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Investigation of Industries Using Superheated Steam and Expected Effects of Using Small Modular Reactor as Heat Source with Superheating Technology

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1. Introduction

Recently, in response to the climate crisis, there has been an emphasis on greenhouse gas reduction policies in South Korea. As part of these efforts, initiatives such as RE100 (Renewable Energy 100) and CF100 (Clean Future 100) have gained attention. Thus, industries with high greenhouse gas emissions, including steel, cement, automotive, semiconductor, and display manufacturing, among others, require the development of technologies to achieve carbon neutrality.

However, the geographical characteristics of South Korea make it difficult to achieve practical carbon neutrality with renewable energy only. Therefore, in the situation of South Korea, CF100 is being prioritized over RE100 as a policy. This signifies the emergence of nuclear power generation as a method to produce heat and electricity without emitting carbon dioxide into the atmosphere, and economically produce electricity.

To accelerate the transition to clean energy within the next 30 years and address the increasing demand for power, measures are being taken to stabilize the electricity supply. As a response, there is a policy initiative to mandate the installation of distributed energy sources, as outlined in the "Special Law on the Activation of Distributed Energy." This policy aims to promote the installation of distributed energy sources and expand sustainable energy use.

The Small Modular Reactor (SMR) has minimal site constraints, enabling it to serve as a distributed energy source. It plays a role in addressing intermittency issues associated with variable renewable energy sources such as solar and wind energy. Additionally, it can replace coal-fired power plants, provide steam for heavy industries, and be integrated with hydrogen production, showcasing its versatility and potential for innovation as a clean energy source.

The steam cycle of innovative SMR utilizes steam at approximately 300 degrees Celsius to generate 170MWe of power [1]. Subsequently, some of the steam can be used to supply heat to various industrial processes, including steel production, cement manufacturing, and hydrogen production, through post-combustion steam superheating technology (Fig 1).

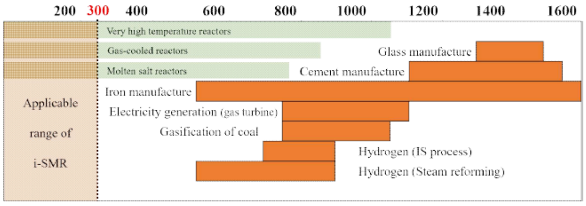

Fig 1. Temperature range by product process and temperature range of 4th generation reactors and innovative SMR [2]

This can lead to a reduction in carbon dioxide emissions generated during the production of saturated steam. From Figure 2, 27% of the carbon dioxide generation in South Korea occurs in the manufacturing and construction industries. Most of the carbon dioxide generation in this field is caused by fossil fuel combustion to produce high-temperature heat and steam. Therefore, in this study, the authors will find out the industries that account for a significant proportion of CO_2 emissions and suggest a technical approach to reduce greenhouse gas emissions by using low temperature steam from SMR and superheat to increase temperature for industrial application.

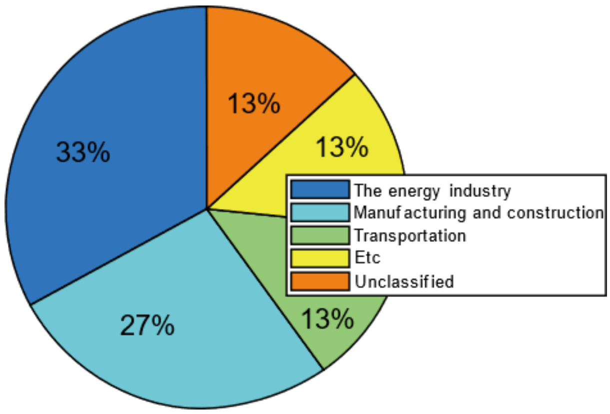

Fig 2. Carbon dioxide emissions by sector in the domestic energy field [3]

2. Review of industrial sector

2.1 The petroleum chemical industry

The petrochemical industry is an industry that produces basic hydrocarbon feedstocks from the distillation of crude oil, using petroleum products such as naphtha and natural gas as raw materials. This process results in the production of unsaturated hydrocarbons, which are then utilized to manufacture synthetic resins (plastics), synthetic fibers (polyester, nylon), synthetic rubber, various basic chemical products, intermediate chemicals for precision chemistry, and compounds. The maximum temperature in the production process ranges from 800 to 850°C. As of 2019, the greenhouse gas emissions stood at approximately 7.2244 million tons of CO_2 equivalent, making the petrochemical industry the second-largest emitter of greenhouse gases in the South Korean industrial sector [4]. The industry's greenhouse gas emissions account for approximately 8.5% of the total national emissions and about 15.3% of the industrial sector emissions. As shown in Table 1, fuel combustion accounts for nearly half of greenhouse gas emissions in the total petrochemical and oil refining industries. Utilizing steam produced by innovative SMRs in the pyrolysis process with the application of superheating technology is expected to reduce the amount of carbon dioxide emitted during fuel combustion.

[Table 1. Greenhouse gas emissions from petrochemical and oil refining industries (1000 tonnes of carbon dioxide[5])

		2018	2019	2020
Fuel combustion	Oil refining	17,434	20,136	17,797
	Chemistry	26,401	28,779	31,490
Evasion	Oil	276	269	246
Industrial process and production	Chemistry	30,956	29,819	28,875
Indirect emission (electricity)	Oil refining	6,370	6,079	5,156
	Chemistry	24,025	22,303	19,275
Sum		105,463	107,385	102,838
Percentage of total national emissions (%)		14.00%	14.50%	14.80%

2.2 The steel industry

The steel industry is an industrial sector that involves melting iron-containing materials such as iron ore and iron scraps to produce molten iron. After reducing impurities, the molten iron undergoes processes such as casting and rolling to produce final steel products such as hot-rolled steel sheets, cold-rolled steel sheets, plates, rebars, and steel pipes. The maximum temperature required in the production process ranges from 600 to 1600°C. In 2019, the steel industry emitted approximately 1.2061 billion tons of CO_2eq (CO_2eq is the amount of greenhouse gas emissions converted into carbon dioxide, the representative greenhouse gas.) in greenhouse gases, making it the industry with the highest greenhouse gas emissions in the South Korean industrial sector. The global steel market size, as of 2023, is estimated to be $110.23 billion [6]. Therefore, if the steam produced by the innovative SMR is used for the reduction of iron ore by applying superheating technology, it is expected to reduce the amount of carbon dioxide generated in the process of generating heat and steam.

2.3 Hydrogen production industry (high-temperature water electrolysis)

Solid oxide electrolysis cell differs from conventional electrolysis as it is a hydrogen production method where steam is electrolyzed at high temperatures to produce hydrogen, allowing for more efficient utilization of electrical energy. The required maximum temperature during the process ranges from 650 to 850°C, and the overall market size for hydrogen production was $329 million as of 2020. If 15.03 kg of carbon dioxide is generated for 1 kg of hydrogen production from steam methane reforming method, the derived carbon dioxide emissions from hydrogen production are calculated to be 33.66 million tons as of 2020. The introduction of steam superheating technology is expected to reduce the carbon dioxide emissions generated during the steam production process. According to Figure 3, it is anticipated that energy equivalent to 10 kWh/kg, consumed during the steam generation process (Stage 1), can be saved, and utilizing a nuclear-integrated Solid Oxide Fuel Cell (SOFC) system can result in a 25% reduction in overall energy consumption.

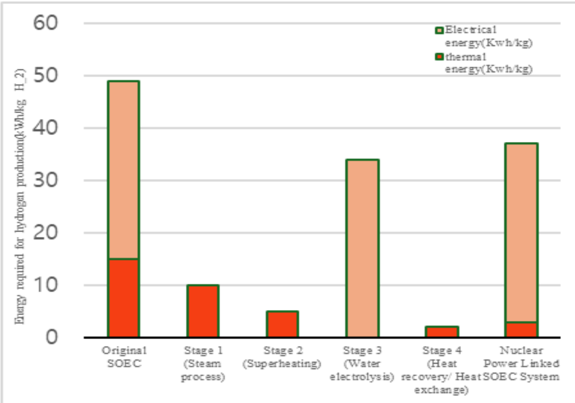

Fig 3. Example of Thermal Energy Reduction Effect of SOEC system [7]

2.4 The cement industry

The cement industry involves extracting raw materials such as limestone and using various mixing processes and chemical reactions to produce cement. This industry requires high temperatures during the calcination process (preheater - 900°C, kiln - 1450°C). As of 2019, the greenhouse gas emissions were approximately 42.54 million tons of CO_2eq, and the market size was $34.348 billion as of 2022, expected to grow to $53.743 billion by 2030. Greenhouse gases emitted from the cement industry are primarily composed of CO_2 generated during the thermal decomposition process of limestone used as a cement raw material (Process CO_2), accounting for about 60%. The combustion of fossil fuels (bituminous coal) used for clinker production contributes to the remaining 40% of CO_2 emissions (Combustion CO_2). If steam produced by innovative SMRs is utilized in clinker production with the application of superheating technology, it is anticipated that the amount of carbon dioxide generated during the steam saturation process will decrease.

3. Steam superheating technology

3.1 H_2 oxy-combustion

Hydrogen pure oxy-combustion is an emerging power generation technology that combusts hydrogen and pure oxygen. Hydrogen pure oxy-combustion turbines have advantages over fuel cells in terms of economics and technology maturity because they can reutilize existing baseload infrastructure to generate additional large-scale power without carbon emissions, and the unit cost of power generation is expected to be like that of the connected baseload. Previously, only heat required for district heating and desalination could be supplied by SMRs, but if superheated steam of about 300 degrees Celsius produced by pressurized water reactor-type SMRs is raised to 500 degrees Celsius or higher with pure oxygen combustion of hydrogen, the high temperature steam can be supplied to industries that require high-temperature heat. In the case of high-temperature water electrolysis using pressurized light water reactors, the steam temperature is below 300ºC, so an additional heat source is required to heat the steam to 750ºC, but the energy required for steam heating is from 300ºC to 700ºC is only about 30% of the total heating energy compared to the energy used to produce 750ºC steam from liquid water at room temperature [8].

3.2 Electric heaters

Heating method utilizing an electrical heater can be also considered. The process allows for precise temperature control and fast response time, making it ideal for industrial processes that require precisely controlled heating. Components such as heating elements, insulator, and control systems are needed, which maximize the efficiency and safety of the heating process. Electric heaters have a low environmental impact due to the absence of combustion, and low heat losses due to the direct conversion of electricity into heat [9]. However, the method has limit on the maximum achievable temperature due to the limitation on the heater surface material which can potentially corrode due to high temperature steam. Moreover, since electricity is a valuable commodity to produce from nuclear heat, thermodynamically the whole process can be destroying exergy needlessly too much.

4. Conclusions

Table 2. The expected reduction of CO_2 emission (in 10,000 tonnes of carbon dioxide)

	2019	2020
The petroleum chemical industry	92,472	
Steel industry	116,345	
Hydrogen production industry		330.66
Cement industry	38,833	
Sum	247,650	330.66

South Korea is planning to install more renewable energy and increase the installation of distributed energy to reduce greenhouse gas emissions. It is possible to reduce greenhouse gas emissions by utilizing steam superheating technology combined with nuclear, especially in industries that require high-temperature process heat. The application of the suggested technology to petrochemical, steel, hydrogen production, and cement industries is expected to contribute to the industrial sector's reduction of greenhouse gases. To reach the high temperature requirement of industries, a technology is needed to superheat steam by 300~500 ºC more from the SMR produced steam. As shown in Figure 4, SMR can separate some steam after power generation and increase it to 500 degrees Celsius or higher by applying superheating technology to the low temperature steam.

Therefore, a future innovation for iSMR that can be developed is to not only serving as a distributed energy source but also provide high temperature process heat to the industries via superheating steam in a renewable way.

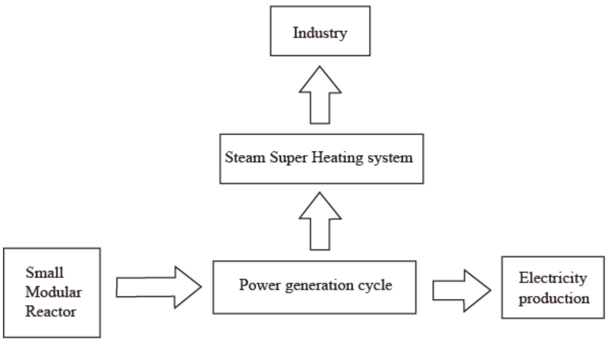

Fig 4. Design of SMR with steam superheating system

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