in 2020 is produced by water electrolysis, the available by-product is about 2125×10^6 Nm^3. On the other hand, the current oxygen demand is four times more than the available by-product oxygen as shown in Fig. 2. In addition, as mentioned above, the potential oxygen demand is 346×10^6 $\mathrm{Nm}^3/\mathrm{yr}$ in electric arc furnaces and 1313×10^6 $\mathrm{Nm}^3/\mathrm{yr}$ in glass melting, where energy efficiency would be improved by the utilization of oxygen. When oxygen-blown NGCC with a 400 MW e capacity is installed, the annual requirement for oxygen is 1273×10^6 $\mathrm{Nm}^3/\mathrm{yr}$ (LF = 80%). Fig. 8 shows the new oxygen demand in these three processes (electric arc furnace, glass melting and oxygen-blown NGCC on the horizontal axis). In Fig. 8, the potential supply of by-product oxygen is shown by the dotted line. The total oxygen demand in only three processes is larger than the potential supply of by-product oxygen from water electrolysis hydrogen. In addition to the oxygen demand shown in Fig. 8, there would be large quantities of oxygen demand in other processes in the future. Consequently, although the assumption that the future hydrogen demand would be met by water electrolysis looks unrealistic, even in a situation such as this, the opportunity for consuming the by-product oxygen would exist.

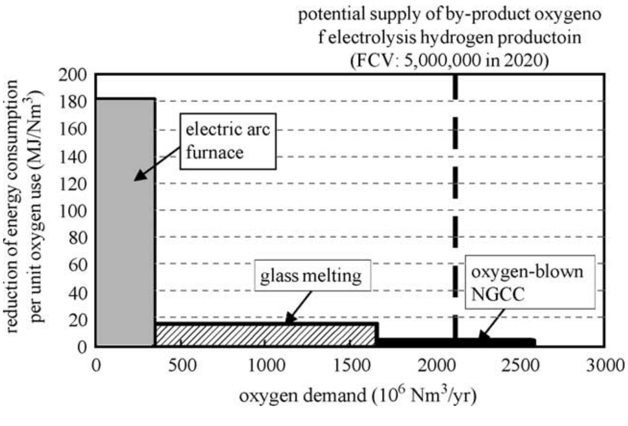
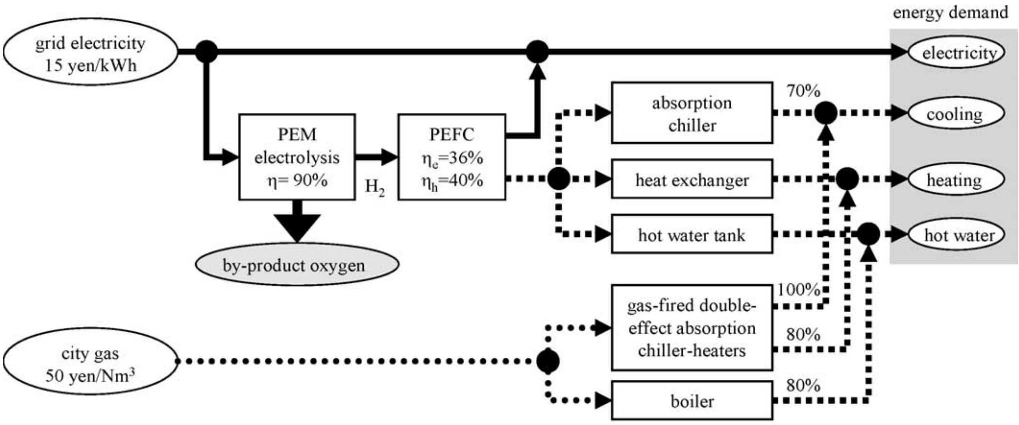
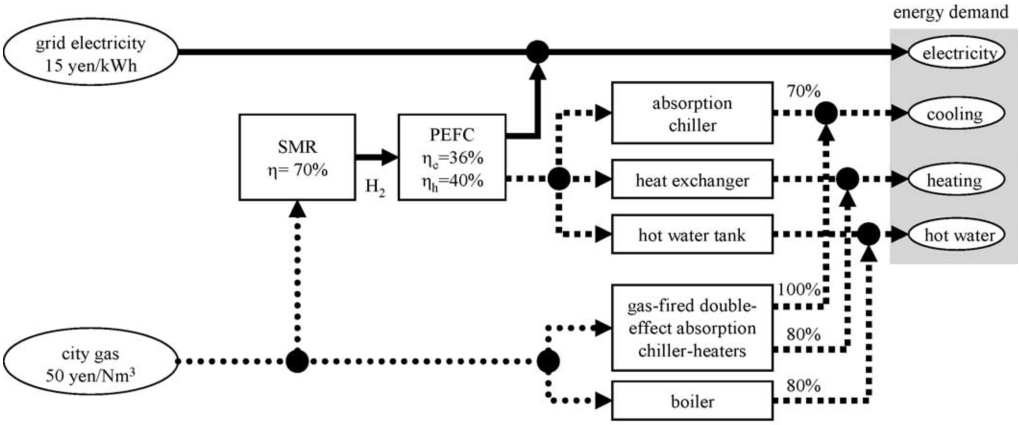


Fig. 8. Comparison between potential supply of by-product oxygen and oxygen demand.

In Fig. 8, the perpendicular axis shows the reduction of primary energy consumption per unit of oxygen use. The colored square in Fig. 8 means ‘potential oxygen demand’ times ‘primary energy reduction per unit of oxygen use’. Therefore, each colored square shows the potential of primary energy reduction by the large-scale utilization of by-product oxygen of each technology. The energy-reduction potential of utilizing oxygen in the electric-furnace sector is large, though the oxygen demand is not large. The reduction of primary-energy consumption in oxygen-blown NGCC, which is the reduction from oxygen-blown NGCC with a cryogenic air-separation system, is small compared with the other industrial processes, though there would be much potential demand. The total reduction in primary energy consumption by utilizing by-product oxygen in these three processes reaches about 89,000 TJ/yr. In addition to the oxygen demand shown in Fig. 8, there would be large quantities of oxygen demand in other processes. As a result, if by-product oxygen from water electrolysis hydrogen production is fully utilized, it could contribute to improving the energy efficiency of many industrial processes.



System A hydrogen production by PEM electrolysis



System B hydrogen production by SMR

Fig. 9. Electricity and heat-supply systems to hospital.

6. Economics of utilizing by-product oxygen for medical purposes

6.1. Evaluation model

In this study, we performed an economic assessment of utilizing by-product oxygen for medical use. Assuming two energy systems, as shown in Fig. 9, we calculated the difference in operational cost for meeting electricity and heat demand in hospitals. In both systems, electricity and heat demand are mainly met by proton exchange membrane fuel cell-co-generation system (PEFC-CGS) with utility electricity and city gas compensating for the shortfall. The only difference between the two energy systems is the hydrogen-production process, (i.e. PEM water electrolysis in system-A and SMR in system-B). The difference in operational cost between the two systems therefore corresponds to the difference in the cost of hydrogen production, including the cost of investment in PEM or SMR. Table 1 shows the assumed hydrogen cost produced by PEM and SMR [12,22] together with the retail price of utility electricity and city gas used in this study. The hydrogen production cost is assumed to be about 63 yen/Nm^3 (0.58 US\$/Nm^3) for PEM electrolysis, and 25 yen/Nm^3 (0.23 US\$/Nm^3) for SMR. The hydrogen cost of PEM is as much as 255% that of SMR. By using these hydrogen production costs, the breakeven cost of by-product oxygen is calculated to be:

$$(0.58-0.23)(\mathrm{US/Nm^3\ of\ H_2})/0.5(\mathrm{m_3\ of\ O_2/Nm_3\ of\ H_2}) = 0.7(\mathrm{US/m_3\ of\ O_2}) \qquad (1)$$

This cost is much cheaper than the actual retail price of oxygen in most hospitals in Fig. 6, although the cost of filling cylinders/tanks and shipping should be added to this cost to make it comparable with the actual cost of oxygen used in the hospitals. Therefore, if the by-product oxygen is produced somewhere else, and then transported and fully utilized in hospitals, it might offset the high cost of PEM electrolysis hydrogen production. The by-product oxygen is still wasted, however, if there is not enough demand for it. In this paper, therefore, we conducted the study on the utilization of the by-product oxygen assuming on-site hydrogen and oxygen production by PEM electrolysis in hospitals.

In system-A, we assumed that by-product oxygen is available without any additional cost, while oxygen cost is required in system-B. The oxygen cost in system-B is based on the actual price from a survey taken

Table 1
Assumption of electricity price and city gas retail price

Electricity	Variable	14.47 yen/kW h (0.13 US$/ kW h)	July–September
		13.15 yen/kW h (0.12 US$/ kW h)	Others
	Fixed	1625 yen/kW/month (15.08 US$/kW/month)	
City gas	Variable	50 yen/Nm^3 (0.46 US$/ Nm^3)	
Hydrogen	PEM	63 yen/Nm^3 (0.58 US$/ Nm^3)	Include investment cost
	SMR	25 yen/Nm^3 (0.23 US$/ Nm^3)	Include investment cost

Lifetime of hydrogen production system: 10 years for PEM and 20 years for SMR annual interest rate; and 5% for PEM and SMR.

Table 2
Assumption of electricity and heat demand in hospital

	Annual demand	Maximum demand
Electricity	170 kW h/m^2/yr	50 W/m^2
Hot water	80 Mcal/m^2/yr	40 kcal/m^2/h
Heating	74 Mcal/m^2/yr	82 kcal/m^2/h
Cooking	80 Mcal/m^2/yr	90 kcal/m^2/h

at 877 hospitals shown in Fig. 6, ranging from 60 yen/Nm^3 (0.82 US$/Nm^3) to 10,000 yen/Nm^3 (35 US$/Nm^3). In the following calculation, we focus on 160 hospitals where data on total floor space is available.

In most of the 160 hospitals, CGS is currently not installed. Therefore, to estimate the hydrogen demand for PEFC-CGS in hospitals, we surveyed the size of existing conventional-type CGSs already installed in hospitals, and examined the relationship between the size of CGS and the total floor space of the hospital. As a result, we found the size of CGS per 1 m^2 total floor space is 0.0194 kW on average. We then formulated the relationship between the capacity of CGS and the total floor space of the hospital as shown in Eq. (2)

$$\text{capacity of CGS in hospital (kW)} = 0.0194 \times \text{total floor space (m}^2\text{)} \tag{2}$$

For example, when the total floor space is 10,000 m^2, a suitable electrical capacity for the CGS would be 194 kW e. As actual demand data is not available for each of the 160 hospitals, we used the typical demand data set on electricity and heat as shown in Table 2. The maximum electricity demand in hospital is assumed to be 0.05 kW/m^2. Considering the capacity of PEFC-CGS assumed in Eq. (2), almost 40% of maximum electricity demand can be met by PEFC-CGS.

6.2. Economic assessment for utilizing by-product oxygen

Assuming the constant output operation of PEFC-CGS throughout a year, we calculated the annual hydrogen consumption and by-product oxygen supply for 160 hospitals. Fig. 10 shows the results.

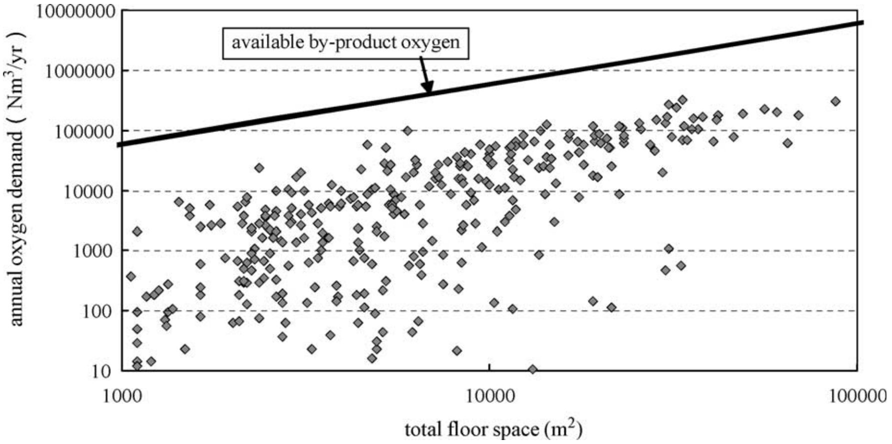


Fig. 10. Comparison between annual oxygen demand and available by-product oxygen.

Fig. 11. Comparison of hydrogen cost between system-A and -B including oxygen cost.

The by-product oxygen supply is at least 10 times larger than the actual oxygen demand. In terms of the balance of demand and supply, the use of by-product oxygen in hospitals is not a sound application. As mentioned above, however, the oxygen price for medical use is very high. Therefore, even if large quantities of by-product oxygen are wasted, its use could have some economic merit.

By comparing the actual oxygen cost and the estimated energy cost required for electricity and heat supply to hospitals, we made an economic assessment for utilizing by-product oxygen in hospitals. Fig. 11 shows the hydrogen cost in system-A relative to the total cost of hydrogen and oxygen in system-B. In this study, the hydrogen cost of PEM is assumed to be as much as 255% that of SMR. When the oxygen cost in system-B is taken into account, the cost in system-A decreases. In some hospitals, the hydrogen cost in system-A is almost the same as that in system-B, including oxygen cost. Consequently, the effective utilization of by-product oxygen in hospitals where the oxygen price is very high for safety reasons would contribute to reducing the relative cost of hydrogen produced by PEM electrolysis. It looks meaningless if only 10% of by-product oxygen is effectively used because of the assumption that all the hydrogen for PEFC is produced by electrolysis. Therefore, some hydrogen should be produced by SMR to eliminate the wasted by-product oxygen. We will examine an optimal condition regarding the capacity of PEFC-CGS and the ratios of hydrogen production by electrolysis and SMR as a next step in this work.

7. Conclusion

In this study, we discussed the potential demand for by-product oxygen and its contribution to energy saving. As there is a potential demand for large quantities of oxygen, there might be substantial potential for utilizing the by-product oxygen of electrolysis hydrogen production. If the by-product oxygen can be utilized effectively, it would contribute to the improvement of the energy efficiency of various industrial processes and electric power production, as well as the reduction of CO_2 emissions. Even if large quantities of by-product oxygen are wasted, its use in hospitals would have economic merit.

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