# TECHNO-ECONOMIC EVALUATION OF HYDROGEN INFRASTRUCTURE FROM RENEWABLE ENERGY RESOURCES: APPLICATION TO KOREAN HYDROGEN ECONOMY

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**Abstract**— In this study we present a new framework for the design and economic evaluation of hydrogen infrastructure using renewable energy resources. First, we model a renewable hydrogen supply system (RHSS) including various renewable energy resources along with hydrogen technologies such as production, storage and transport. We then develop a multi-period deterministic optimization model for the RHSS using a mixed integer linear programming (MILP) technique. With the proposed model we identify the optimal RHSS configuration and its operation strategy. We finally apply the model to design problem of the hydrogen infrastructure for the future Korea.

**Index Terms**— Hydrogen, MILP, Optimization, Renewable Energy.

## I. INTRODUCTION

The growing concern about the depletion of fossil fuels and climate change by its combustions have motivated research efforts to develop a sustainable and eco-friendly energy system. Especially, energy issues in the transportation sector need to be resolved immediately, since it accounts for roughly an 18% and 25% of the carbon dioxide emission and primary energy use, respectively [1-3].

Hydrogen is one of attractive alternative energy carriers because it can be used to power fuel cell vehicles which have near-zero carbon dioxide emissions [4,5]. In addition, hydrogen can be produced from various primary energy resources such as non-renewable (e.g. natural gas, coal and petroleum) and renewable resources (e.g. biomass, solar, wind energy) [6-8]. This diversity of available energy resources, contributes to highly secure fuel supplies without energy imports from foreign countries[5,6,9,10].

The hydrogen infrastructure issues suchas producing, storing and delivering hydrogen should be addressed before introducing such a wide use of hydrogen in real world[1,5,6,10]. Thus, how to design and manage the hydrogen infrastructure can play a critical factor to achieve success of hydrogen as an energy carrier and fuel [9,10].

Many attempts have been made for design and analysis of hydrogen infrastructure; the design and operation of hydrogen supply chain including production, storage and transportation of hydrogen [9,11-13]; the studies about demand uncertainty for hydrogen supply chain [5,10,14]; the multi-period model to address the optimal design and planning for hydrogen supply system [15-18];other topics about hydrogen infrastructure such as environment impact and safety and life cycle assessment (LCA) [19-24].

Although hydrogen is an eco-friendly energy resource, it should be produced from renewable energy source (RES) via green technology in order to minimize overall carbon dioxide emissions [25-28]. For instance the amount of emitted $CO_2$ in the stage of the hydrogen production from fossil fuels is almost same to that amount by fossil fuels combustion [29-32].

Many studies have dealt with the problems of assessment and analysis of hydrogen production system from RES; the estimation of potential for renewable energy source (RES) based hydrogen production [25-28]; the economic evaluation of hydrogen production from wind [29-31], PV [32-34] and biomass [35-37]; the design of RES based hydrogen supply chain [38-40].

In spite of the large number of assessment of renewable hydrogen production system, there is lack of study for (1) the integration of various types of different renewable sources and technologies, and (2) the assessment of seasonal and regional data of RES.

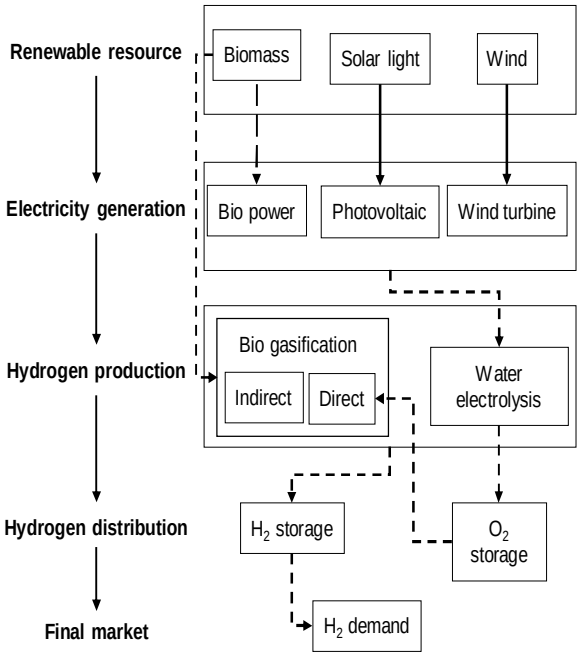



**Fig. 1 Superstructure of renewable hydrogen supply system.**

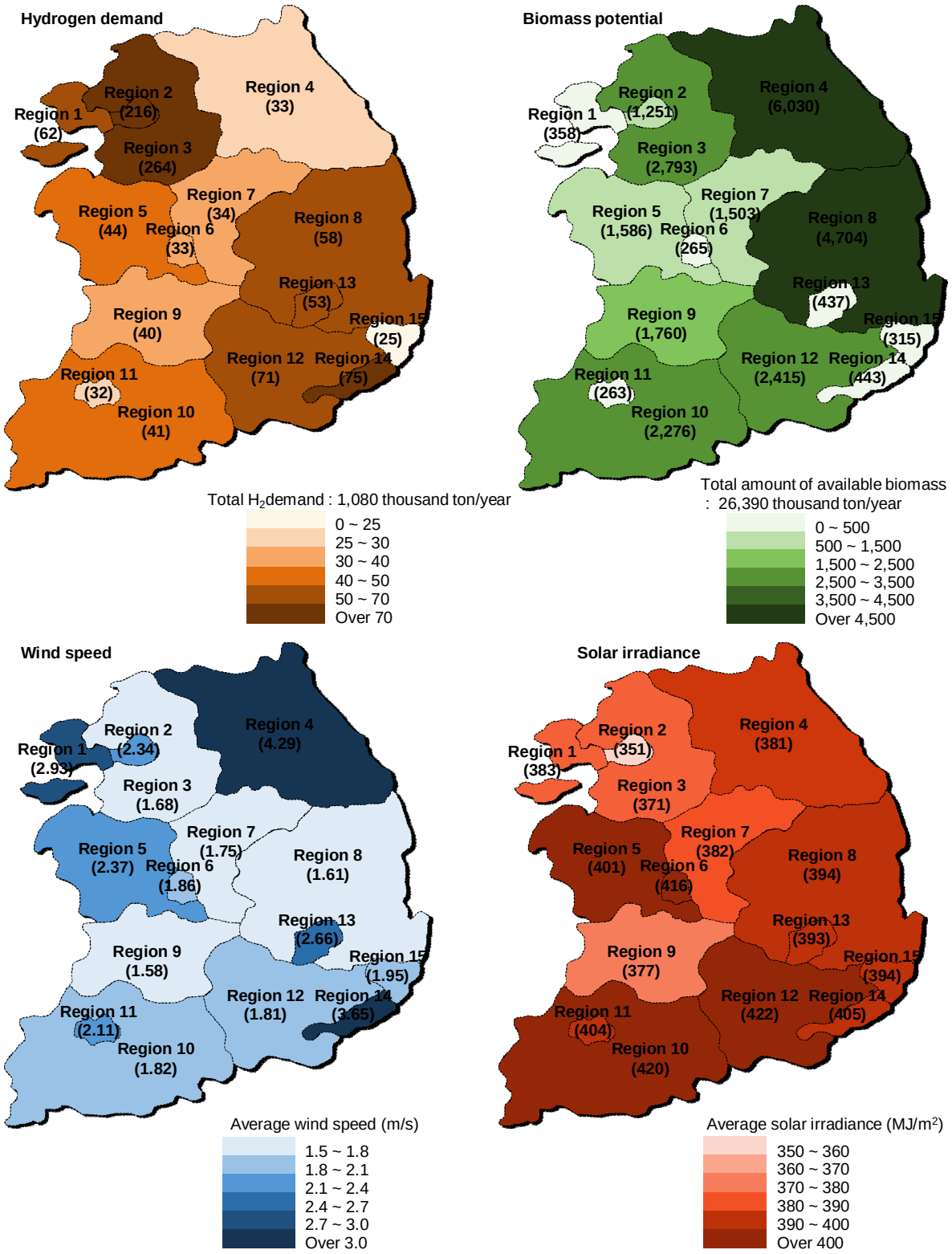



**Fig. 2 Hydrogen demand, biomass potential, wind speed and solar irradiance of Korea.**

Accordingly, the goal of this paper is to develop a methodical framework for the design, operation and techno-economic evaluation of RES based hydrogen supply system. In developing this framework, this study (1) generates the Renewable Hydrogen Supply System (RHSS). The RHSS includes various primary renewable sources, and storage, production and transportation technologies of hydrogen (2) develops a multi-period deterministic optimization model for the optimal design and operational strategies of the RHSS with the time-varying regional hydrogen demand and the potential of RES, and (3) applies the proposed model to the renewable hydrogen system of future Korea.

This paper is composed as follows. Section 2 introduces the features of the RHSS. The mathematical formulation of the optimization model (MILP) is described in section 3. In section 4, a real case study of Korea is used to demonstrate the feasibility of the proposed model and section 5 discusses the obtained results of the case study.

## II. RENEWABLE HYDROGEN SUPPLY SYSTEM (RHSS)

The main objectivesof this study are (1) to create the multi-period deterministic optimization model for designing the RHSS bydetermining the optimal configuration and operational strategy withthe minimized total network cost and (2)to evaluate the techno-economic feasibility of the RHSS by comparing the results to economics of other energy systems. The superstructure of the RHSS is shown in Fig. 1.

## III. OPTIMIZATION MODEL

To achieve the goal of this study, we develops a new multi-period deterministic optimization model which is extended based upon the previous works [9-11]. Particularly, the proposed model is formulated as an MILP to include the variables for the integration technologies and temporal changes of demand and RES. The model for the optimal planning and design of hydrogen infrastructures is summarized as follows:

$$\underset{x,y}{\text{Minimize}}\ U\{\textit{Total network cost}\}$$

$$\text{Subject to}$$

$$\left.\begin{array}{ll} & \text{Demand satisfaction} \\ & \text{Mass \& energy balance} \\ h(x,y)=0 & \text{Renewable energy source selection} \\ g(x,y)\le 0 & \text{Site allocation} \\ & \text{Transport network design} \\ & \text{Technology capacity} \end{array}\right\}$$

$$x\in\Re^{n},\ \ y\in Y=\{0,1\}^{m}$$

where the goal is to find values of the operational (x)and strategic (y) decision variables, subject tothe set of equality (h(x, y)) and inequality (g(x, y))constraints, such that the objective function (U) is optimized.

## IV. CASE STUDY: THE HYDROGEN SUPPLY CHAIN IN REPUBLIC OF KOREA

To illustrate the capability of the proposed model, we apply the model to design problem of hydrogen infrastructure of Korea in the future. First we divide Korea into fifteen administration regions and consider twelve month as a time period to plan monthly operation strategy. Thus, there are regional and monthly differences in the demand profile as well as in the potential of RESs. For instance, when the potential of biomass in a certain region during a specific time period is high, that of wind or solar energy might be low.

To conduct the Korea design problem, a lot of economic and technical parameters of the selected technologies such as minimum and maximum capacities, capital cost, unit operating cost and conversion efficiency are needed. In this study, we adoptedthe parameters from the previous works [9-11]. The regional hydrogen demand and the RES potentials (biomass, wind speed and solar irradiance) of Korea aredepictedin Fig. 2.

## V. RESULT AND DISCUSSIONS

The results of optimization including the optimal configuration and operational strategy of the RHSS of Korea is shown in Figs. 3 and 4, respectively.

As shown in Fig. 3 129 bio direct gasification (large size) and 56 electrolysis (medium size) facilities are established to satisfy the required hydrogen demand. Especially, Region 4 has the highest number of bio direct gasification facilities (36), due to the low cost of site for facility and the highest potential of biomass. Although Regions 2, 6, 11, 13 and 14 require the relatively high hydrogen demand, a hydrogen production facility is not installed in these regions because these regions are the high population density and the relatively expensive cost of site for facility.

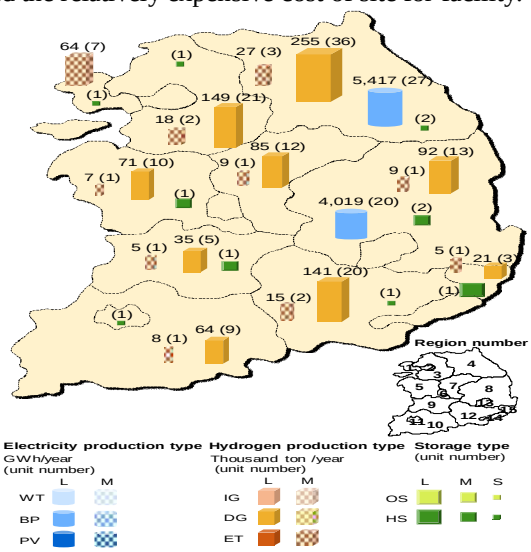



**Fig. 3 Optimal network configuration in future Korea.**

In addition, Fig. 3showsthat 47 bio power facilities are established for supplyingthe generated electricityto electrolysis facilities which are installed for hydrogen production.On the other hand, PV and wind turbine are not established in all regions at all; this is due to the low irradiance level and wind speed in Korea. Fig. 4 presents the monthly flow rate of hydrogen, biomass and oxygen of four seasons; we selects the only results of January, April

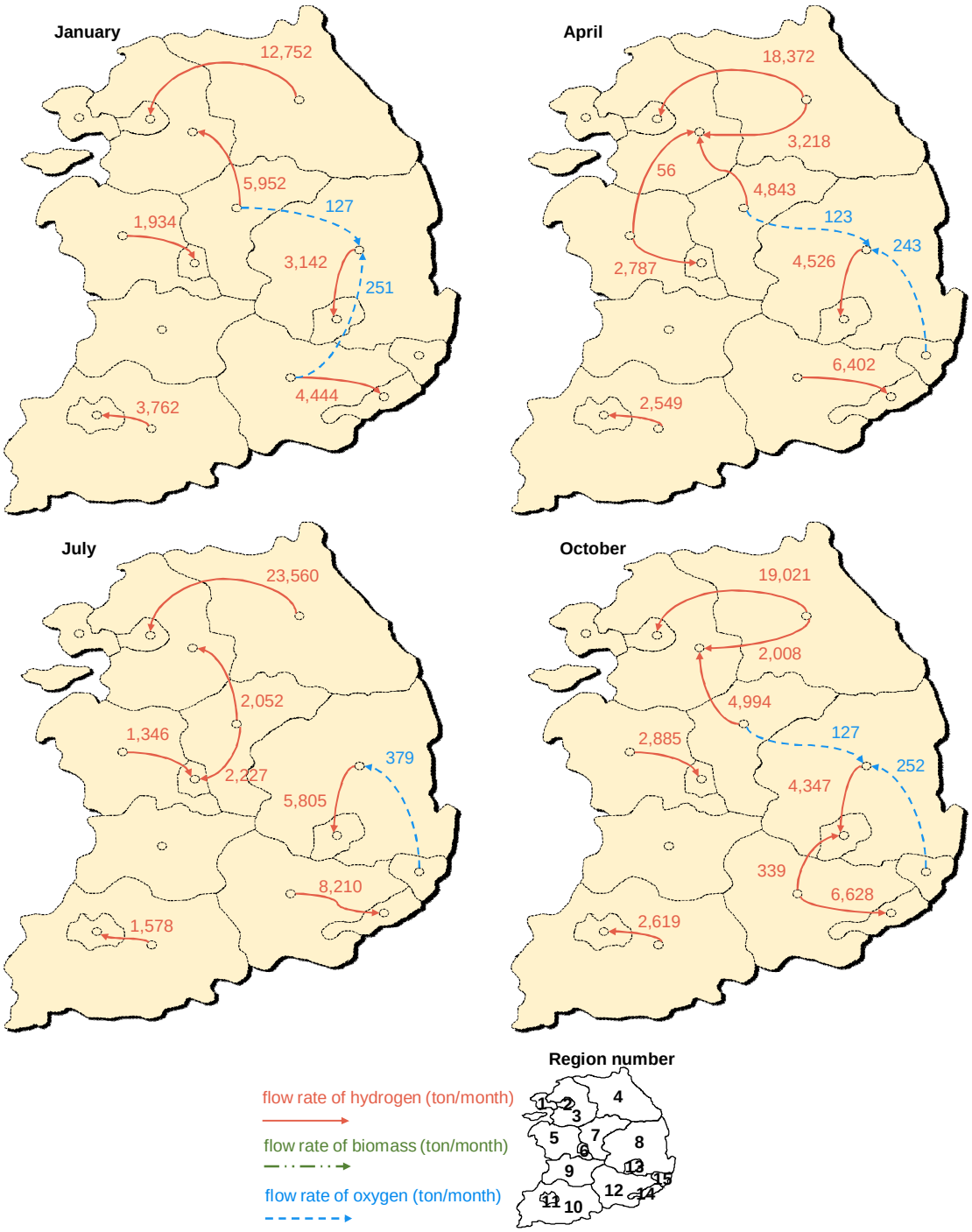



**Fig.4 Optimal network distributions of hydrogen, biomass and oxygen in four seasons.**

July and October because these month represent well the variation in hydrogen demand. Regions 2, 3, 6, 11, 13, and 14 are completely fulfilled by the imported hydrogen from neighboring regions across all time period. The reason for this is that the import of hydrogen from other regions is cheaper than establishing production facilities for self-satisfaction.

In addition, it can be found that oxygen is also transported. This is because the amount of oxygen generated in region 8 is not enough to operate direct gasification facilities installed in region 8. It is explained by the fact that the establishment of both direct gasification and electrolysis facilities is profitable than energy production only by the indirect gasification or electrolysis.

The costs of the examined network configuration are summarized in Table 1. As seen in this table, the costs of facilities and biomass feedstock are the cost driver of total network cost. The main reason for this is that the investment cost of renewable facilities is expensive and the amount of hydrogen produced from direct gasification facilities accounts for 84.4% of the total production of hydrogen.

To analyze the competitiveness of the proposed RHSS

of Korea, we compare the result to other renewable hydrogen systems: wind-based hydrogen (WT-EL), PV-based hydrogen (PV-EL), bio-power-based hydrogen (BP-EL) systems, and the hydrogen system from such three resources (ALL-EL).Fig. 5 shows the levelized cost ($/kg of $H_2$) of four hydrogen systems along with the result of our study. The worst system is the production of electricity from PV facilities followed by hydrogen production of electrolysis at $14.54 per kg of hydrogen, satisfying the huge demand of future Korea. Note that the production of hydrogen only by direct gasification is shown in Fig. 5, since it cannot be operated without the excessed oxygen from the electrolysis facility.

| **Table 1 – Breakdown of total network cost to hydrogen infrastructure ($/year)** | |
|---|---|
| **Capital costs** | |
| Facilities | 8.34 E+08 |
| Transportation modes | 8.79 E+07 |
| Land cost | 4.84 E+08 |
| **Operating costs** | |
| Facilities | 2.22 E+08 |
| Transportation modes | 4.71 E+08 |
| Biomass feedstock | 9.64 E+08 |
| **Total supply cost** | 3.06 E+09 |
| **By product credit** | |
| Electricity sale | - |
| Oxygen sale | 3.41 E+07 |
| **Total network cost** | 3.03 E+09 |
| **Levelized cost of hydrogen ($/kg of hydrogen)** | **3.08** |

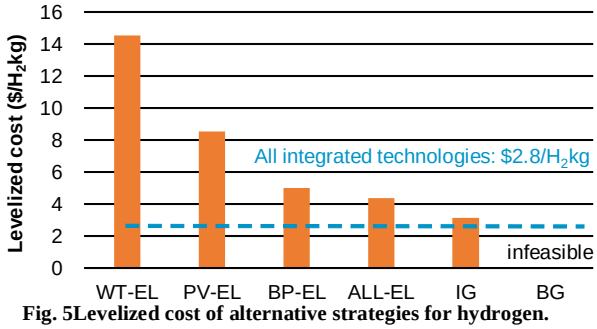



**Fig. 5Levelized cost of alternative strategies for hydrogen.**

## CONCLUSIONS

In this study, we presented an optimization-based approach for systematic design and analysis of renewable hydrogen supply system. Based on the superstructure that includes various types of RESs and technologies such as production, storage and transportation, we developed a multi-period deterministic optimization model to determine the optimal configuration and operational strategy of theRHSS. Then, we apply the proposed model to the design problem of the future Korea hydrogen economy.

As a result, major findings are as follows;

- The RHSSof Korea is kind of the centralized system, major production facilities are located to the northeast regions (regions 4 and 8).
- Direct gasification of biomass and water electrolysis using renewable electricity are the most profitable hydrogen production ways in Korean situation.
- The resulted total network cost of the RHSS of future Korea is estimated to be 3.08$/kg of $H_2$, which show the system is a relatively competitive system to other systems.

While this study focused on design and operation of a future hydrogen using a *snap-shot method*. Future research needs to be extended to study a long-term investment strategy for economic transitionto a sustainable hydrogen supply system.

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