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# Existing and anticipated technology strategies for reducing greenhouse gas emissions in Korea's petrochemical and steel industries

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ABSTRACT

This study examines the existing and anticipated technology strategies for reducing greenhouse gas (GHG) emissions in Korea's petrochemical and steel industries. The results of the cluster analysis identify three types of technology strategies employed by firms for reducing GHG emissions: "wait-and-see" "in-process-focused", and "all-round" strategies. The "in-process-focused" strategy was the most widely used strategy, followed by the "all-round" strategy. However, firms in these industries are expected to change their technology strategies to "treatment-reliance", "inbound-substitution", and "all-round" strategies in 5–10 years by employing a wider range of technology options to respond more effectively to the issue of GHG emissions. The demand for new energy sources and raw material substitutes is expected to strengthen in the near future as related technologies advance rapidly and become more widely available.



## 1. Introduction

Mitigating global warming has become one of the most important issues in the Asia-Pacific region. For instance, South Korea (hereafter "Korea") and China recently announced their own medium-term mitigation goals to reduce greenhouse gas (GHG)[1] emissions by 30% below the business-as-usual level by 2020 and carbon intensity by 40%–45% below 2005 levels, respectively. These changing national policies on global warming in this region have been a main driver behind changes in firms' and industries' responses to GHG emissions. The steel and petrochemical industries are two major GHG emitters. These two industries accounted for approximately 52.2% of the total GHG emissions by the Korean industrial sector in 2005 (Han et al., 2008). These industries are very energy-intensive industries, and therefore, energy and $CO_2$ emissions have been key issues on their sustainable production agenda. However, the energy efficiency of Korean industries, particularly that of the more energy-intensive petrochemical and steel industries, has generally outpaced that of their counterparts in other countries (IEA, 2009). As a result, reducing GHG emissions has been very challenging and costly, and firms in these industries have been forced to consider a wide range of technology options to respond to the issue of global warming and achieve $CO_2$ reduction targets more effectively because energy efficiency cannot be the only strategy (Gielen et al., 2002).

With global warming and GHG emissions surging as a legitimate business concern, an increasing number of studies have attempted to provide a better understanding of firms' technology strategies and promote the transformation of entire trajectories of technological innovation in an era of global warming (Rynikiewicz, 2008; Van de Poel, 2002). However, previous research on technology strategies for reducing GHG emissions has been limited in the following ways. First, most of the previous studies addressing this topic have focused on examining how new approaches or technologies could be applied to industries from science and engineering perspectives. Recently, some studies have suggested more comprehensive approaches and techniques to help managers evaluate and select their firms' sustainable production technologies by considering various economic, environmental, and social aspects simultaneously, including the analytical network process (e.g., Tseng et al., 2009b), quality function deployment (e.g., Lin et al., 2010), and the fuzzy analytical hierarchy process (e.g., Tseng et al., 2009a). However, very few studies have investigated firms' technology selection and implementation in their response to global warming and GHG emissions from a business or technology strategy perspective. Second, previous studies of technology

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[1] In this paper, GHGs refer to the six types of GHGs addressed by the Kyoto Protocol, namely carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), sulfur hexafluoride ($SF_6$), hydrofluorocarbons (HFCs), and perflourocarbons (PFCs).

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strategies for GHG reductions have typically focused on Western or Japanese firms (Rynikiewicz, 2008; Moors, 2006; Gielen et al., 2002), and thus, very few have addressed the technology strategies of the steel and petrochemical industries in Asia, particularly those in Korea.

Third, as many as 50 studies have explained changes in firms' environmental strategies (Kolk and Mauser, 2002). Previous studies have argued that firms' environmental strategies change over time (Lee and Rhee, 2007). A firm's strategic selection of technologies for sustainable or cleaner production can change through dynamic interactions among stakeholders and newly emerging technologies (Lee and Rhee, 2005). Berkhout et al. (2009) explained how sustainable technological change can occur in developing countries by integrating the concepts of the socio-technical regime and systems innovation and suggested that late-developing countries are more likely to follow sustainable development paths than the trajectories of economic transformation shown in previous cases of industrialization, namely high resource intensity and high pollution. Further, the resource and environmental profile of a late-developing country can vary according to various factors influencing the socio-technical regime, including resource endowments, government policies, and the accumulation of technological and innovation capabilities (Berkhout et al., 2009). However, few studies have explained how a firm's dominant technology strategy for cleaner and sustainable production, specifically for reducing GHG emissions, changes and why.

In light of these gaps in previous research, this study explores the following research questions about firms' technology strategies and their transformation for addressing global warming and GHG emissions in the petrochemical and steel industries:

- What are the existing and anticipated (in the near future) types of technology strategies employed by firms in Korea's petrochemical and steel industries for reducing GHG emissions?
- How will these technology strategies change in 5–10 years?
- What are the characteristics of these technology strategies and anticipated changes?

The rest of this paper is organized as follows: Section 2 provides a framework based on previous research for conceptualizing technology options for GHG reductions available to the steel and petrochemical industries. Section 3 presents a brief overview of the data and research methods. Section 4 presents the results of the survey and case studies and discusses their implications. Section 5 concludes by discussing the contribution and limitations of the study and providing some interesting avenues for future research.

## 2. Technology strategies for reducing GHG emissions

### 2.1. Technology options

A technology option is a set of diverse technologies that firms select, adopt, and implement to address various issues surrounding climate change and GHG emissions. Previous studies have suggested and categorized some technology options. For instance, Moors (2006) classified three technology strategies for sustainable production systems of metals according to the radicalness of technological innovation: incremental, in-process, and radical innovation. Rynikiewicz (2008) suggested three categories of measures for reducing GHG emissions: material substitution, servicizing, and process innovation. Other researchers have grouped technology options into two or three categories from a stage model perspective: the end-of-pipe and cleaner production technologies (Lee and Rhee, 2005). Based on these studies, the present paper proposes a new classification method for technology options by considering the following two aspects: the energy and material flow and the radicalness of technological innovation. The first dimension (the vertical axis) specifies the movement routes of energy and materials to which technology options are more relevant. The second dimension (the horizontal axis) describes the extent to which technology options are radical in a term of innovation. Based on this framework, the study presents five technology options (Fig. 1). Each option is a component of a firm's technology strategy for reducing GHG emissions.

#### 2.1.1. The energy and material flow

This framework identifies three areas of the energy and material movement: inbound, in-process, and outbound. The inbound movement represents the source of energy and raw materials used in the production process, including fossil and renewable energy sources. The technologies related to the substitution of energy sources and raw materials belong to the inbound area. The in-process movement refers to the manufacturing process in which final products are produced. Some examples include various energy-saving and process innovation activities and technologies for reducing GHG emissions and for improving their efficiency and productivity. The outbound movement is a place in which GHG emissions occur as a byproduct of main products. If GHG emissions are not controlled, then they can pollute the air and contribute to global warming. GHG treatment is a technology related to the outbound movement, e.g., carbon capture and storage (CCS) technology.

#### 2.1.2. The radicalness of technological innovation

The present study considers two types of innovation: incremental and radical. A technology can be categorized as an incremental innovation if it requires minimal technological changes based on existing principles and performance improvements are relatively minor. When technologies lead to a major change in systems, processes, and products based on the application of a higher degree of new knowledge, they can be classified as a radical innovation. This distinction between incremental and radical innovation is consistent with the distinction between "technological regimes" and "niches" in previous research on socio-technical transitions. A social-technical regime represents a complicated set of technologies, skill attributes, markets, individuals, processes, and products that engage in an exchange relationship with one another, and thus, radical shifts in technological regimes require structural changes in the incumbent

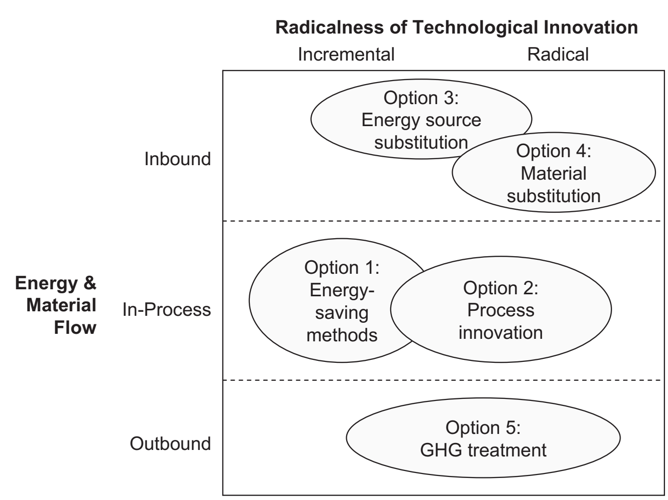


**Fig. 1.** Technology options for reducing GHG emissions.

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socio-technical system. By contrast, a niche refers a small change conceived and developed on the margin of the incumbent regime (Smith, 2007). This distinction also can be understood based on the common definitions of the Oslo manual: an incremental innovation as something “new to the firm” and a radical innovation as something “new to the world” (OCED, 1996).

However, Smith (2007) argued that there is rarely a clear-cut niche-regime distinction in practice, and thus, the present study uses the distinction between incremental and radical innovation as a framework for better understanding an emerging spectrum of practices and technologies for sustainable or cleaner production. In the steel and petrochemical industries, which require a high level of capital investment and whose production equipment is depreciated over a long period of time, most innovations tend to be incremental (Moors, 2006).

### 2.1.3. Technology options for reducing GHG emissions

In a matrix with two dimensions (i.e., the energy and material flow and the radicalness of technological innovation), five technology options can be set. These can include a number of technologies and/or approaches that have been identified in previous research as effective in reducing GHG emissions (Table 1).

(1) The *energy-saving option* is a technology option involving all energy-efficient and emission reduction technologies and programs in production processes. This option has been the highest-priority option for energy-intensive industries such as the steel and petrochemical industries. This technology option includes the improvement of the efficiency of existing processes through facility and/or equipment retrofits, energy system optimization, and energy recovery from waste materials. It requires less capital and can easily reach given targets. However, the energy-saving option can achieve only a 10–30% reduction in the environmental burden over a 50-year time horizon (Moors, 2006).

(2) The *process innovation* option includes all the technologies that lead to relatively radical innovations in a firm’s production processes. Industry experts have suggested that radical changes are necessary in energy-intensive and high-pollution industries to achieve as much as 80–95% reductions in GHG emissions (Moors, 2006). For instance, there has been growing interest in the breakthrough ULCOS (Ultra–Low-$CO_2$ Steelmaking) technology because practitioners anticipate that this technology could help firms reduce their $CO_2$ emissions by as much as 50%. This technology option also encompasses the redesigning of products that can reduce raw material use and facilitate carbon-free production.

(3) The *energy source substitution* option is a technology option focusing on the substitution of fuels with lower GHG emissions for traditional energy sources. There is a diverse range of substitutable energy sources such as liquid propane gas (LPG) and renewable energy sources such as solar energy and wind power. Although this technology option does not require many changes in production systems, processes, and equipment, its adoption and implementation by industries depend heavily on the technological progress of the utility industry as well as the cost of substitutable energy sources.

(4) The *material substitution* option is a technology option emphasizing changes in the product formula. Through product redesigns (new formulas) and breakthrough product technologies, it aims to fundamentally substitute carbon-free materials for carbon-intensive ones in products. For instance, feedstock use accounts for approximately 60% of the total energy use in the petrochemical industry, and thus, substituting less carbon-intensive sources such as synthetic organic materials for feedstock is considered to be one of the most important alternatives that may reduce GHG emissions (Gielen et al., 2002).

(5) The *GHG treatment* option is a technology option that aims to prevent GHG emissions from entering the atmosphere by capturing and storing non-$CO_2$ GHGs (e.g., methane and nitrous oxide) as well as $CO_2$ from large point sources in steel and petrochemical production processes. There has been growing interest in installing facility units that can capture $CO_2$ from hydrogen production in the petrochemical industry and from coke-based iron production in blast furnaces in the steel industry.

**Table 1**
Technology options for climate change and related research.

| Technology options | Related technologies |
|---|---|
| Energy-saving methods | • Energy efficiency programs (Korhonen et al., 2004)<br>• Better housekeeping (Jeswani et al., 2008)<br>• Plant retrofitting (Schultz and Williamson, 2005)<br>• Energy recovery (Gielen et al., 2002) |
| Process innovation | • Product redesigns (Weinhofer and Hoffmann, 2010; Rynikiewicz, 2008)<br>• Process improvements (Jeswani et al., 2008; Kolk and Pinkse, 2005)<br>• Breakthrough technologies such as the Ultra-Low-$CO_2$ Steelmaking technology (Rynikiewicz, 2008) |
| Energy source substitution | • Renewable energy sources (Korhonen et al., 2004)<br>• Substitution of less carbon-intensive fuels (Tjan et al., 2010) |
| Material substitution | • Product redesigns (Weinhofer and Hoffmann, 2010; Rynikiewicz, 2008)<br>• System innovation (Rynikiewicz, 2008)<br>• Raw material substitution (Gielen et al., 2002) |
| GHG emission capture & storage | • $CO_2$ separation, capture, and utilization (Korhonen et al., 2004; Tjan et al., 2010) |

## 2.2. Technology strategies for reducing GHG emissions

Technology strategies for reducing GHG emissions can be understood as the pattern of a firm’s selection of technologies used for managing its direct and indirect GHG emissions. Technology strategies may vary across firms even within the same industry. A firm faces a number of strategic technology options when it responds to the issue of global warming, particularly to regulatory pressure to reduce GHG emissions. This is because managerial perceptions and interpretations of risks and opportunities associated with this issue vary across firms. Furthermore, organizational capabilities and the availability of slack resources also vary across firms (Jeswani et al., 2008). These differences in firms’ technology choice can lead to distinct types of technology strategies.

## 3. Research design

### 3.1. Data

A survey and case study were employed for this present study. First, a survey was conducted to empirically identify the technology strategies employed by firms in Korea’s petrochemical and steel industries for reducing GHG emissions. The sample for the survey was drawn from the two industries. As of July 2009, there were 37 petrochemical and 34 iron and steel firms registered as members of the Korea Petrochemical Industry Association and the Korea Iron and Steel Association, respectively. The questionnaires were sent by email to senior executives and managers representing operations, energy resource, environmental management, and production technology departments. All of the recipients were well acquainted with the policies, practices, and technologies associated with their firms' responses to climate change. A total of 25 questionnaires (13 petrochemical and 12 steel firms) were returned (a 35% response rate).

Second, a case study was carried out to investigate why the respondents' technology strategies for reducing GHG emissions varied. A case study is considered the best research method for theory building (Eisenhardt, 1989). In-depth interviews were conducted with managers of six firms in the petrochemical and steel industries, focusing on what technology options they were using or planning to use to address GHG emissions and global warming and why. Each interview took approximately 2 h.

The petrochemical and steel industries were for the survey and the comparative case study for two reasons. First, these industries are the most energy-intensive industries and two major GHG emitters in Korea. These two industries accounted for more than 50% of total GHG emissions by the Korean industrial sector in 2005 (Han et al., 2008), and thus, the Korean government as well as the public have put considerable pressure on these industries to reduce GHG emissions. Second, these two industries were selected to control for external influences such as the strength of environmental regulations and industry-wide environmental standards because these two industries have very similar characteristics in terms of energy use, GHG emissions, and domestic/global environmental regulations.

### *3.2. Measurement and data analysis*

A measurement instrument was developed based on the five technology options described in Section 2.1.3 (Fig. 1 and Table 1). Each of these five options was measured on a five-point Likert-type scale reflecting the level of the firm's technology adoption and implementation (see the Appendix). The survey was devised to measure firms' future plans to adopt technology options as well as their existing technology strategies.

The data was analyzed in three steps. In the first step, a cluster analysis was conducted to determine the types of existing technology strategies employed by the firms for reducing GHG emissions. An adequate number of clusters were drawn through a hierarchical clustering procedure (Ward's method). The explanatory power and pseudo *F*-value from this cluster analysis verified that the three clusters were a valid classification. Then a non-hierarchical clustering procedure (*K*-mean method) was applied to assign the 25 firms to the clusters (Hair et al., 2006). In the second step, another cluster analysis was conducted to determine the types of anticipated technology strategies employed by the firms for reducing GHG emissions. In the third step, the sample firms were classified according to the period (i.e., the present and the future) and the frequency of each type of technology strategy for each period was calculated to analyze the anticipated changes in technology strategies.

The responses were divided into two groups (responses that were returned early and those returned late) to test for non-response bias. The results of *t*-tests with these two groups of responses ($n_1 = 16$, $n_2 = 9$) indicate no significant differences between survey items.

## 4. Results and discussion

### *4.1. Adoption of technology options*

The results of the descriptive analysis indicate the ways in which each technology option was adopted and implemented by the petrochemical and steel industries in Korea (Fig. 2). Among the five technology options, the energy-saving and process innovation options were the most widely adopted and implemented technology options in these industries. The petrochemical industry was more likely to prefer the energy-saving and process innovation options (4.00 and 3.92, respectively) than the steel industry (3.63 and 3.58, respectively), whereas the steel industry was more likely to prefer the energy source substitution and raw material substitution (3.17 and 3.08, respectively) than the petrochemical industry (3.08 and 3.00, respectively). However, there were no statistically significant differences between the two industries.

The results suggest that material substitution and energy source substitution options are likely to surge as major technology options in the two energy-intensive industries in the near future (in 5–10 years), although the energy-saving and process innovation options are likely to remain as the most preferred technology options (Fig. 3). Petrochemical and steel production processes are very energy intensive, and energy efficiency is closely related to production costs and profits. This is why the energy-saving option has been prioritized in these industries for a very long time and why many measures with energy-saving potential have already been implemented (Holmgren and Sternhufvud, 2008). In particular, in the context in which firms have already achieved the highest level of energy efficiency (e.g., Korea and Japan), a more diverse range of technology options are needed for them to meet a more challenging GHG emission reduction target. Substituting new and renewable energy sources such as biomass, photovoltaic,

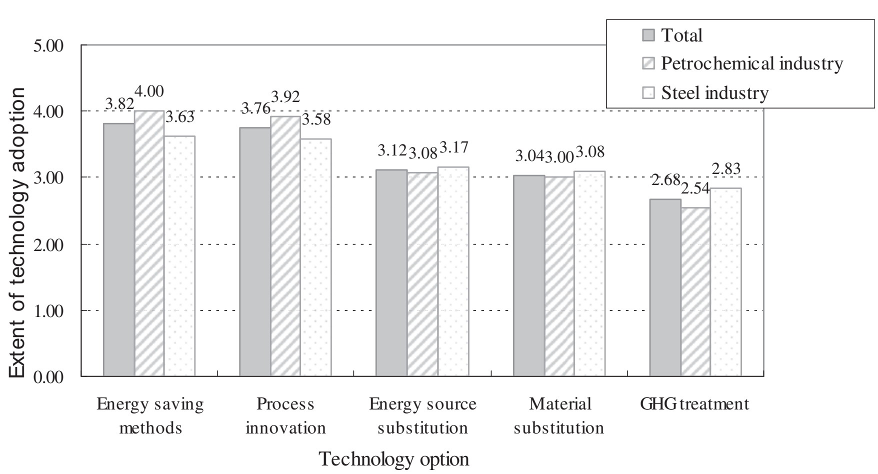


**Fig. 2.** Adoption of technology options.

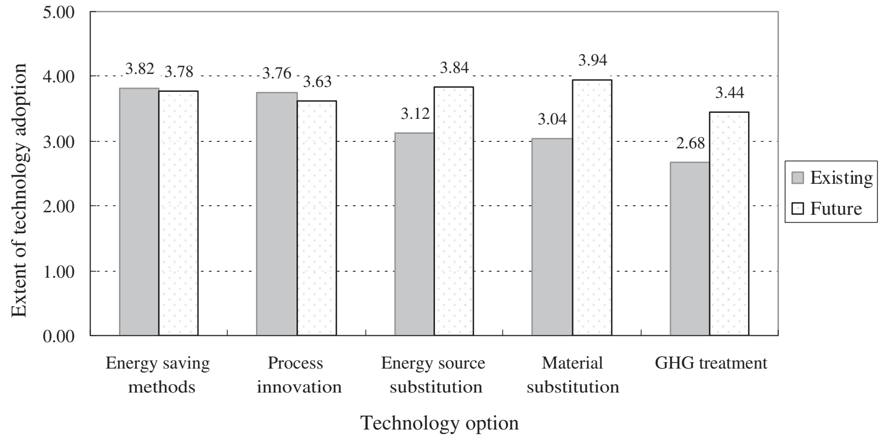


**Fig. 3.** Anticipated changes in the adoption of technology options.

and wind for current fossil fuels can help reduce indirect GHG emissions from the consumption of electricity, heat, or steam.

### 4.2. Types of technology strategies for reducing GHG emissions

#### 4.2.1. Existing technology strategies

The results of the cluster analysis identify three types of technology strategies employed by the sample firms for reducing GHG emissions. Table 2 summarizes the results, including the mean scores for each technology option and the number of cases belonging to each technology strategy group.

*4.2.1.1. Wait-and-see strategy.* The first cluster (the "wait-and-see" technology strategy) scored very low for all five technology options, indicating that the firms in this group did not take GHG emissions into account seriously. These firms tended to be dismissive of the risk implied by GHG emissions and decided not to react, and thus, they showed little interest in adopting and implementing various technology options. This cluster lagged behind all the other clusters in terms of the ability to address GHG emissions. Only 8% of the respondents belonged to the "wait-and-see" group.

*4.2.1.2. In-process-focused strategy.* The second cluster (the "in-process-focused" strategy) included the firms that showed a relatively high level of technology adoption in terms of the energy-saving and process innovation options. For this cluster, the main technological concern was to reduce GHG emissions by using options related to in-process technologies. Approximately 64% of the firms belonged to this strategy group. This technology strategy has been the key strategy for firms in Korea's petrochemical and steel industries. The firms in this group were not likely to be interested in technology options related to the inbound movement of energy and raw materials, such as alternative energy sources and raw material substitutes. Instead, they were likely to prefer technology options related to in-process technologies because the successful adoption and implementation of inbound technologies depend heavily on technological advances in other sectors such as material and energy industries.

*4.2.1.3. All-round strategy.* The last cluster (the "all-round" technology strategy) scored higher than the other two clusters for all the technology options. The firms belonging to this group engaged in a wide range of technology options combining in-process (the energy-saving and process innovation options) and inbound (the energy source substitution and raw material substitution options) technologies. This cluster was more likely than the other two clusters to search for new ways to reduce GHG emissions, including GHG treatment technologies.

#### 4.2.2. Anticipated technology strategies

The results of the cluster analysis also identify three types of anticipated technology strategies for reducing GHG emissions, that is, those strategies that the sample firms were expecting to employ in the near future to address GHG emissions. Table 3 shows the results.

*4.2.2.1. Treatment-reliance strategy.* The first cluster showed average scores for all of the technology options. The firms in this group focused mainly on the GHG treatment option (3.13). This suggests that when they face the pressure to dramatically reduce GHG emissions in the future, they are most likely to select GHG treatment technologies such as CCS. This is why this cluster is named the "treatment-reliance" technology strategy. This cluster is more advanced than the existing cluster of the "wait-and-see" strategy in terms of the ability to address GHG emissions. However,

**Table 2**
Cluster analysis and technology strategies.

| | Cluster | | |
|---|---|---|---|
| | Wait-and-see strategy | In-process-focused strategy | All-round strategy |
| Energy-saving technology | 1.50 | 3.78 | 4.57 |
| Process innovation | 1.50 | 3.75 | 4.43 |
| Energy source substitution | 1.50 | 2.88 | 4.14 |
| Raw material substitution | 1.50 | 2.63 | 4.43 |
| GHG treatment | 1.50 | 2.50 | 3.47 |
| Number of cases | 2 (8.0%) | 16 (64.0%) | 7 (28.0%) |

**Table 3**
Cluster analysis and anticipated technology strategies.

| Technology option | Cluster | | |
|---|---|---|---|
| | Treatment-reliance strategy | Inbound-substitution strategy | All-round strategy |
| Energy-saving technology | 2.75 | 3.90 | 4.62 |
| Process innovation | 2.67 | 3.73 | 4.57 |
| Energy source substitution | 2.88 | 3.90 | 4.86 |
| Raw material substitution | 3.03 | 3.95 | 4.86 |
| GHG treatment | 3.13 | 3.50 | 3.71 |
| Number of cases | 8 (32.0%) | 10 (40.0%) | 7 (28.0%) |

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it is likely to lag behind all the other future clusters. Approximately 32% of the respondents anticipated this technology strategy.

*4.2.2.2. Inbound-substitution strategy.* The firms in this cluster scored relatively high for the material substitution, energy source substitution, and energy-saving options (3.90, 3.95, and 3.90, respectively). Although the firms in this cluster continued to emphasize other technology options such as the process innovation and GHG treatment options (3.70 and 3.50, respectively), they placed greater emphasis on changing and substituting raw materials and energy sources in the case more dramatic GHG reductions. Approximately 40% of the respondents anticipated this strategy, indicating that it is likely to play a major role in GHG reductions in the near future. Because the material substitution and energy source substitution options are likely to surge as major technology options in the two energy-intensive industries in the near future, more firms are expected to prioritize these options.

*4.2.2.3. All-round strategy.* The last cluster, named the "all-round" strategy because it is very similar to the existing "all-round" strategy, scored higher than the other two technology strategies for reducing GHG emissions. The subtle difference between the existing and anticipated all-round strategies lies in which technology options they emphasize. For instance, in-process technology options such as the energy-saving and process innovation options are considered as the most important options in the existing "all-round" strategy (3.57 and 4.43, respectively), whereas inbound technology options such as the raw material and energy source substitution options are likely to be the most important technology options in the anticipated "all-round" strategy (4.86 and 4.86, respectively).

### 4.3. Anticipated changes in technology strategies for reducing GHG emissions

The frequency of changes from existing technology strategies to anticipated strategies was analyzed. Fig. 3 shows the anticipated trend in the adoption and implementation of technology options for reducing GHG emissions in 5–10 years. Fig. 4

First, noteworthy is that the "wait-and-see" firms were likely to adopt the "treatment-reliance" strategy in the near future. These firms were reluctant to address GHG emissions and thus tended to respond in a passive manner. This suggests that if these firms are pressured to achieve dramatic GHG reductions in the future, they are likely to rely on GHG treatment or end-of-pipe pollution control technologies because they are not likely to have the ability to reduce GHG emissions at the source.

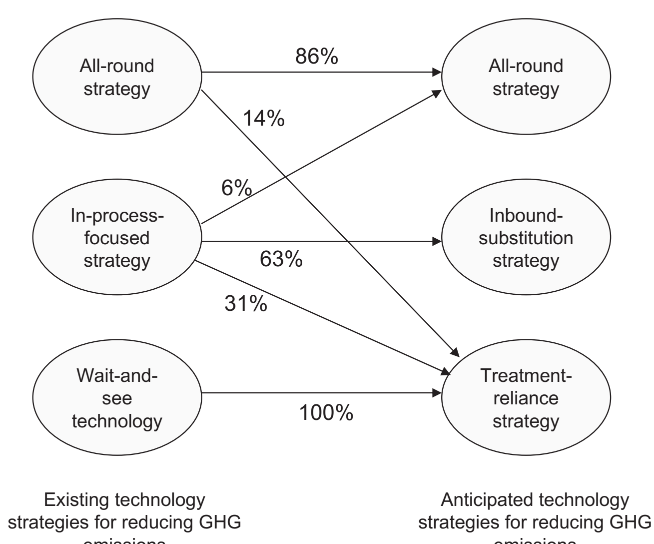


**Fig. 4.** Anticipated changes in technology strategies.

Second, a majority of the firms (63%) in the "in-process-focused" cluster anticipated their shift to the "inbound-substitution" strategy cluster. These firms emphasized energy-saving and process innovation technologies for reducing GHG emissions, and thus, they achieved a high level of energy and production efficiency. Ironically, this implies that there is little room for further improvements. Thus, these firms are likely to seek solutions outside production processes, such as alternative energy sources and raw material substitutes, to avoid the high risk associated with switching existing production facilities. In addition, 31% of the firms in the "in-process-focused" cluster anticipated taking the "treatment-reliance" strategy. The results suggest that GHG treatment technologies are likely to attract increasing attention even from the "in-process-focused" firms. Then the question is whether such technologies are technologically and economically viable. Some firms in this cluster (6%) anticipated taking the "all-round" strategy in the future.

Third, most of the firms in the "all-round" strategy cluster (86%) anticipated that they would maintain the same technology strategy in 5–10 years. The "all-round" firms were more likely than those in the other clusters to adopt or implement a wide range of technologies to address GHG emissions and global warming and thus more likely to accumulate capabilities to address these issues. Their accumulated experience, knowledge, and ability are likely to enable them to continue searching for new ways to reduce GHG emissions in the near future. However, some of the "all-round" firms (14%) anticipated a shift to the "treatment-reliance" cluster depending on their situation in the near future. For instance, if dramatic increases in production volume and energy use are expected in 5 years, then the "all-round" firms are likely to seriously consider GHG treatment options because the other technology options cannot meet required GHG reduction targets in a short period of time.

These anticipated changes in technology strategies for reducing GHG emissions are consistent with the expectation of industry experts, who have suggested that major technological changes would be required for necessary reductions in GHG emissions because GHG emission targets are likely to be tightened in both developed and developing countries and improvements in existing processes would not be sufficient (Rynikiewicz, 2008; Korhonen et al., 2004). Developing new technologies and implementing them typically take many years or decades. Korea's petrochemical and steel industries have thus far focused on energy-saving and in-process technologies. However, they are likely to consider an increasingly wider range of technology options as new technologies for reducing GHG emissions continue to be developed and become more practical.

### 4.4. Case studies of anticipated changes in technology strategies

The results of the cluster analysis suggest that firms in Korea's petrochemical and steel industries are likely to adopt different technology strategies for reducing GHG emissions but do not indicate why. Thus, a case study was conducted to determine why firms may choose different technology options in the near future.

*4.4.1. Case 1: K-Chem (from the "wait-to-see" to the "treatment-reliance" strategy)*

K-Chem produced building materials such as plaster boards. Its production consisted of drying, filtering, and rolling processes. The process of drying raw materials and final products accounted for almost 99% of its total energy consumption. K-Chem's factory generated approximately 20,000 tons of $CO_2$ a year, and K-Chem monitored the level and source of its $CO_2$ emissions since 2008 through a carbon inventory system. However, it did not take $CO_2$ reductions seriously for two reasons: First, K-Chem managers considered the level of its $CO_2$ emissions to be far lower than that for the petrochemical industry. Second, the technology for producing plaster boards is a mature technology, and thus, there is little room for breakthrough technologies for more efficient and cleaner production. K-Chem planned to introduce GHG treatment technologies such as CSS if the regulatory and social pressure to reduce $CO_2$ emissions became too great for K-Chem to ignore. A manager commented that K-Chem would consider adopting GHG treatment technologies such as CCS in the future but only if such technologies became affordable.

#### 4.4.2. Case 2: Y-Chem (from the "in-process-focused" to the "treatment-reliance" strategy)

Y-Chem was a petrochemical manufacturer producing ethylene. In the pyrolysis process, naphtha is heated and separated into ethylene and two byproducts: hydrogen and methane. All of these gases are reused as raw materials for electricity generation, and a sizable sum of $CO_2$ comes from this power generation process. Y-Chem's $CO_2$ emissions reached 3 million tons per year, making it the single largest emitter of $CO_2$ emissions in Korea's petrochemical industry. In recent years, Y-Chem faced considerable pressure to reduce its GHG emissions. In response, Y-Chem prioritized production efficiency, reducing its energy use and GHG emissions. It invested approximately USD 600 million in production retrofit projects in the last four years, which allowed it to achieve a high level (98%) of process efficiency and reduce 600,000 tons of $CO_2$. Ironically, this huge retrofit success left Y-Chem very little room for further improvements. The chief manager of the utility and environmental department at Y-Chem anticipated that GHG treatment technologies would be Y-Chem's only option in the future for further reducing GHG emissions unless the firm overhauled the entire production process or stopped reusing byproducts as raw materials for electricity generation.

#### 4.4.3. Case 3: L-Chem (from the "in-process-focused" to the "inbound-substitution" strategy)

L-Chem produced polyvinyl chloride (PVC), acrylonitrile-butadiene-styrene (ABS) resin, and polyethylene (PE) fiber. L-Chem's seven manufacturing plants, which involve highly energy-intensive processes, generated a total of 3 million tons of $CO_2$ per year. L-Chem addressed the energy crisis and global warming by increasing its process and energy efficiency. For this, the firm consulted experts and implemented more than 100 energy-saving projects every year for 15 years. L-Chem introduced an internal emission trading scheme (ETS) in 2008 that assigned emission targets to the seven manufacturing plants and allowed them to trade their own emission credits when necessary to meet the targets. This internal ETS induced the plant managers to focus on reducing $CO_2$ emissions. Through those energy-saving projects and the ETS, L-Chem achieved a high level of energy and production efficiency, which in turn provided it with little room for further improvements. L-Chem recently started searching for alternative strategies for further reducing GHG emissions. The managers in the energy, utility, and environmental departments at L-Chem started examining the technological and economic feasibility of cogeneration plants, which are expected to facilitate the partial substitution of renewable energy sources for existing fossil fuel sources. This effort was part of L-Chem's precautionary measure in response to the possibility of the future need for dramatic reductions in GHG emissions.

#### 4.4.4. Case 4: P-Chem (from the "in-process-focused" to the "all-round" strategy)

P-Chem was the second largest producer of synthetic rubber in the world. It generated approximately 150,000 tons of $CO_2$ per year. P-Chem was well aware of the issue of climate change, particularly global and domestic regulations on GHG emissions. For this, the firm prioritized process innovation. For instance, it patented the ultra-low-temperature polymerizing process, which led to a 50% reduction in energy use and emissions per product unit. Through such breakthrough process innovations, P-Chem accumulated distinctive capabilities specialized in energy efficiency and emissions abatement, which in turn enabled the firm to search for and adopt a wider range of technology options from the substitution of raw materials and energy sources to continuous process improvements and breakthrough process innovations.

#### 4.4.5. Case 5: H-Chem (from the "all-round" to the "treatment-reliance" strategy)

H-Chem, a producer of vinyl chloride monomer (VCM), generated 1.2 million tons of $CO_2$ per year. To reduce $CO_2$ emissions, the firm made use of diverse technology options such as improving process efficiency and substituting energy sources. For instance, H-Chem substituted methanol (a byproduct of its own manufacturing process) for coal-based energy sources, reducing $CO_2$ by approximately 4000 tons per year. H-Chem also monitored GHG emissions from its plants by establishing a carbon inventory system in 2008. However, the firm showed little interest in developing and adopting new process technologies because its managers believed that the process technology for producing VCM was already mature. Recently, H-Chem considered reusing conventional coal-based energy sources because its production volume continued to increase, making power shortages a more serious problem. H-Chem planned to build a cogeneration plant by using coal as the raw material for electricity, which would result in a sharp increase in its $CO_2$ emissions. A manager at H-Chem described this situation as a dilemma. Although there was increasing pressure on H-Chem to reduce GHG emissions, it required more electricity, and it did not possess any innovative process technology that could address this challenge. He mentioned that the firm had no choice but to wait for GHG treatment technologies to become economically viable.

#### 4.4.6. Case 6: S-Steel (from the "all-round" to the "all-round" strategy)

S-Steel was the largest steel manufacturer in Korea. It generated approximately 650 million tons of $CO_2$ per year, making it the single largest emitter of $CO_2$ in Korea. S-Steel considered GHG abatement to be the most critical and strategic issue because it was deeply related to energy use, production costs, and regulation compliance. The firm addressed this issue by taking various approaches, including the development of breakthrough technologies for producing steel, the improvement of production efficiency, the establishment of monitoring systems for GHG emissions, and the acquisition of emission credits. For instance, S-Steel successfully introduced FINEX, a second-generation steelmaking technology that does not require the preparation of iron ore and thus reduces $CO_2$ emissions dramatically. The firm also established a carbon inventory system that enabled its managers to accurately monitor GHG emissions from manufacturing sites and increased its own carbon fund to search for new approaches or acquire emission credits. However, reducing GHG emissions remained a huge challenge for S-Steel because it was one of the largest $CO_2$ emitters in Korea and because there was increasing regulatory and social pressure on the firm to further reduce GHG emissions. S-Steel's managers anticipated that they would consider all available

**Table 4**
Case summary.

| Items | Cases | | | | | |
|---|---|---|---|---|---|---|
| | K-Chem | Y-Chem | L-Chem | P-Chem | H-Chem | S-Steel |
| Products | Plaster boards | Ethylene | PVC, ABS, PE | Synthetic rubber | VCM | Steel |
| Anticipated change in the technology strategy | "wait-to-see" → "treatment-reliance" | "in-process-focused" → "treatment-reliance" | "in-process-focused" → "inbound-substitution" | "in-process-focused" → "all-round" | "all-round" → "treatment-reliance" | "all-round" → "all-round" |
| GHG emissions (ton $CO_{2e}$/year) | 20,000 | 3 million | 3 million | 150,000 | 1.2 million | 650 million |
| Characteristics | ■ Low GHG emissions (low pressure to reduce emissions)<br>■ Low awareness of the issue of GHG emissions<br>■ No other breakthrough production technologies | ■ High GHG emissions (high pressure to reduce emissions)<br>■ High energy efficiency achieved<br>■ Comparative economics of GHG treatment technologies | ■ High GHG emissions (high pressure to reduce emissions)<br>■ High energy efficiency achieved<br>■ Very mature production technology (no other breakthrough production technologies) | ■ Relatively low GHG emissions<br>■ High awareness of the issues surrounding GHG emissions and global warming<br>■ Production innovation capabilities | ■ High GHG emissions (high pressure to reduce emissions)<br>■ High energy efficiency achieved<br>■ Huge increase in production and energy (no other breakthrough production technologies) | ■ Very high GHG emissions (very high pressure to reduce emissions)<br>■ High awareness of the issue of GHG emissions<br>■ Production innovation capabilities |

technology and management options. First, the firm continued to invest in developing and adopting breakthrough technologies such as the hydrogen-reduction process, while benefiting from energy efficiency improvements in existing operations. Second, S-Steel anticipated making dramatic reductions in GHG emissions by substituting next-generation products such as the super-high-strength steel plate for the existing steel plate. This new product is 10% lighter than existing products, allowing it to reduce production-related $CO_2$ emissions by more than 13%. Third, S-Steel considered substituting some of its existing fossil fuel sources with renewable energy sources such as photovoltaic power generation. Finally, S-Steel anticipated using new GHG treatment technologies such as CCS to reduce $CO_2$ emissions if no other technology options could help S-Steel to achieve future GHG reduction targets.

*4.4.7. Summary of cases*

These cases demonstrate that the firms changed their technology strategies for reducing GHG emissions continuously (Table 4). However, they showed different trajectories. The results identify four factors influencing anticipated changes in the firms' technology strategies: (1) the firm's awareness of the issue of GHG emissions, (2) the maturity of production technologies, (3) the comparative economics of technology options, and (4) production innovation capabilities.

First, firms that are not sensitive to GHG emissions and climate change are more likely to employ GHG treatment technologies. For example, K-Chem was not sensitive to GHG emissions and was thus reluctant to address the issue. Thus, K-Chem is likely to consider GHG treatment technologies first when it is forced to reduce GHG emissions. Second, the maturity of production technologies is likely to influence firms' choice of technology options for reducing GHG emissions. The more mature the production technology, the more likely the firm is to depend on treatment and inbound substitution technologies because managers tend to conclude that mature production technologies leave little room for further improvements in the production process, thereby seeking outside solutions. Third, technology strategies for reducing GHG emissions vary according to the comparative economics of technology options. For example, Y-Chem and H-Chem anticipated using the "treatment-reliance" strategy in the near future, whereas L-Chem focused on the "inbound-substitution" strategy. Such differences in the trajectory of technology strategies are induced by differences in firms' perspectives on the comparative economics of technology options. Y-Chem and H-Chem managers expected that end-of-pipe technologies for GHG capture and treatment would be more economically viable than energy source or raw material substitution technologies because they believed that the latter would require a more dramatic change in the product formula or deeper collaboration with energy providers, whereas L-Chem managers believed otherwise. Fourth, firms' innovation capability may have considerable influence on their choice of technology options for reducing GHG emissions. For instance, P-Chem and S-Steel anticipated following the "all-round" technology strategy in the near future. Their production innovation capabilities, accumulated through investments in new production technologies such as the ultra-low-temperature polymerizing process and FINEX technology, enabled P-Chem and S-Steel to continue their search for a wider range of technology options for reducing GHG emissions.

## 5. Conclusion

*5.1. Research contributions and implications*

The present study analyzed existing and anticipated technology strategies for reducing GHG emissions in Korea' petrochemical and steel industries by conducting a cluster analysis and case study. First, the results identify three types of technology strategies employed by firms in Korea's petrochemical and steel industries: the "wait-and-see", "in-process-focused", and "all-round" strategies. Second, the results suggest that energy-saving and process innovation options are the most widely adopted and implemented technology options in Korea's petrochemical and steel industries. However, inbound options involving energy sources and raw materials are expected to emerge within 5–10 years as one of the most widely used technology alternatives for reducing GHG emissions. Third, existing technology strategies are expected to be replaced by the following technology strategies in the near future: the "treatment-reliance", "inbound-substitution", and "all-round" strategies. Fourth, there may be dominant transition paths from existing to anticipated strategies. The "wait-and-see" firms are likely to move toward the "treatment-reliance" strategy within 5–10 years, whereas most of the "in-process-focused" firms are expected to shift to the "inbound-substitution" strategy. Most of the "all-round" firms are likely to maintain their existing technology strategies in the future. The results of the case study identify four factors influencing changes in firms' technology strategies: the awareness of the issue of GHG emission, the maturity of production technologies, the comparative economics of technology options, and production innovation capabilities.

This study contributes to the literature in the following ways: First, this paper proposes a framework for conceptualizing firms' technology strategies for reducing GHG emissions. The framework combines several technology options that are specifically related to GHG reductions and indicates the radicalness of technological innovation and the energy/material flow. The five technology options—the energy-saving, process innovation, energy source substitution, raw material substitution, and GHG treatment options—are expected to provide a better understanding and a more accurate characterization of firms' technology selection and implementation in response to the GHG issue from business and strategic perspectives. Second, few studies have explored the technology transition in response to climate change and GHG emissions. In this regard, the present paper provides important insights into how firms' choice of technology strategies for reducing GHG emissions may change in the future and why. Third, this study's framework and findings can be applied to other countries in Asia (e.g., China and India) because recent situations in these countries are very similar to those in Korea. For example, GHG emissions in China and India have increased sharply, making GHG reductions one of the most important policy issues in these countries. In addition, the petrochemical and steel industries in China and India rank among the heaviest polluters. However, the level of their energy efficiency has increased sharply, reflecting the levels in Western countries and Korea. Thus, petrochemical and steel firms in Asia are likely to search for a wider range of technology options for reducing GHG emissions in the near future, which can lead to the use of different types of technology strategies.

The results of this empirical study have a number of important implications for practitioners as well as for policymakers who are serious about reducing GHG emissions and mitigating climate change. First, the tightening of GHG emission standards in Asia has put increasing pressure on major polluters such as the petrochemical and steel industries. Firms in energy-intensive industries have relied mainly on technology options such as energy efficiency and process improvements to reduce GHG emissions. Firms in the petrochemical and steel industries should consider a wider range of technology options such as raw material/energy source substitution and GHG treatment options. Second, changes in technology strategies for reducing GHG emissions are influenced by several factors, including the firm's awareness of the issue of global warming, the maturity of production technologies, the comparative economics of technology options, and production innovation capabilities. Among these, firms' accumulated innovation capability is the most important enabler of firms' efforts to seek and adopt a wider range of technology options. In this regard, firms should continue to invest in, develop, and secure breakthrough production technologies. Third, GHG treatment technologies represent one of the most important technology options for reducing GHG emissions in the near future. However, such technologies (e.g., CCS) are in the early stages of development. Thus, the cost of installing GHG treatment equipments is not expected not to decline to economically self-sustaining levels until 2030 (McKinsey & Company, 2008). In this regard, firms should carefully monitor the developmental trajectory of GHG treatment technologies and consider alternative strategies for reducing GHG emissions to prepare for an event in which appropriate treatment technologies are not available. Fourth, firms in the petrochemical and steel industries should focus more on substituting renewable energy sources for existing fossil fuel sources. The adoption and implementation of renewable energy sources depend heavily on the technological progress of the utility industry as well as on changes in the country's national grid. Therefore, firms should cooperate with related industries such as the utility and raw material industries when choosing the inbound substitution option to reduce GHG emissions.

Finally, the results of the case study clearly illustrate that firms with sufficient production innovation capabilities are likely to pursue the "all-round" option for reducing GHG emissions. In addition, well-designed and appropriate policies can induce firms to seriously consider environmental issues such as climate change in their decision-making processes, which in turn can enhance their environmental performance through innovation (Porter and Van der Linde, 1995). This implies that policymakers should induce the petrochemical and steel industries to focus more on reducing GHG emissions by implementing measures such as mandatory emission reduction targets and market-based emission trading schemes (Lee, forthcoming).

### *5.2. Research limitations and future research*

This study suggests directions for future research by stating some limitations. First, the survey results may not accurately reflect near-term outcomes because the respondents answered the questionnaire based entirely on their personal expectations. In this regard, future research should verify this study's results, particularly those for anticipated changes in technology strategies, by employing longitudinal data. Second, the sample was obtained from directories targeting specific industries. However, the relatively small sample might have led to some statistical bias. Third, the survey was limited to the petrochemical and steel industries, and thus, the generalizability of the results to other industries may be limited. In this regard, future research should employ longitudinal data, address more specific technology options, and include a wider range of industries to provide a better understanding of technology strategies for reducing GHG emissions.

## Appendix. Questionnaire items

*Existing technology options* *(1 = very low to 5 = very high)*

Our company (or production plant) has been adopting and implementing the following technologies to reduce greenhouse gas (GHG) emissions:

Energy-saving and efficiency improvements.
New process technologies (process innovation)

Energy source substitution (e.g., renewable energy purchasing)
Raw material substitution (e.g., formula change and carbon-free material use)
GHG (e.g., $CO_2$, methane, and $N_2O$) capture and storage systems.

*Future technology options* *(1 = very low to 5 = very high)*

Our company (or production plant) is planning to adopt and implement the following technologies to reduce greenhouse gas (GHG) emissions in 5–10 years:

Energy-saving and efficiency improvements.
New process technologies (process innovation)
Energy source substitution (e.g., renewable energy purchasing)
Raw material substitution (e.g., formula change and carbon-free material use)
GHG (e.g., $CO_2$, methane, and $N_2O$) capture and storage systems.

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