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# Design and operation of renewable energy sources based hydrogen supply system: Technology integration and optimization

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ABSTRACT

The benefits of hydrogen as a clean and efficient fuel can be realized fully only when hydrogen is produced from renewable energy sources (RES). In this study, a new methodology is proposed to identify the optimal configuration and operation of an RES-based hydrogen supply system. The key is a superstructure-based optimization model using mixed-integer linear programming (MILP), which can integrate multiple resources and various technologies, such as electricity generation (e.g., wind turbine, photovoltaic panel, and dish-stirling power systems) and hydrogen production technologies (e.g., water splitting using alkaline electrolyzer and biomass gasifier), to minimize the total annual cost. The performance of the proposed methodology was validated through an application study on Jeju Island, Korea. In the case study, process economics and main cost drivers were analyzed. In addition, the effect of integration of technologies along with different resources on the economics was discussed.

## 1. Introduction

The depletion of fossil fuels and effects to the environment from consuming them have stimulated global interests in a sustainable energy system. The current carbon-based energy system should be switched to a new energy system that can balance energy supply and demand, protect the environment, and ensure energy security and economic viability. Among various alternatives, hydrogen-based systems are one of the most promising solutions to succeed the current system.

The main advantage of hydrogen as an energy carrier is the diversity in production of primary resources. Hydrogen can be produced from not only nonrenewable energy sources, such as oil, natural gas, and coal, but also renewable energy sources (RES), including wind, biomass, and solar energy. This diversity in production source contributes significantly to balancing energy supply and demand and ensuring energy security.

Employing RES for hydrogen production is central for better transition to a sustainable hydrogen economy because hydrogen is a low- or zero-emission energy from the end users perspective [1]. For instance, the use of hydrogen in fuel cell vehicles (FCV) offers a number of advantages over using conventional transportation fuels; e.g., better fuel economy and lower greenhouse gas and air pollutant emissions [2,3]. To successfully implement the RES-based hydrogen production system, it is essential to analyze the features of the system components (e.g., RES potentials and conversion technologies) and their interactions and to design new future hydrogen systems with suitable technologies [4]. In particular, the economic viability of the RES-based hydrogen production system depends strongly on identifying the optimal configuration of the integrated system. Thus, one of the challenging questions for design of RES-based hydrogen production systems is which energy sources and what configuration should be selected with what capacity for regionally different potentials for RES and hydrogen demands?

Many studies have explored the design and integration of RES-based hydrogen production systems. Several authors have assessed the availability and potentiality of RES for hydrogen production using the approaches based on geographical information system (GIS) [5–9]. Also, researchers have developed approaches and models for the development of hydrogen production and supply systems, which range from the supply chain and infrastructure design [10–12] to a focus on the components of the

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system including hydrogen production, storage technologies, and utilization options (e.g., FCV and refueling stations) [13–17]. Recently, the hybrid renewable energy systems for hydrogen production, mainly concentrating on solar, wind, and geothermal energy options, have been studied; a new design methodology for the optimal sizing [18], a hybrid system using photochemical conversion of solar energy [19], design and implementation of hybrid systems in Turkey [20,21], an integrated solid oxide fuel cell gas turbine and biomass gasification system [22], a demonstration of a mobile renewable house [23], an exergy analysis of a hybrid photovoltaic (PV) and wind system [24], a dynamic framework of an RES-based hydrogen system for the transportation sector [25], and an exploration of resource constraints in an RES hydrogen economy [26].

Despite the numerous studies focused on the assessment of RES-based hydrogen production systems, there is a lack of study on identification of integration opportunities of different technologies that process different energy sources, and evaluation of the benefits from these integrations. There were attempts at assessment of integrated systems, but they focused on specific systems, i.e., systems with specified resource(s) and limited technology combinations.

To design the optimal RES-based hydrogen system, it is necessary to investigate all integration opportunities including energy harvesting technologies (e.g., wind, solar, and biomass power generation) and hydrogen production technologies (e.g., electrolysis, thermochemical water splitting, and biomass gasifying). In addition, it is important to identify the strategy for efficient operations of a RES-based hydrogen system to improve the economic feasibility.

In this paper, a new methodology for design and operation of an RES-based centralized hydrogen system is proposed. In developing this methodology, a superstructure including different hydrogen supply pathways from extracting the primary resource to satisfying hydrogen demand is first generated (Section 2), and then the technologies are modeled (Section 3). Based on the technical performance parameters of the technologies, a network optimization model is developed for the underlying superstructure using mixed-integer linear programming (MILP) (Section 4). Finally, the performance of the proposed methodology is investigated through application on Jeju Island, Korea (Section 5).

## 2. RES-based hydrogen supply system

The RES-based centralized hydrogen supply system is composed of various conversion technologies along with corresponding mass (e.g., water and biomass) and energy (e.g., electricity) flows. To provide a holistic view for the possible system configurations, a superstructure, which is a network-based representation, is considered (Fig. 1).

In the RES-based hydrogen supply system, five primary resources are considered: wind, solar light, solar heat, biomass, and sea water. These resources are used to produce necessary energy (i.e., electricity) and material (i.e., water) or directly converted to hydrogen. To estimate the potentials of the RESs, meteorological data, such as wind speed, solar radiation, and availability of biomass, is used. Note that the biomass in this study indicates a lignocellulosic feedstock including crop residues and woody wastes, to avoid the conflict between energy and food production [27].

The technologies considered in this study are classified into three main groups: electricity generation, hydrogen production, and hydrogen supply. Each is described in detail below.

### 2.1. Electricity generation

For the PV system, the flat plate type, which consists of a PV array and direct current (DC)-to-alternating current (AC) inverter, is considered [28]. For the solar power system, which uses concentrated solar thermal energy for electricity generation, the central tower and the dish-stirling power systems are considered. The central tower system consists of a heliostat field (focusing solar thermal energy onto a receiver at the top of the tower), central tower, receiver, and steam generation plant [29]. The dish-stirling system consists of a parabolic dish, receiver, and stirling engine. The collector focuses solar energy on the receiver, which transfers heat to the engine to work for driving an electric generator [30]. The bio power system, which is very similar to a coal-fired power plant, consists of various preprocessing processes (e.g., handling, size reduction, and drying), a combustor, a steam turbine, and an electricity generator [31]. Finally, five types of wind turbines are considered according to the power rate by blade diameter and tower height.

### 2.2. Hydrogen production

The electricity, generated by the wind turbine, PV, bio power, and solar power technologies, is used for the production of hydrogen via electrolysis technology. In this study, one type of technology, i.e. an alkaline electrolyzer, which is the most extensively used type in modern industry due to its various advantages (e.g., energy-efficient and scalable enough for mass production), is considered [32–34].

Thermochemical water splitting using solar thermal energy is also an attractive technology for large-scale production of hydrogen. Its simple processing principle leads to high energy conversion efficiency [4,35,36]. Among various types of thermochemical water splitting technologies, the Counter Rotating Ring Receiver Reactor Recuperator (CR5), which is an innovative solar thermochemical heat engine with high efficiency in solar-to-chemical conversion, is selected [36,37]. The CR5 can be built up with flexible capacity according to production strategy [38]. Whereas the CR5 is initially developed for carbon dioxide splitting to carbon monoxide production, it is also very efficient for water splitting [39].

Regarding the biomass gasification for hydrogen production, two types of technologies are considered: an oxygen-blown direct fired entrained flow (hereafter referred to as direct gasifier) and indirectly heated air blown, atmospheric fluidized bed (henceforth referred to as indirect gasifier) [40]. The required oxygen in a direct gasifier can be supplied from either water electrolysis or thermochemical water splitting technologies. Both biomass gasification technologies include not only a gasifier but also various processes that follow, such as gas clean-up, reformation, water gas shift reaction, and pressure swing adsorption [33,41,42].

### 2.3. Hydrogen supply

After production, the hydrogen is brought to appropriate pressure and transported to a storing facility that has a series of tanks to be stored as compressed hydrogen ($CH_2$). Finally, the $CH_2$ is delivered from the storage facility to the customer, to satisfy hydrogen demand.

## 3. Technology modeling

### 3.1. Electricity generation technology

#### 3.1.1. Wind turbine

The energy output generated by a wind turbine is dependent mostly on the mean wind speed at the location. To represent the behavior of the wind (i.e., the frequencies of the wind speed)