Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Energy 29 (2004) 1297–1308

ENERGY

www.elsevier.com/locate/energy

Time to realization: Evaluation of CO_2 capture technology R&Ds by GERT (Graphical Evaluation and Review Technique) analyses

Takanobu Kosugi [a,1,*], Ayami Hayashi [a], Tsuyoshi Matsumoto [b], Keigo Akimoto [a], Koji Tokimatsu [a], Hajime Yoshida [c], Toshimasa Tomoda [a], Yoichi Kaya [a]

[a] *Research Institute of Innovative Technology for the Earth, 9-1 Kizugawadai, Kizu-cho, Soraku-gun, Kyoto 619-0292, Japan*
[b] *Department of Applied Chemistry, Seikei University, 3-3-1 Kichijoji-Kitamachi, Musashino-shi, Tokyo 180-8633, Japan*
[c] *16th Floor, Muza Kawasaki Central Tower, 1310 Omiya-cho, Saiwai-ku, Kawasaki, Kanagawa 212-8554, Japan*

Abstract

R&D (research and development) processes of CO_2 capture technologies having different levels of energy efficiency are evaluated through GERT (Graphical Evaluation and Review Technique) analyses. Five types of the technologies are targeted for evaluation: chemical absorption, physical adsorption, membrane separation, O_2/CO_2 recirculation boiler, and integrated hydrogen separation gas turbine technologies. These technologies are decomposed into elemental technologies, and network charts are constructed which express R&D processes of the target technologies for the GERT analyses. Data on the elemental technology R&Ds are collected through a questionnaire to Japanese experts in 2001, and are used for the evaluation. The obtained results include that (1) the average expected time periods required for the completion of the target technology R&Ds are in the range of 16 and 19 years, except for a shorter R&D time of 13.8 years for the chemical absorption CO_2 capture technology having the conventional energy efficiency, (2) though the R&D success probabilities are relatively high for the chemical absorption type CO_2 capture technologies, they become lower as the energy efficiency becomes higher, which implies that the R&Ds of the capture technologies other than the chemical absorption type are also recommended for the successful completion of the capture technology which has the highest energy efficiency among the target technologies, and (3) additional R&D investments on large scale equipment such as tower, blower and pumping technologies are cost-effective for accelerating the target technology R&Ds.

---

[*] Corresponding author. Tel.: +81-75-466-3471; fax: +81-75-465-7853.
E-mail address: kosugi@sps.ritsumei.ac.jp (T. Kosugi).

[1] Currently at: College of Policy Science, Ritsumeikan University, 56-1 Toji-in Kitamachi, Kita-ku, Kyoto 603-8577, Japan

0360-5442/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2004.03.088

1. Introduction

CO_2 sequestration into aquifers, coal beds and the ocean is regarded as one of the future options of global warming mitigation and national and international efforts have been made for its development [1]. The greatest problem to solve for its practical use is the high cost of CO_2 capture, and great developmental efforts will be required to achieve lower cost CO_2 capture technologies.

The intention of this research is to provide information useful to the planning of cost effective development of lower cost capture technologies, based on a systems analysis using the GERT technique [2]. The authors successfully made a similar analysis on the development of IGCC (integrated coal gasification combined cycle) and natural gas combined cycle power generation technologies of higher thermal efficiencies [3]. The same methodology was used for this research on developmental process analysis of lower cost CO_2 capture technologies as well.

We made a wide range of investigation on CO_2 capture technologies which are expected to be developed within the next 30 years; chemical absorption, physical adsorption, membrane separation, oxygen combustion of fuel, etc. The high cost of capture technologies comes from a great amount of energy consumption in the capture processes: regeneration of chemical absorbents, vacuum pumping, oxygen production, etc. We set three kinds of target technologies for each type of the investigated capture technologies, corresponding to their energy efficiency levels. The R&D processes of the target CO_2 capture technologies were modelled as network charts consisting of elemental technologies of the target technologies and 'AND'/'OR' logics. Data on expected R&D time periods of these elemental technologies and on the effect of additional investment in elemental technology developments were collected through a questionnaire to experts [4]. The collected data were put into the network chart models and analyses were made to evaluate standard total R&D times of the CO_2 capture technologies, reductions in the total R&D times caused by additional R&D investments in the elemental technologies, etc.

2. Evaluated technologies

The following five types of CO_2 capture technologies were chosen as the target technologies and evaluated in this paper: chemical absorption, physical adsorption, membrane separation, O_2/CO_2 recirculation boiler, and integrated hydrogen separation gas turbine technologies. Each of them was decomposed into elemental technologies [4]. All the technologies were presumed to be used for commercial plants having a large unit capacity of 1×10^5 Nm^3-CO_2-captured/h (equivalent to about 5 kt-CO_2/d),[2] a practically sufficient durability and an economically acceptable cost.

Table 1 shows the target CO_2 capture technologies and their energy efficiencies. According to our literature survey, we assumed three levels of energy efficiency for each type of capture technology; 'conventional', 'energy saving' and 'advanced energy saving', except for the integrated

---

[2] The largest scale CO_2 capture plant produced by a Japanese company has been commercially operated in Malaysia since 1999; its unit capacity of CO_2 capture is 3.4×10^3 Nm^3/h (approximately 160 t/d) [5]. A large scale plant of about 1×10^5 Nm^3/h-unit capacity has never been verified though some trial designs of such a plant have been made [6,7].

Table 1
Evaluated CO_2 capture technologies and their energy efficiencies

Type	Conventional	Energy saving	Advanced energy saving
Chemical absorption	0.37 (0.21)[a] [90]	0.31 (0.15)[a] [90]	0.27 (0.11)[a] [90]
Physical adsorption	0.40 (0.24) [90]	0.35 (0.19) [90]	0.31 (0.15) [90]
Membrane separation	0.39[b] [60]	0.34[b] [60]	0.27[b] [60]
O_2/CO_2 recirculation boiler	0.33 (0.15) [90]	0.31 (0.13) [90]	0.29 (0.11) [90]
Type	LNG-fueled	Coal-fueled (IGCC)	
Integrated H_2 separation gas turbine	51% [95]	40% [95]	

For each type of chemical absorption, physical adsorption, membrane separation and O_2/CO_2 recirculation boiler technologies, the indicated energy efficiency is calculated from a decrease in net power output which is caused by the application of the CO_2 capture technology to the reference coal-fired thermal plant, expressed in kWh_e per kilogram of liquefied CO_2 captured. The reference plant is assumed to have desulfurization and de-NO_X equipment.
Figures in parentheses are the efficiencies of CO_2 separation without liquefaction.
For integrated hydrogen separation gas turbine technologies, the indicated are net power generation efficiencies on higher heating value basis.
Figures in brackets indicate CO_2 recovery factors.
All the technologies are presumed to be used for commercial plants which have a unit capacity of 1×10^5 Nm^3-CO_2-captured/h (equivalent to about 5 kt-CO_2/d), a practically sufficient durability and an economically acceptable cost.

[a] Assuming an integrated chemical absorption system where the heat energy for regenerating a chemical absorbent is supplied by low pressure steam extracted from steam turbine [8,9].

[b] Assuming CO_2 liquefaction after one-stage membrane separation [10].

hydrogen separation gas turbine technology as shown below. Note that we cannot compare the CO_2 capture technologies based simply on these figures since the energy efficiencies of these technologies widely vary depending on the kind of their application plants. A major reason for this is that the efficiency dependence on the CO_2 concentration of the flue gas to be processed is different among the technologies.

2.1. Chemical absorption technology

In this technology, CO_2 is captured from the flue gas of power plants by using a chemical absorbent such as amine solutions. Heat energy is consumed to regenerate the chemical absorbent so that the net power output of the plant is reduced. When a pilot plant of chemical CO_2 capture from a conventional COM (coal-oil-mixture)-fired plant was constructed in the 1990s, the power plant output loss was 27% [11], which is equivalent to the power reduction of 0.40 kWh per kilogram of CO_2 separated without liquefaction. This power loss will be minimized in an integrated chemical absorption system where the regeneration heat energy is supplied by low pressure steam extracted from a steam turbine [8,9].

Low regeneration energy solvents, a large scale absorption/regeneration tower and a blower were considered as the elemental technologies to be developed for the commercial chemical absorption technologies. Three regeneration energy levels were assumed with respect to the absorbents corresponding to the capture energies of 0.37, 0.31 and 0.27 kWh/kg-CO_2, which values include CO_2 liquefaction energy of 0.16 kWh/kg-CO_2, when the technologies were adopted for coal-fired power plants.

2.2. Physical adsorption technology

This technology is to capture CO_2 from a boiler exhaust gas by using the PSA (pressure swing adsorption) or PTSA (pressure and temperature swing adsorption) method. Though the output power reduction due to CO_2 separation was 0.52 kWh/kg-CO_2 in a physical adsorption pilot plant (volume of processed gas = 1000 Nm^3/h) equipped in a COM-fired power plant [11], it will be lowered thanks to efficiency improvements of the vacuum pump and blower by scaling up.

The elemental technologies necessary to achieve the physical adsorption technologies were considered CO_2 adsorbents, large scale valves for the adsorption tower, vacuum pump and blower. The three levels of the physical adsorbent performance were assumed corresponding to the energy consumptions in CO_2 capture and liquefaction of 0.40, 0.35 and 0.31 kWh/kg-CO_2 attained in coal-fired power plants.

2.3. Membrane separation technology

This technology has been expected to attain a high efficiency CO_2 capture from the exhaust gas of a power plant. The elemental technologies of the membrane separation technologies include various kinds of CO_2 separation membrane and the vacuum pump applicable to the physical adsorption technology. Each membrane technology was decomposed into membrane material technologies and the technologies of membrane formation and assembling the membranes into modules. The membranes are made of polymer or inorganic type materials; both types of the membranes can be optionally hybridized with the permeation of carrier solution behaving as a chemical absorbent to enhance CO_2 separation performance [12].

Three CO_2/N_2 separation factor levels of 35, 100 and 1000 were targeted for the membrane technologies, corresponding to the assumed capture energies of 0.39, 0.34 and 0.27 kWh/kg-CO_2 (liquefied) when the technologies were applied for coal-fired power plants [10].

2.4. O_2/CO_2 recirculation boiler technology

A power plant adopting this type of CO_2 capturing technology utilizes oxygen and circulated flue gas as oxidant to burn fuel [13]. CO_2 gas can be directly captured since the flue gas consists of only CO_2 and steam. This power plant needs no de-NO_X equipment. To realize this technology, elemental technologies of air separation to generate oxygen and O_2/CO_2 combustion boiler should be developed. We considered two oxygen production technologies based on cryogenic separation and physical adsorption methods. The oxygen production energies were assumed to be 0.34 and 0.31 kWh/Nm^3-O_2 for the cryogenic separation method, 0.31 and 0.28 kWh/Nm^3-O_2 for the physical adsorption method. The mechanical elemental technologies such as vacuum pumping required for developing the physical adsorption method were considered the same as those required for the physical CO_2 adsorption technologies.

A similar CO_2 capture technology that utilizes a high temperature gas turbine of oxygen combustion is also known [14]. This gas turbine technology has already been evaluated in our other paper [3] as a NO_X control technology.

2.5. Integrated hydrogen separation gas turbine technology

This technology has been proposed to provide a new power generation system, and named a ‘hydrogen decomposed gas turbine’ system by a group in Japan [15,16], where innovative hydrogen separation membranes are incorporated. There are two types of system depending on the fuel to be burned: LNG (liquefied natural gas) or coal.

When LNG is used as fuel, the natural gas is reformed and the hydrogen is separated simultaneously from the reformed gas at a temperature of approximately 500 °C by using membrane reformers that incorporate both reforming catalysts and hydrogen separation membranes [15]. The residual gas including CH_4 and CO is combusted at the after-burner with pure oxygen so that high concentration CO_2 is captured directly.

For the system using coal as fuel, the ‘hydrogen decomposed IGCC’ is proposed which consists of the oxygen blown coal gasification equipment, the gas separation equipment and the combined cycle power generation equipment [16]. The gasified coal is cleaned up and is controlled to contain H_2 and CO_2 by a shift conversion process, and the H_2 is separated through membranes. The permeated H_2 gas is supplied to the gas turbine, and the residual CO_2 gas is captured.

According to Moritsuka et al. [15,16], these systems are estimated to have high net thermal efficiencies of 51 and 40%, respectively, for the LNG-fueled system and the coal-fueled system, on the higher heating value basis. Since these systems apply high temperature hydrogen separation membranes, ceramic and metallic membranes were considered as the elemental technologies.

3. Evaluation by GERT analyses

The target CO_2 capture technologies were decomposed into elemental technologies, and network charts were constructed to express the R&D processes for evaluating by GERT analyses. GERT is a systems analysis technique for project management whose function is extended from PERT (Program Evaluation and Review Technique) [2].

We collected data on R&D periods for the elemental technologies through a questionnaire to Japanese experts in November 2001 [4]. In the questionnaire, we asked the experts to identify the standard[3] expected R&D time period, and the reduction in the R&D time they expected to be caused by an additional investment of 1 billion yen, for each elemental technology. The affiliations of the experts were manufacturing companies, energy utility companies and universities, etc. Answers arrived from 43 out of 56 experts.

The collected data were processed statistically. Since the standard expected R&D times were different among respondents, the R&D times were treated as probabilistic distributions. The success probability of a target technology R&D was calculated regarding the R&D as a failure in case the expected R&D time of any one of the elemental technologies was longer than 15 years. By using the data, GERT analyses were made stochastically regarding the standard total

---

[3] We notified the experts that ‘standard’ means no unexpected change in the circumstances or in the society in general.

R&D time and the R&D time reduction due to the additional investment in a similar way to our previous study [3] which evaluated R&D processes of advanced combined cycle power generation technologies.

4. Results

4.1. Total R&D time

Fig. 1 shows the calculated success probabilities and probability distributions of the standard total R&D times required for accomplishing the developments of the target CO_2 capture technologies.

For each CO_2 capture technology, the estimated success probability of the 'conventional' type is the highest followed by those of 'energy saving' and 'advanced energy saving' types. In general, the differences in the probability are only less than 0.1 between 'conventional' and 'energy saving' types, which are relatively small compared to those between 'energy saving' and 'advanced energy saving' types. This implies that the technology gap is much wider between 'energy saving' and 'advanced energy saving' types than between 'conventional' and 'energy saving' types. The only exception is the membrane separation technology whose success probability greatly deteriorates as the efficiency becomes higher. A reason for the very low success probability of 0.29 for the 'advanced energy saving' type membrane separation technology is considered because the R&D of this technology is almost unforeseeable since it needs some breakthroughs. The success probability is comparatively low for the integrated hydrogen separation gas turbine technology whose development requires several innovative elemental technologies such as high temperature hydrogen separation membranes.

The estimated standard total R&D time for each CO_2 capture technology is the shortest for the'conventional' type, and becomes longer as the energy efficiency becomes higher. The average total R&D times of all the technologies are, however, close in the range of approximately 16–19 years, except for a shorter R&D time of 13.8 years for the 'conventional' type of chemical absorption technologies.

CO_2 capture plants based on the chemical absorption method have been widely operated on a small scale and their capacities are expected to be expanded relatively easily compared to those of other capture technologies. However, a compact plant design is required for the large capacity commercial plant to achieve an economically acceptable installation cost by means of developing very large scale absorption and regeneration towers. The estimated R&D times imply that the development of such large scale tower technologies will take longer than about 10 years according to the expert answers.

4.2. Reduction in total R&D time by additional investment

Fig. 2 shows the reductions in total R&D time of the target technologies by a reduction in R&D time and also by an additional investment (1 billion yen) calculated for each elemental technology. For the details of the calculation method, see Hayashi et al. [3]. Also shown is the standard expected R&D time of each elemental technology based on the questionnaire [4].

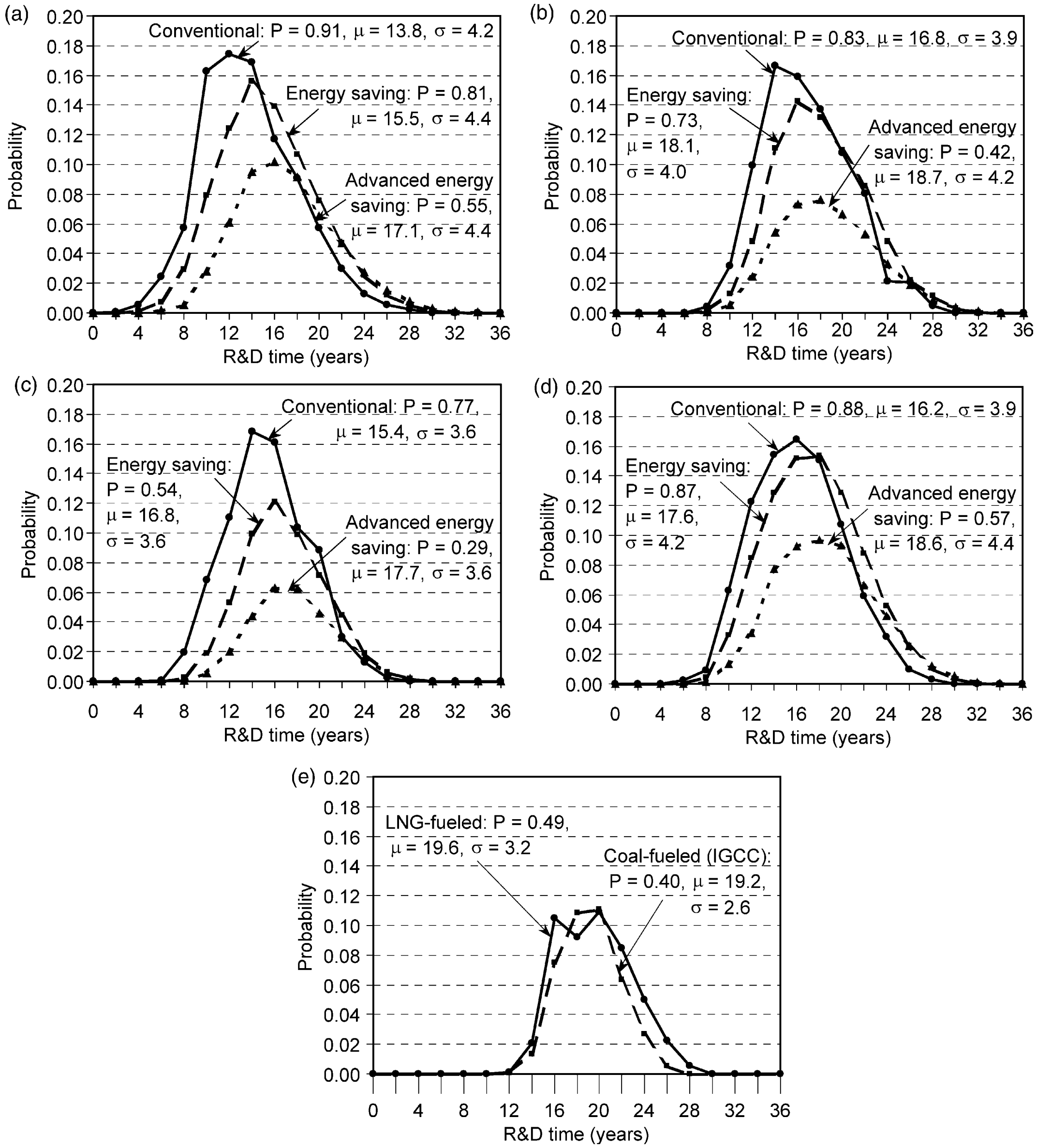

Fig. 1. Estimated success probabilities and the probability distributions of standard total R&D times of CO_2 capture technologies. (a) Chemical absorption, (b) Physical adsorption, (c) Membrane separation, (d) O_2/CO_2 recirculation boiler, (e) Integrated H_2 separation gas turbine. (P: success probability, μ: average total R&D time (year), σ: standard deviation of R&D time (year).)

For each type of target technology, Fig. 2 lists the elemental technologies which have relatively large effects of the additional investment on reduction in the total R&D time. The tendencies of the two kinds of effects are similar but it should be noted that the two are different and

(a)

Type of target technology	Elemental technology to be developed	Reduction in R&D time of target technology		Standard R&D time (year)
		By reduction in R&D time of elemental technology (year / year)	By additional investment (year / 1 billion yen)	
Conven-tional	Absorption/regeneration tower	0.37	0.66	5.8 [1.00]
	Blower for fixed pressure operation (efficiency = 75%)	0.34	0.48	5.1 [1.00]
	Absorbent with conventional regeneration heat energy [a]	0.12	0.12	3.8 [0.94]
Energy saving	Absorption/regeneration tower	0.34	0.61	5.8 [1.00]
	Blower for fixed pressure operation (efficiency = 75%)	0.31	0.44	5.1 [1.00]
	Absorbent – energy saving type [b]	0.14	0.19	6.1 [0.93]
Advanced energy saving	Absorption/regeneration tower	0.29	0.52	5.8 [1.00]
	Absorbent – advanced energy saving type [c]	0.18	0.39	9.2 [0.69]
	Blower for fixed pressure operation (efficiency = 75%)	0.26	0.36	5.1 [1.00]

[a] An example regeneration heat is 3.5 MJ/kg-CO_2 supplied by low pressure steam of 140 °C extracted from steam turbine.

[b] An example regeneration heat is 2.9 MJ/kg-CO_2 supplied by low pressure steam of 120 °C extracted from steam turbine.

[c] An example regeneration heat is 2.6 MJ/kg-CO_2 supplied by low pressure steam of 100 °C extracted from steam turbine.

Target corrosion rate of all absorbents is assumed 5 mills per year or less.

(b)

Type of target technology	Elemental technology to be developed	Reduction in R&D time of target technology		Standard R&D time (year)
		By reduction in R&D time of elemental technology (year / year)	By additional investment (year / 1 billion yen)	
Conven-tional	Blower for variable pressure operation (efficiency = 75%)	0.24	0.41	6.3 [1.00]
	Vacuum pump (efficiency = 75%)	0.23	0.37	5.8 [0.93]
	Valve for adsorption tower	0.20	0.35	5.8 [0.96]
	CO_2 adsorbent with conventional adsorption performance [a]	0.08	0.09	5.2 [0.94]
Energy saving	Blower for variable pressure operation (efficiency = 75%)	0.23	0.39	6.3 [1.00]
	Vacuum pump (efficiency = 75%)	0.23	0.36	5.8 [0.93]
	Valve for adsorption tower	0.19	0.33	5.8 [0.96]
	CO_2 adsorbent – energy saving type [b]	0.07	0.09	7.8 [0.88]
Advanced energy saving	Blower for variable pressure operation (efficiency = 75%)	0.22	0.39	6.3 [1.00]
	Vacuum pump (efficiency = 75%)	0.23	0.36	5.8 [0.93]
	Valve for adsorption tower	0.19	0.33	5.8 [0.96]
	CO_2 adsorbent – advanced energy saving type [c]	0.06	0.09	8.9 [0.61]

[a] Assumed equivalent to Ca-X type zeolite that was used in a pilot plant [11].

[b] Adsorption performance of reducing power consumption by 20% than the case of using conventional Ca-X type zeolite.

[c] Adsorption performance of reducing power consumption by 40% than the case of using conventional Ca-X type zeolite.

(c)

Type of target technology	Elemental technology to be developed	Reduction in R&D time of target technology		Standard R&D time (year)
		By reduction in R&D time of elemental technology (year / year)	By additional investment (year / 1 billion yen)	
Conven-tional	Vacuum pump (efficiency = 75%)	0.31	0.49	5.8 [0.93]
	Polymer membrane material ($CO_2/N_2 = 35$)	0.12	0.14	6.6 [0.96]
	Forming and modularization of polymer membrane ($CO_2/N_2 = 35$)	0.10	0.10	5.9 [0.92]
	Forming and modularization of inorganic membrane ($CO_2/N_2 = 35$)	0.09	0.09	7.5 [0.83]
	Inorganic membrane material ($CO_2/N_2 = 35$)	0.06	0.07	7.1 [0.84]
Energy saving	Vacuum pump (efficiency = 75%)	0.29	0.47	5.8 [0.93]
	Forming and modularization of inorganic membrane ($CO_2/N_2 = 100$)	0.10	0.16	8.3 [0.83]
	Inorganic membrane material ($CO_2/N_2 = 100$)	0.09	0.07	7.8 [0.73]
	Support material for facilitated transport (FT) membrane ($CO_2/N_2 = 100$)	0.03	0.03	7.5 [0.60]
	Forming and modularization of FT membrane	0.02	0.03	8.1 [0.67]
Advanced energy saving	Vacuum pump (efficiency = 75%)	0.29	0.47	5.8 [0.93]
	Inorganic membrane material ($CO_2/N_2 = 100$)	0.07	0.06	7.8 [0.73]
	Forming and modularization of hybrid type inorganic membrane	0.04	0.05	8.5 [0.63]
	Forming and modularization of hybrid type FT membrane	0.03	0.05	8.0 [0.61]
	Support material for facilitated transport membrane ($CO_2/N_2 = 100$)	0.04	0.04	7.5 [0.60]

Target durable period of all membrane technologies is assumed 8×10^4 hours under 40°C.

Fig. 2.

(d)

Type of target technology	Elemental technology to be developed	Reduction in R&D time of target technology		Standard R&D time (year)
		By reduction in R&D time of elemental technology (year / year)	By additional investment (year / 1 billion yen)	
Conven-tional	Oxygen combustion boiler	0.77	1.09	7.8 [1.00]
	Cryogenic air separation with conventional separation energy [a]	0.10	0.11	4.2 [0.96]
Energy saving	Oxygen combustion boiler	0.74	1.05	7.8 [1.00]
	Cryogenic air separation – energy saving type [b]	0.06	0.11	7.2 [0.95]
	Blower for variable pressure operation (efficiency = 75%)	0.00	0.01	6.3 [1.00]
	Valve for adsorption tower	0.00	0.01	5.8 [0.96]
	Vacuum pump (efficiency = 75%)	0.00	0.00	5.8 [0.93]
	Absorbent for air separation with conventional performance [b]	0.00	0.00	5.1 [1.00]
Advanced energy saving	Oxygen combustion boiler	0.66	0.94	7.8 [1.00]
	Blower for variable pressure operation (efficiency = 75%)	0.03	0.04	6.3 [1.00]
	Absorbent for air separation – energy saving type [c]	0.03	0.04	7.5 [0.91]
	Valve for adsorption tower	0.01	0.02	5.8 [0.96]
	Vacuum pump (efficiency = 75%)	0.01	0.02	5.8 [0.93]

[a] Oxygen production energy = 0.34 kWh/Nm^3-O$_2$ (normal pressure; purity > 93%).

[b] Oxygen production energy = 0.31 kWh/Nm^3-O$_2$. [c] Oxygen production energy = 0.28 kWh/Nm^3-O$_2$.

(e)

Type of target technology	Elemental technology to be developed	Reduction in R&D time of target technology		Standard R&D time (year)
		By reduction in R&D time of elemental technology (year / year)	By additional investment (year / 1 billion yen)	
LNG-fueled	Hydrogen-air combustion gas turbine	0.21	0.33	7.8 [0.83]
	Modularization of membrane reformer (reforming ratio = 90%)	0.09	0.13	7.5 [0.94]
	Forming and modularization of ceramic H_2 separation membrane	0.09	0.13	7.9 [0.78]
	Ceramic material for high temperature H_2 separation membrane [a]	0.08	0.12	7.9 [0.79]
	Metallic material for high temperature H_2 separation membrane [a]	0.08	0.11	7.5 [0.79]
	Forming and modularization of metallic H_2 separation membrane	0.06	0.08	7.3 [0.72]
	CH_4-O_2 combustion gas turbine	0.04	0.05	6.9 [0.89]
Coal-fueled (IGCC)	Hydrogen-air combustion gas turbine	0.21	0.33	7.8 [0.83]
	CO-O_2 combustion gas turbine	0.12	0.19	8.0 [0.88]
	Forming and modularization of ceramic H_2 separation membrane	0.09	0.13	7.9 [0.78]
	Ceramic material for high temperature H_2 separation membrane [a]	0.08	0.11	7.9 [0.79]
	Metallic material for high temperature H_2 separation membrane [a]	0.07	0.11	7.5 [0.79]
	Forming and modularization of metallic H_2 separation membrane	0.06	0.08	7.3 [0.72]
	O_2 blown coal gasification (cold gas efficiency = 80%)	0.01	0.01	6.1 [0.89]

[a] Perm-separations of H_2/CO_2 and H_2/CO are 500 both at 500°C.

Target durable period of all membrane technologies is assumed 8×10^4 hours under 500°C.

Fig. 2. Estimated reductions in total R&D time of target technologies due to additional R&D efforts for each elemental technology. (a) Chemical absorption, (b) Physical adsorption, (c) Membrane separation, (d) O_2/CO_2 recirculation boiler, (e) Integrated H_2 separation gas turbine. (Figure in bracket is the success probability defined as the number of answerers who expect the standard R&D time period shorter than 15 years divided by the number of total answerers for each elemental technology.)

that the effect of the additional investment has a larger practical meaning for the planning of the R&D. Additional R&D efforts to the following elemental technologies are evaluated to be effective for reducing the total R&D time of each target technology.

4.2.1. Chemical absorption technology

The effects of additional R&D investments are large for the elemental technologies of large scale absorption/regeneration tower and blower. Although the ‘energy saving’ type absorbent technology is essentially required in order to improve the target technology from ‘conventional’ up to ‘energy saving’ type, the effect is relatively small for this material technology compared to the scaling up technologies. The effect is, on the other hand, comparatively large for the ‘advanced energy saving’ type absorbent technology.

4.2.2. Physical adsorption technology

Additional investments in technologies for large scale blowers of variable pressure operation, for vacuum pumping, and for adsorption/desorption towers with switching valves are effective for expeding the physical adsorption technology R&Ds. Higher efficiency CO_2 adsorbent technologies, which are indispensable to improve the CO_2 capture energy efficiency, have relatively small effects on reduction in the total R&D accomplishment time by the additional R&D investment.

4.2.3. Membrane separation technology

The estimated reduction in the total R&D time caused by the additional R&D investment is large for the large scale vacuum pumping technology. As for the membrane materials and their modularization technologies, polymer membrane-related technologies have larger effects than inorganic membrane technologies for the ‘conventional’ type membrane separation technology; while for the ‘energy saving’ type the inorganic membrane technologies have large effects of additional R&D efforts. The effects are small for organic (facilitated transport) membrane and inorganic membrane technologies to be developed for the ‘advanced energy saving’ type and there is no apparent difference between them.

4.2.4. O_2/CO_2 recirculation boiler technology

The oxygen combustion boiler technology is a core elemental technology which requires the longest R&D time among the elemental technologies, and is the most R&D investment-effective way to shorten the total R&D times of the target technologies.

4.2.5. Integrated hydrogen separation gas turbine technology

The hydrogen–air combustion gas turbine technology has the largest effect of the additional R&D investment among the elemental technologies. The ceramic membrane technologies for hydrogen separation have slightly larger effects than the metal membrane technologies.

5. Conclusion

In this study, GERT-type network charts were constructed to evaluate the R&D processes of five types of CO_2 capture technologies having different levels of CO_2 capture energy efficiency. Data on R&D time periods of various elemental technologies were collected through a questionnaire to experts. The collected data were put into the GERT models to evaluate the CO_2 capture technology R&Ds, and the overall R&D times and the success probabilities for realizing the target technologies were estimated.

The target technology R&D times were estimated to be in the range of 16 and 19 years, except for a shorter R&D time of 13.8 years for the chemical absorption CO_2 capture technology of the conventional type.

In general, chemical absorption technologies were estimated to have shorter expected R&D times and higher R&D success probabilities compared to other types of the CO_2 capture technologies evaluated. However, the R&D success probabilities become lower as the energy efficiency becomes higher. For example, the success probability of the chemical absorption CO_2 capture technology of the advanced energy saving type, having the highest efficiency of 0.27 kWh/kg-CO_2 among the target technologies, was estimated to be only about 0.55 whereas that of the energy saving type was 0.81. Hence, in parallel with the R&Ds of the chemical absorption CO_2 capture technologies, those of other types of capture technologies are recommended to be conducted so as to mitigate risks of the R&Ds of advanced high efficiency CO_2 capture technologies being unsuccessful.

Also found were the elemental technologies in which additional R&D investments were cost-effective to accelerate the target technology R&D. Additional R&D investments on large scale equipment such as tower, blower, vacuum pumping and oxygen combustion boiler technologies were evaluated to shorten the R&D times of the relevant target technologies by about 0.4 years/billion yen or longer. The R&D of the chemical absorbent technology of the advanced energy saving type, which can be regenerated by low temperature heat energy, was also estimated to be cost-effective.

We hope the obtained results are useful to make rational and effective R&D strategies for realization of CO_2 capture technologies in the near future.

Acknowledgements

The experts answers to the questionnaire are greatly appreciated. The study presented in this paper is a part of a project sponsored by New Energy and Industrial Technology Development Organization, Japan.

References

[1] International Energy Agency Working Party on Fossil Fuels. Solutions for the 21st century: zero emissions technologies for fossil fuels, Technology status report. Paris: International Energy Agency, 2002.

[2] Pritsker AAB, Happ WW. GERT: Graphical Evaluation and Review Technique, Part I, Fundamental. Journal of Industrial Engineering 1966;17(5):267–74.

[3] Hayashi A, Akimoto K, Kosugi T, Tokimatsu K, Yoshida H, Tomoda T, Kaya Y. Evaluation of advanced combined cycle power systems development using GERT. In: Proceedings of the 5th IASTED International Conference on Power and Energy Systems, Tampa, 2001:310–315.

[4] Kosugi T, Hayashi A, Akimoto K, Tokimatsu K, Matsumoto T, Yoshida H, Tomoda T, Kaya Y. Evaluation of R&D processes of high efficient CO_2 capture technologies based on a questionnaire to experts in Japan. In: Proceedings of the 5th International Symposium on CO_2 Fixation and Efficient Utilization of Energy and the 4th International World Energy System Conference, Tokyo, 2002:263–268.

[5] Mimura T, Matsumoto K, Iijima M, Mitsuoka S. Development and application of flue gas carbon dioxide recovery technology. In: Greenhouse Gas Control Technologies, Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies, Cairns, 2000:138–142.

[6] Simmonds M, Hurst P, Wilkinson MB, Watt C, Roberts CA. A study of very large scale post combustion CO_2 capture at a refining&petrochemical complex. In: Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, 2002: 39–44.

[7] Slater M, West E, Mariz CL. Carbon dioxide capture from multiple flue gas sources. In: Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, Kyoto, 2002: 103–107.

[8] Mimura T, Shimojo S, Suda T, Iijima M, Mitsuoka S. Research and development on energy saving technology for flue gas carbon dioxide recovery and steam system in power plant. Energy Conversion and Management 1995;36(6-9):397–400.

[9] Bolland O, Undrum H. Removal of CO_2 from gas turbine power plants: evaluation of pre- and postcombustion methods. In: Greenhouse Gas Control Technologies, Proceedings of the 4th International Conference on Greenhouse Gas Control Technologies, Interlaken, 1998:125–130.

[10] Research Institute of Innovative Technology for the Earth. Project of CO_2 fixation and utilization using catalytic hydrogenation reaction-current state of research and development. Tokyo: New Energy and Industrial Technology Development Organization, 1998.

[11] Ohta H. CO_2 separation and removal technologies in measures to cope with global warming. The Separation Technology 1997;27(5):312–9 (in Japanese).

[12] Teramoto M, Ohnishi N, Takeuchi N, Kitada S, Matsuyama H, Matsumiya N and Mano H. Separation and enrichment of carbon dioxide by capillary membrane module with permeation of carrier solution. Separation and Purification Technology, 2003:30(3):215–27.

[13] Okawa M, Kimura N, Kiga T, Takano S, Arai K, Kato M. Trial design for a CO_2 recovery power plant by burning pulverized coal in O_2/CO_2. Energy Conversion and Management 1997;38(Suppl.):S123–7.

[14] Koda E, Takahashi T. Study on the advanced closed-cycle gas turbine system. In: Proceedings of the 5th International Symposium on CO_2 Fixation and Efficient Utilization of Energy and the 4th International World Energy System Conference, Tokyo, 2002:350–355.

[15] Moritsuka H. CO_2 capture using a hydrogen decomposed from natural gas turbine. In: Proceedings of ASME TURBO EXPO 2001, New Orleans, 2001:2001-GT- 0093.

[16] Moritsuka H, Koda E. Proposal of hydrogen decomposed IGCC power generation system—1st. report: performance of HYDE-IGCC using high temperature ceramic membrane, report no. W99022. Tokyo: Central Research Institute of Electric Power Industry, 2000.