Effective Utilization of By-product Oxygen of Electrolysis Hydrogen Production

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Abstract

Hydrogen should be produced by renewable energy resources to avoid fossil fuel consumptions and greenhouse gas emissions. A water electrolysis using PEM is considered a promising hydrogen production method although the hydrogen cost by PEM would be very high as compared with the other mature technologies such as steam methane reforming (SMR). We focus on the effective utilization of by-product oxygen of electrolysis hydrogen production. In this study, we discuss the potential demand of by-product oxygen and evaluate the contribution of by-product oxygen for improving process efficiency. In terms of economy, taking into account the utilization of by-product oxygen for a medical use, we compare the hydrogen production cost between PEM electrolysis and SMR.

1. Introduction

Hydrogen is one of the most promising energy carriers for future energy system and 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 fuel cell power generation system. Hydrogen used as main energy carrier could offer an answer to the threat of global climate change and avoid undesirable factors associated with the use of fossil fuels. Although it is estimated that hydrogen is more expensive than fossil fuels, hydrogen made from renewable energy resources is a virtually inexhaustible, environmentally benign energy resources that could meet most of our future energy needs and avoid the cost for environment and health problems associated with fossil fuels.

Hydrogen is a long term option. The production, storage and distribution facilities must be improved and developed. In the short run, hydrogen will be produced from fossil fuels such as natural gas by steam methane reforming (SMR), existing very mature technology. In the long run, however, hydrogen must be produced by renewable energy resources to avoid fossil fuel consumptions and greenhouse gas emissions. In other words, hydrogen has a considerable potential to overcome the limitation of intermittent renewable energy resources and can therefore benefit the development of them. For example, a water electrolysis by proton exchange membrane (PEM) is considered a promising method to produce hydrogen by renewable energy resources, such as wind, photovoltaic, etc., due to the high efficiency. Currently, even in case of well-established alkaline water electrolysis, the hydrogen production cost by electrolysis is high in comparison to fossil fueled hydrogen production technologies such as SMR because of the high investment cost and the high electricity cost. However, technological improvements in both electrolysis technologies and electricity production technologies from renewable energy resources could make the production of hydrogen by electrolysis very attractive for the future.

When hydrogen is produced by water electrolysis process, half the number of moles of oxygen is produced simultaneously as a by-product of hydrogen. If large quantities of hydrogen are required to be produced from renewable resources by electrolysis process, by-product oxygen also will be produced in large scale. In such the situation, by-product oxygen should be fully utilized, because oxygen is an important industrial gas utilized in many processes such as combustion, semiconductor production, wastewater treatment, etc. The effective utilization of oxygen would improve energy efficiency of some industrial processes [1]. While by-product oxygen in 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 simultaneous utilization of hydrogen and by-product oxygen. For example, 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 furnace and glass melting as well as for treatment of municipal solid waste (MSW) and wastewater. In addition, the utilization of by-product oxygen could contribute to reduce the large amount of electricity consumed in the oxygen production by air separation technologies, such as cryogenic air separation and pressure swing absorption (PSA). In order to fully utilize by-product oxygen, the balance between by-product oxygen and oxygen demand is very important. If the oxygen demand is not so large relative to the potential supply of by-product oxygen by water electrolysis hydrogen production, large quantities of by-product oxygen must be wasted.

In this study, we discuss the potential demand of by-product oxygen and its contribution to energy saving. First we show the brief introduction of oxygen production technologies and hydrogen production technologies. Second, we show the current and future oxygen demand and the potential of energy efficiency improvement by utilizing by-product oxygen in industry. Then we compare the oxygen demand with potential supply of by-product oxygen of hydrogen production by electrolysis. Finally, we evaluate the economy for utilizing by-product oxygen for medical use.

2. Oxygen Production Technologies

An air separation unit using a conventional, multi-column 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 kWh/Nm^3-O_2. Oxygen purity of cryogenic process can be higher than 99 vol. %. Because of high purity requirement, the oxygen for medical use is normally produced by cryogenic process. Neither technology excepting electrolysis is expected to challenge cryogenic air separation for large quantities production of oxygen especially at high purity. In Japan, oxygen demand was $9{,}615\times10^6$ Nm^3 in 2001 [2, 3], and is produced mainly by cryogenic process. Because cryogenic air separation consists of five major processes, i.e. air compression, air pre-treatment, heat exchange, cryogenic separation and oxygen compression, it is utilized for large scale production larger than 8,000 Nm^3/h, and is not suitable for a small scale on-site oxygen production.

Adsorption process is based on the ability of some natural and synthetic materials such as zeolites to preferentially adsorb nitrogen. The regeneration of 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. Oxygen purity of adsorption process is typically 93 – 95 vol.%. The required energy in adsorption process is also about 0.5 kWh/Nm^3-O_2. Adsorption process is used for smaller application as compared to cryogenic process.

Some non-cryogenic processes, i.e. chemical air separation process, membrane process and ion transport membrane, are also available.

3. Electrolysis Hydrogen Production

Hydrogen can be produced from a variety of fossil and non-fossil resources through energy use 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, thermo-chemical water decomposition, and photo-chemical, -electrochemical and - biological 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 to produce large quantities of hydrogen. Currently, about 99% of world hydrogen is produced from fossil fuels, primarily natural gas [4]. Hydrogen production efficiencies of SMR with the capacity of over one million Nm^3-H_2/day are in the range of 63 to 85 % (based on higher heating value (HHV) of hydrogen) and the investment costs range from 270 to 500 US$/kW [5-8]. In the capacity of over one million Nm^3-H_2/day, SMR technology has the least-expensive investment cost in comparison to other fossil fueled hydrogen production methods. This process also produces carbon dioxide, one of the main greenhouse gases, which is unwanted. In order to obtain pure hydrogen, purification steps in the downstream of the SMR plant are necessary to remove undesired compounds (carbon dioxide, etc.).

Water electrolysis is also well-established technology and the most widely used method for 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 and its efficiencies are around 70 to 80 % (HHV). Alkaline water electrolysis is striving to pursue higher efficiency by increasing operating temperature or electrolyzing under pressurized circumstances. The current investment cost of an alkaline electrolysis is approximately 500 US$/kW [5, 7, 9, 10]. The investment cost of alkaline electrolysis hydrogen production is higher than that of SMR, though the efficiency is comparable with SMR. PEM is used as electrolyte instead of alkaline aqueous solutions, and is considered a promising method due to the extreme volume reduction. Currently, the investment cost for PEM electrolysis is over 1,000 US$/kW [10, 11], and 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. Because of cost reasons, electrolysis is used mainly in small plant.

Renewable energy resources, e.g. wind, photovoltaic (PV), solar thermal and hydropower, are all efficient resources of the electricity required for water electrolysis. Although the hydrogen produced by renewable resources based electricity is very expensive in most cases, it is attractive because of very pure and clean energy carrier. In the long run, however, hydrogen should be produced by renewable energy resources to avoid fossil fuel consumptions 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 water electrolysis process in a future, by-product oxygen also will be produced in large scale. When DC electricity is passed between 2 electrodes (anodes 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:

* Anode : $2\ H_2O \text{--->} O_2 + 4\ H^+ + 4\ e^-$
* Cathode : $4\ H^+ + 4\ e^- \text{--->} 2H_2$
* Global reaction : $2\ H_2O \text{--->} 2\ H_2 + O_2$

For example, when the electrolysis efficiency is 71 %, the electricity of 5,000 kWh would produce hydrogen of 1,000 Nm^3 of and oxygen of 500 Nm^3. Because the electricity of 250 kWh is required to 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 4,750 kWh on electrolysis, raising the electrolysis efficiency to 76 %.

While by-product oxygen can be harmlessly vented, it seems more prudent to explore its possible large-scale utilization. In this case, the balance between by-product oxygen and oxygen demand is very important. If the oxygen demand is not so large relative to the possible supply of by-product oxygen in hydrogen production by water electrolysis, large quantities of by-product oxygen must be wasted. In this study, therefore, we discuss the potential demand of oxygen on the basis of the survey of both current oxygen demand and new technologies utilizing oxygen for improving energy efficiency.

4. Oxygen Demand

Fig. 2 shows the oxygen demand in Japan. The total oxygen demand was about $9{,}615\times10^6\ Nm^3$ in 2001. There are some new applications utilizing oxygen for improving energy efficiency of industrial processes. Followings are details of oxygen demand in some industrial processes.

4.1 Blast Furnace

A blast furnace process involved in steelmaking process is the largest oxygen consumer in industry. In the latest blast furnace process, oxygen is highly utilized to improve the productivity. In Japan, blast furnace consumed oxygen of $8{,}037\times10^6$ Nm^3 in 2001, corresponding to 84 % of the total oxygen demand. Oxygen for blast furnace is normally produced on site, because of the large oxygen demand. Normally cryogenic air separation process is utilized. In Japan, almost 70 % of cryogenic air separation is used for supplying oxygen to blast furnace, but 75 % of these systems were built before 1980. Therefore, the existing system will be replaced with new oxygen production system in the near future. At that time, if hydrogen demand for FCVs is large enough and some portion of hydrogen is produced by renewable electricity, electrolysis hydrogen production system can be a good alternative, which supplies hydrogen and by-product oxygen to FCVs and blast furnace, respectively.

4.2 Electric arc Furnace

Electric arc furnace is the largest consumer of oxygen on market place, because large quantities of oxygen used in blast furnace are produced and consumed on site. In 2001, the oxygen demand for electric arc furnace was about 888×10^6 Nm^3, corresponding to 9.2 % of the total oxygen demand in Japan. Adsorption process for producing oxygen is mainly utilized. In 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 was about 380 kWh/t-billet, where 33 Nm^3/t-billet of oxygen was consumed. Recently, the innovative electric furnace developed by NKK, Japan, improves heat efficiency remarkably [12]. The newly developed electric arc furnace process is a fully closed melting shaft furnace, into which scrap is continuously charged from the top of the shaft portion. As scrap falls to the furnace portion, it mixes with molten steel and is melted rapidly. Due to this furnace structure, which enables scrap to be fed into molten steel without interval, heat loss on water-cooled panels and fingers is effectively prevented, thereby maintaining scrap-preheating temperature at around 1,000°C, which results in lower consumption of electricity. In the new electric arc furnace, the consumption of electricity is only 150 kWh/ton-billet with oxygen consumption of 45 Nm^3/ton-billlet. The reduction of electricity consumption per unit oxygen use is 19 kWh/Nm^3-O_2, which corresponds to the reduction of primary energy of 182 MJ/Nm^3-O_2 in the case that the efficiency of electric power generation (η_e) is 38 %.

In Japan, annually 29×10^6 ton of steel is produced by electric arc furnace in 2002. If all existing electric arc furnace is replaced with newly developed electric arc furnace, electricity of 6,634 GWh/yr (or 62,849 TJ/yr with η_e=38%) would be reduced, while additional oxygen of 346×10^6 Nm^3/yr is required, increasing total oxygen demand for electric arc furnace to some $1{,}300\times10^6$ 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 typically account for some 40% of the total heat input, improving efficiency can lead to significant reductions in energy consumption. In a conventional air-blown combustion melting process, energy requirement is approximately 11 MJ/kg-glass [13]. Overall efficiency can be improved by rebuilding the furnace to incorporate a number of energy saving features, i.e. electric boost and supplementary oxygen-blown combustion. Fig. 3 shows the comparison of energy consumption, NO_x emission and CO_2 emission between conventional air-blown combustion furnace and new oxygen-blown combustion furnace. By utilizing oxygen, the energy efficiency can be improved by 40 %. NO_x and CO_2 emissions also can be reduced remarkably. In the oxygen combustion furnace, the ideal oxygen requirement is about 0.3 Nm^3/kg-glass. Taking into account the energy consumption per unit production shown in Fig. 3, the reduction of primary consumption per unit oxygen use is 16 MJ/Nm^3-O_2.

Because of cost reasons, oxygen-blown combustion furnace is not used so much except electric glass production where the price of glass product is relatively high compared to the other glass products. Therefore, if fossil fuel price increases, the shift to the oxygen combustion furnace would be accelerated. In Japan, the annual production of glass product including sheet glass, glass fiber wool products, glass fiber continuous textiles, glass foundation products and glass containers was approximately 4.4×10^6 ton-glass in the last 3 years. If these glass products are produced by oxygen-blown combustion furnace, the estimated oxygen requirement is approximately $1,313\times10^6$ Nm^3/yr. This would reduce the annual energy consumption of glass melting process by 20,951 TJ/yr.

4.4 Electric Power Plant

An electric power plant has a potential to be one of the largest consumer of by-product oxygen. We have proposed a new concept of power generation system with pure oxygen-blown natural gas combined cycle (NGCC). Fig. 4 shows the schematic flow diagram of our proposed system. In our proposed system, 85 % of exhaust is recycled as a working medium of gas turbine. One of the most important features of our proposed system is the component of exhaust, consisting of only CO_2, H_2O and O_2. After the condensation of H_2O, CO_2 can be easily captured without the CO_2 separation unit. This feature could be advantage over a conventional NGCC with air-blown combustion, the cheapest option for electricity production. At present, electric power plants with CO_2 capture unit draw widespread attention as an environmental benign electric power plant. Although the capital cost of conventional NGCC is lower than that of power plants using other fossil fuel, the capital cost including CO_2 capture unit is estimated to be about 1,000 \$/kW, 2 to 3 times higher than that without CO_2 capture [14-17]. The total thermal efficiency is around 45 % instead of 53 % of conventional NGCC without CO_2 capture, because CO_2 separation from flue gas requires large power. Because our proposed system does not need to have CO_2 separation unit, our proposed system could be a cost effective option as a CO_2 capture power plant fueled with natural gas. The economic assessment on our proposed system is not performed in this paper, but will be done 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 the electricity of 400 MW at sending-end. If this system is operated with the load factor (LF) of 80 %, the annual oxygen requirement is 1,273×10^6 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 used 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, i.e. municipal solid waste (MSW). If the syngas is to be used 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 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 partial combustion process, air is used. Although air gasification itself is relatively cheap, downstream gas cleaning is expensive due to the large volumes 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 for using oxygen.

Based on the survey of gasification plant, there are 163 commercial gasification projects consisting of a total of 468 gasifiers [18]. 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 municipal solid waste (MSW) [19]. The requirement of oxygen depends on the feedstock to be gasified. For example, api Energia integrated gasification combined cycle (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 sulphur heavy oil produced by the Falconara refinery, and convert it to syngas and use the gas to generate 280 MW of electricity, plus steam and other gases for use in the refinery [20]. When this plant is operated with the annual load factor 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 to a sort of medicinal supplies, it is produced and delivered within a highly controlled environment. Therefore pure and clean oxygen produced by electrolysis is suitable for medical use. The oxygen demand for medical use was about 105×10^6 Nm^3 in 2001, which is only 1.1 % of total oxygen demand including the oxygen produced on site. With the exception of on site produced oxygen in blast furnace, however, the oxygen for medical use is the third largest demand in Japan. Utilizing oxygen for medical use is not related to the improvement of energy system. However, because of very high price of medical oxygen, effective utilization of by-product 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 (82 UScent/Nm^3) to 10,000 yen/Nm^3 (35 US$/Nm^3). These prices almost correspond to fuel price on Nm^3 basis.

In the latter section, we discuss the economy for using by-product of electrolysis hydrogen production for medical use based on the survey of oxygen demand and price in hospitals.

5. Possibility for consuming by-product oxygen

Hydrogen demand in Japan is estimated to be approximately 15,000 - 20,000×10^6 Nm^3/yr. However, because most of hydrogen is produced and consumed on site such as chemical plant and steel plant, the hydrogen demand on the market place is only about 150×10^6 Nm^3, less than 1 % of actual consumption. Fig. 7 shows hydrogen and oxygen demand in the last 5 years on the market place in Japan. On the market place, oxygen demand is about 9 times as much as hydrogen demand, although large quantities of oxygen are also produced and consumed on site.

In the future, there will be new hydrogen demand. Replacement of fossil fuels by hydrogen in vehicles throughout the world is postulated to occur over the next 50 years as mass production of fuel cell vehicles (FCVs) accelerates. For example, Japan’s target for installing FCVs is 50,000 vehicles in 2010 and 5,000,000 vehicles in 2020, where estimated hydrogen demand is 160×10^6 Nm^3 in 2010 and 4,250×10^6 Nm^3 in 2020, respectively [22]. In the case of Southern California, the projected hydrogen demand is 630×10^6 Nm^3 in 2020, assuming cumulative number of FCVs of 350,000 for passenger cars, 150,000 for light trucks and 330 buses [23]. Fuel cell for stationary use also will consume large quantities of hydrogen.

The new hydrogen demand must be met by additional hydrogen production system instead of existing systems. If the incremental hydrogen requirement is met by water electrolysis process, half the number of moles of oxygen is produced simultaneously as a by-product of hydrogen production. In this study, assuming that estimated hydrogen demand for vehicles use in 2020 in Japan is met by water electrolysis, we compared the amount of by-product oxygen supply and potential demand of oxygen mentioned above. When all hydrogen for vehicles use in 2020 is produced by water electrolysis, available by-product is about 2,125×10^6 Nm^3. On the other hand, the current oxygen demand is 4 times as much as the available by-product oxygen as shown in Fig. 2. In addition, as mentioned above, the potential oxygen demand is 346×10^6 Nm^3/yr in electric arc furnace and 1,313×10^6 Nm^3/yr in glass melting, where the energy efficiency would be improved by the utilization of oxygen. When oxygen-blown NGCC with the capacity of 400 MWe is installed, the annual requirement of oxygen is 1,273×10^6 Nm^3/yr (LF=80%). Fig. 8 shows the comparison between potential supply of by-product oxygen and oxygen demand. In this figure, the perpendicular axis shows the reduction of primary energy consumption per unit oxygen use and the area for each process shows the reduction of primary energy consumption. The energy reduction potential by utilizing oxygen is large in electric furnace 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 cryogenic air separation system, is small as compared to the other industrial processes though there would be much potential demand. In addition to the oxygen demand shown in Fig.8, there would be large quantities of oxygen demand in the future. As a result, by-product oxygen of water electrolysis hydrogen production would be fully utilized and could contribute to improve energy efficiency of many industrial processes.

6. Economy for utilizing by-product oxygen for medical use

6.1 Evaluation model

In this study, we performed the economic assessment for utilizing by-product oxygen for medical use. Assuming two energy systems shown in Fig. 9, we calculated the difference of operation 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) while utility electricity and city gas compensate for the shortage. The difference between two energy systems is only hydrogen production process, i.e. PEM water electrolysis in system-A and SMR in system-B. Therefore, the difference of operation cost between two systems corresponds to the difference of hydrogen production cost including the investment cost of PEM or SMR. Table 1 shows the assumed hydrogen cost produced by PEM and SMR [11,21] 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 % of SMR. 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 surveyed at 877 hospitals shown in Fig. 6, ranging from 60 yen/Nm^3 (82 UScent/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 160 hospitals, currently CGS is not installed. Therefore, in order to estimate the hydrogen demand for PEFC-CGS in hospitals, we surveyed the size of existing conventional type CGS in other hospitals, and formulated the relationship between the capacity of CGS and the total floor space of hospital as shown in eq. (1)

$$\text{capacity of CGS in hospital (kW)} = 0.0194 \times \text{total floor space (m}^2\text{)} \qquad (1)$$

For example, when the total floor space is 10,000 m^2, suitable electrical capacity of CGS would be 194kWe. Because actual demand data is not available for each 160 hospital, 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.(1), 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. 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 good application. However, as mentioned above, the oxygen price for medical use is very high. Therefore, even if the large quantities of by-product oxygen are wasted, the use of by-product oxygen would be economic merit.

By comparing the actual oxygen cost and the estimated energy cost required for electricity and heat supply to hospitals, we performed the 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 % 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 same with that in system-B including oxygen cost. Consequently, the effective utilization of by-product oxygen in hospital where the oxygen price is very high because of safety reason, would contribute to reduce the relative cost of hydrogen produced by PEM electrolysis.

7. Conclusion

In this study, we discussed the potential demand of by-product oxygen and its contribution to energy saving. Because there are the large quantities of potential oxygen demand, the by-product oxygen of electrolysis hydrogen production could be fully utilized, which would contribute to the improvement of various energy efficiency of industrial processes and electric power production, the reduction of CO_2 emission. Even if the large quantities of by-product oxygen are wasted, the use of by-product oxygen in hospital would be economic merit.

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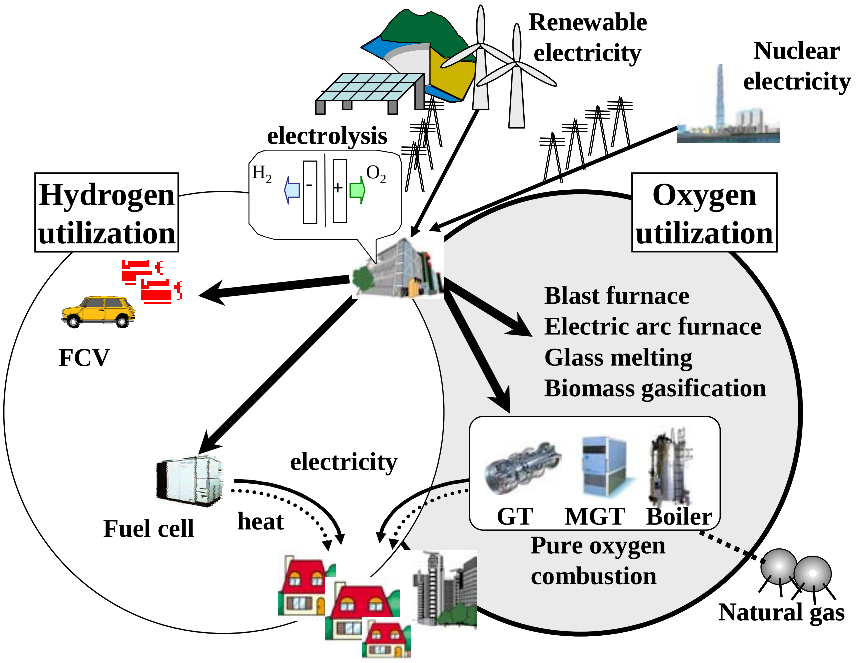


Fig.1 Conceptual diagram of simultaneous utilization of hydrogen and by-product oxygen

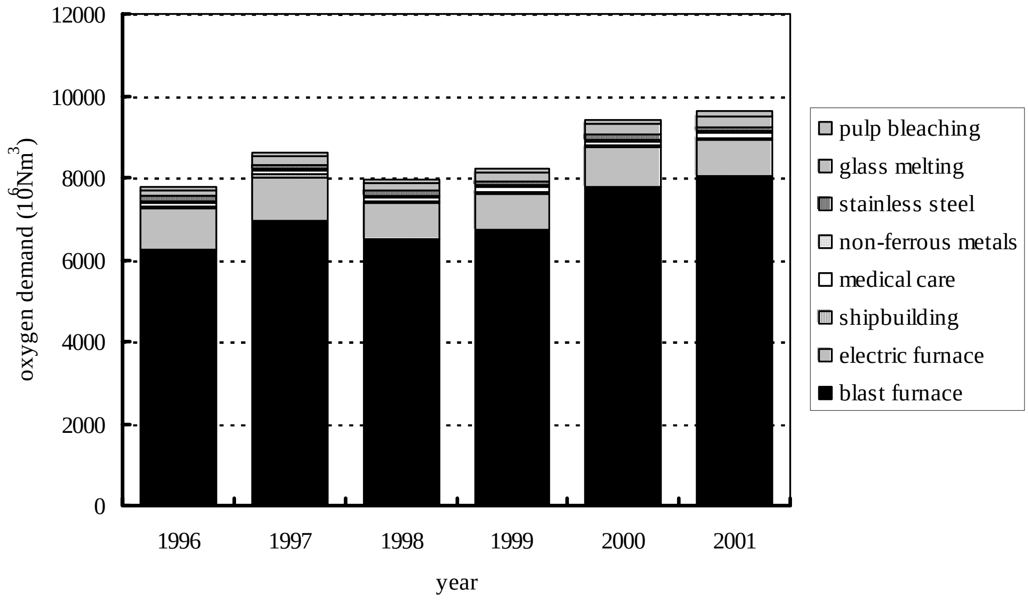
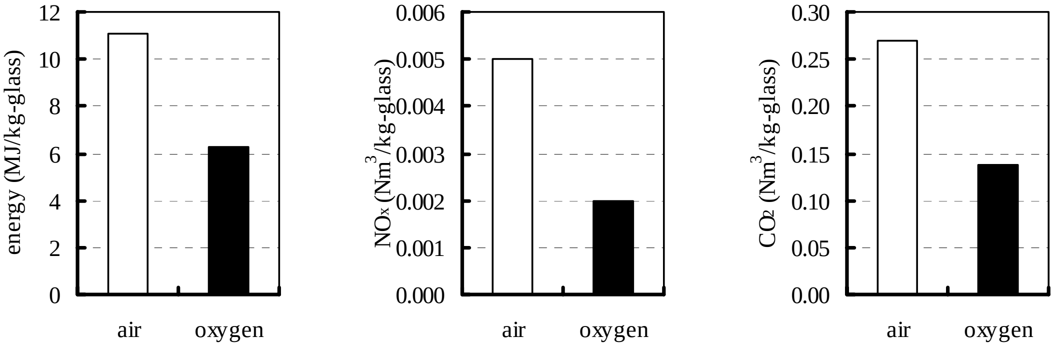


Fig.2 Oxygen demand in Japan



(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

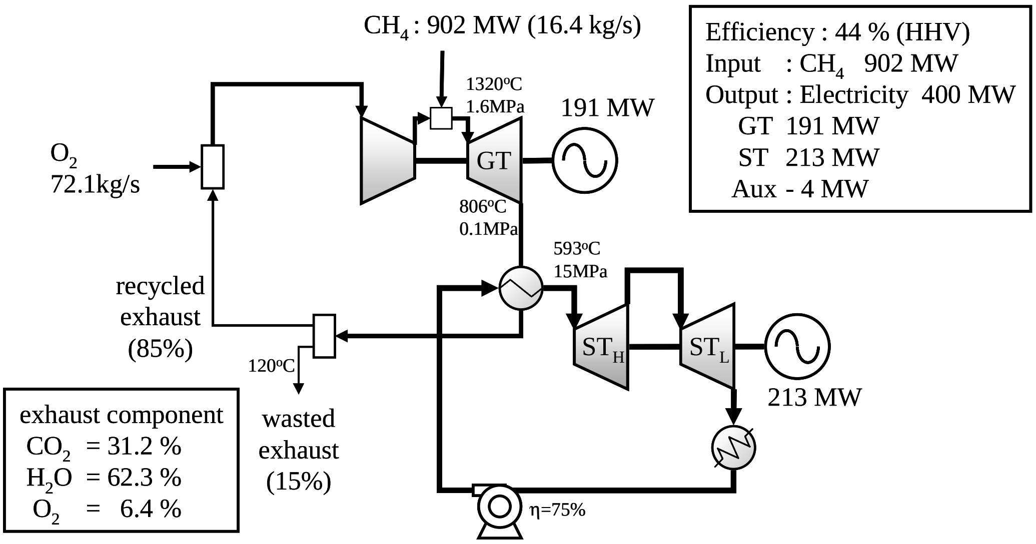


Fig. 4 Oxygen combustion natural gas combined cycle power plant

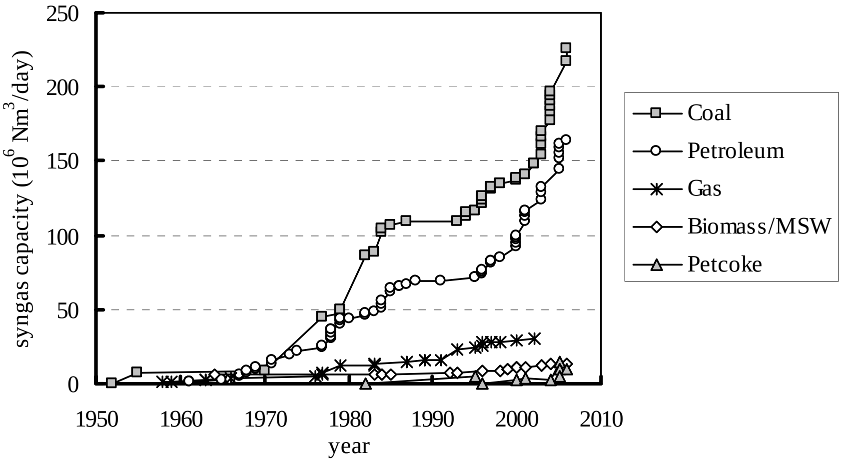


Fig. 5 Cumulative capacity of commercial gasification projects in the world

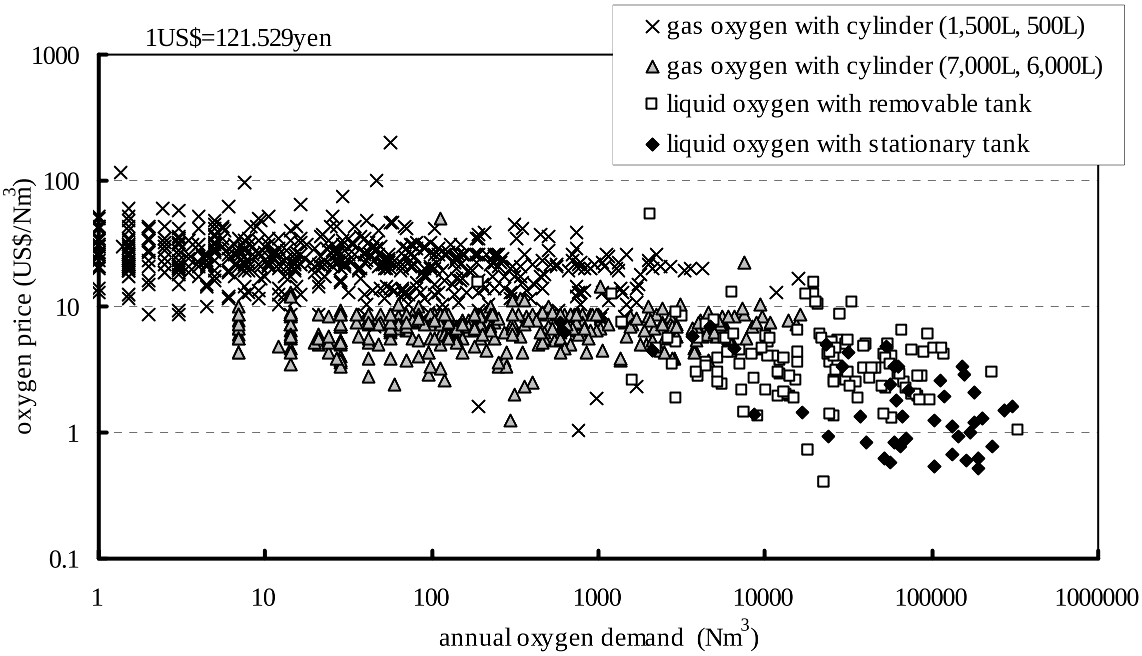


Fig. 6 Retail price of oxygen for medical use in Japan

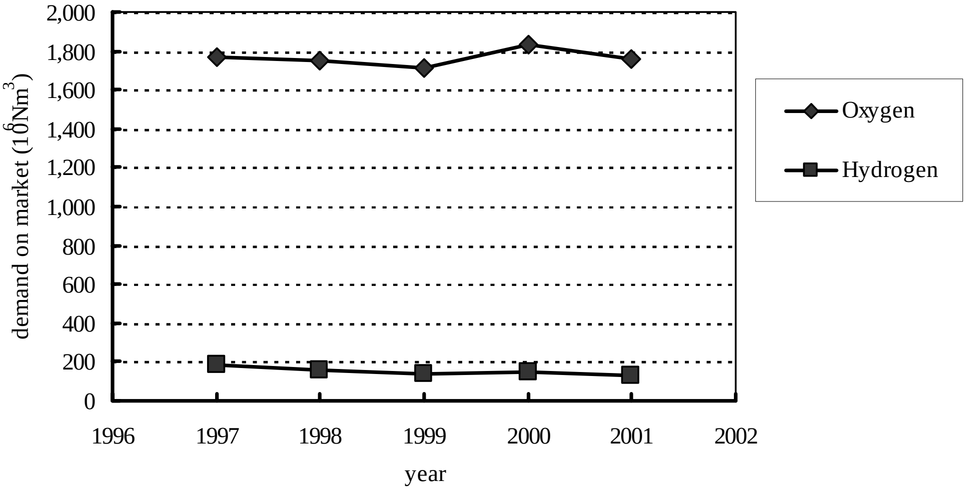


Fig.7 Hydrogen and oxygen demand on market in Japan

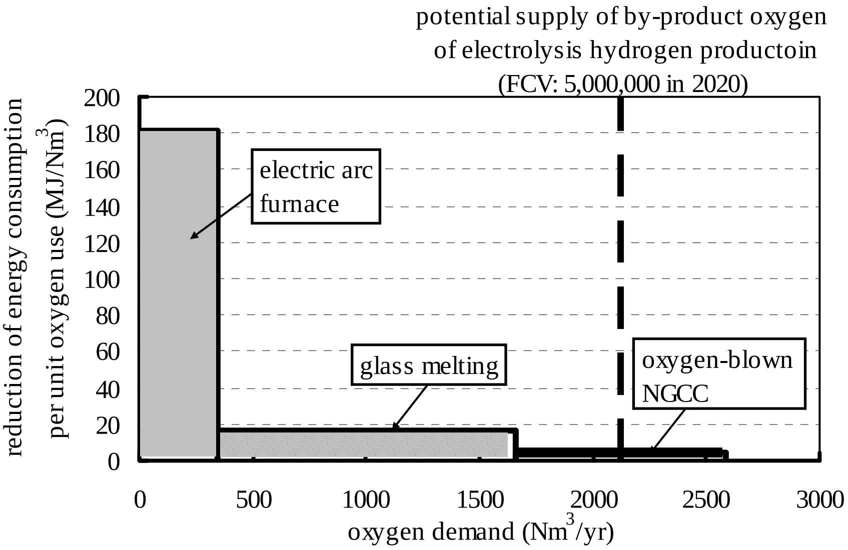
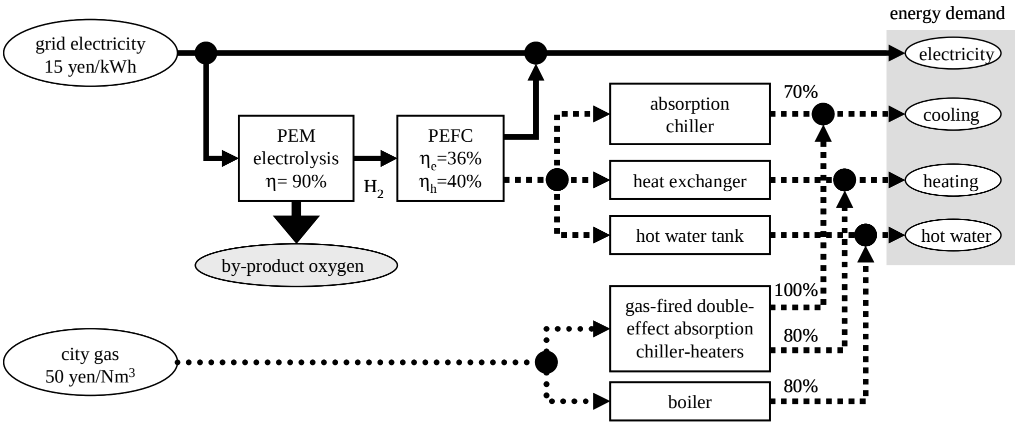
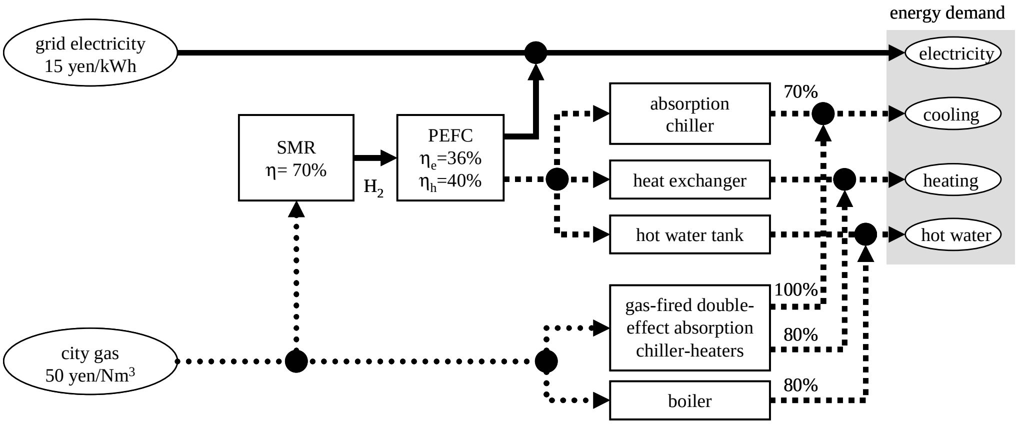


Fig. 8 Comparison between potential supply of by-product oxygen and oxygen demand



(a) hydrogen production by PEM electrolysis



(b) hydrogen production by SMR

Fig.9 Electricity and heat supply system to hospital

Table 1

Assumption of electricity price and city gas retail price

electricity	variable	14.47 yen/kWh (0.13 US$/kWh)	Jul. - Sep.
		13.15 yen/kWh (0.12 US$/kWh)	others
	fixed	1,625yen/kW/month (15.08 US$/kW/month)	
city gas	variable	50 yen/Nm^3 (0.46 US$/$Nm^3$)	
hydrogen	PEM	206 yen/Nm^3 (1.91 US$/$Nm^3$)	include investment cost
	SMR	110 yen/Nm^3 (1.02 US$/$Nm^3$)	include investment cost

Table 2
Assumption of electricity and heat demand in hospital

	annual demand		maximum demand	
electricity	170	$kWh/m^2/yr$	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	$kcal/m^2/h$

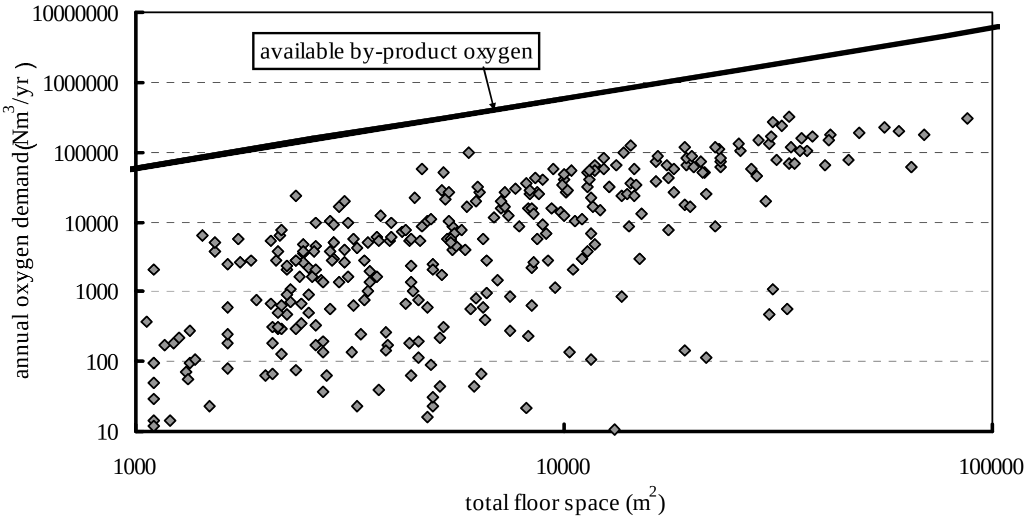


Fig.10 Comparison between annual oxygen demand and available by-product oxygen

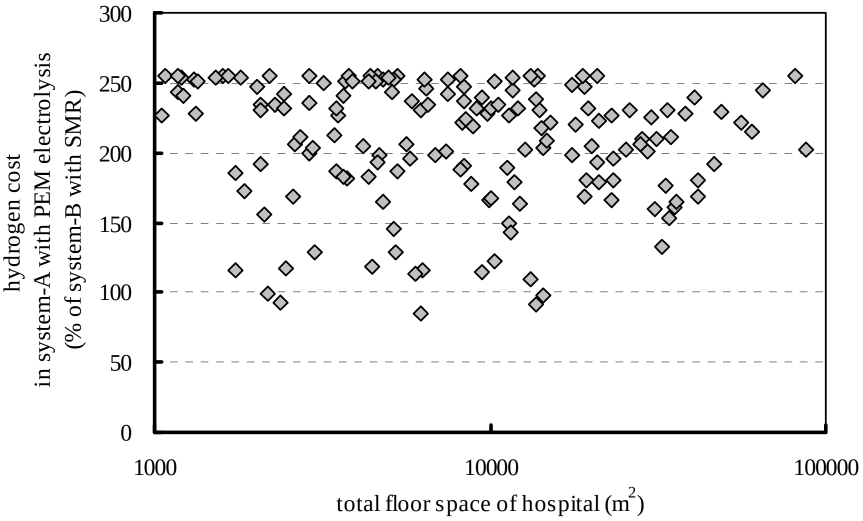


Fig.11 Comparison of hydrogen cost between system-A and system-B including oxygen cost