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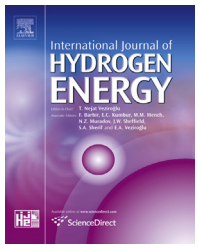

Commercial application scenario using patent analysis: Fermentative hydrogen production from biomass

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ABSTRACT

The main purpose of this study is to use patent analysis to investigate scenarios for future commercial applications of dark fermentation or anaerobic fermentation using biomass or organic matter as feedstock materials. The first step in this study includes a patent search procedure and patent content interpretation, in which 29 technology patents were identified from the US patent database and divided into five groups in accordance with the scope of their technical applications. The following five scenarios of commercial applications of biomass fermentation for hydrogen production were established through a combination of group applications: screening and cultivation of hydrogen-producing bacteria, biomass waste sources, biomass energization application, value enhancement of waste or wastewater treatment systems, and the application of a multi-functional hydrogen production system integrated with other technologies.

Introduction

The development of hydrogen production technology, hydrogen applications, and the hydrogen economy is a very important set of solutions for reducing global dependence on fossil fuels and developing a sustainable energy supply. Hydrogen production is an extremely important aspect of the development and application of hydrogen energy technology. Currently, the predominant hydrogen production methods include coal gasification, natural gas reforming, water electrolysis, solar photocatalysis, thermochemical cycles by nuclear energy, and hydrogen from biomass (or biohydrogen) [1]. Among the biohydrogen production methods, dark fermentation has excellent potential for practical application, and thus, it can be integrated with emerging hydrogen and fuel cell technologies [2]. The advantages of using biological hydrogen production include carbon emission reduction through the reuse of biomass, increase of crop revenue through the reuse of hydrogen production from waste biomass, sustainability of biomass energy, and the reduction of urban waste disposal costs [3].

The commercial production of biohydrogen must go through various developmental stages to move from the

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technology to its widespread application. Vijay reported that there are four stages of the commercialization of a new technology [4]: imagination, incubation, demonstration, and promotion. In the imagination stage, the new technology will be linked to the potential market demand and lead to new products, service concepts, and patent ideas. In the initial incubation stage of an emerging technology, the results of fundamental research will usually be presented through academic papers, while the results of application research will be reflected in the patents. Patents are useful sources of knowledge about technical progress [5]. Patent analysis, therefore, can be applied as a strategy for planning and modeling specific emerging technology developments from the macro level or the micro level [6,7].

Patent analysis is a valuable approach that uses patent data to derive information about a particular industry or technology for use in forecasting [8]. Because the patent process is costly and might take several years, filing a patent generally means that there is optimism about the economic prospects or technical contribution [9]. Levy indicated that the key features of patents, from an economic perspective, are that they encompass new knowledge and they confer monopoly rights to the owner that arise from the right to exclude [10].

Patent data analysis can be used to analyze industry trends in technological innovations [11]. Lee et al. suggested the use of patent data as a proxy measure of technological capability for business planning and building a technology-driven roadmap [12]. Patent analysis can also be used as a tool for enterprises to choose between technology options [13].

Lee et al. also pointed out that conventional patent analysis focuses on understanding the status of technology development and technology information. It does not integrate technology development and commercial perspectives, but it does confirm possible future business opportunities. Lee et al. proposed a technology-driven roadmapping process that starts from capability analysis for technology planning and ends with business opportunity analysis for market planning. They also suggested the use of patent data as a proxy measure for technological capability to complete this process [12].

To investigate the R&D status and trends in hydrogen energy and fuel cells, many scholars have conducted research on these aspects through patent analysis. Pilkington introduced a statistically driven patent-based method that identifies the technological portfolios of industry players; this method was tested using the case of fuel cell technology development [14]. Dongsheng and Xin [15] focused on the research on patents for proton exchange membrane fuel cells (PEMFC). They used the social network analysis (SNA) method to analyze the core patents and assignees of General Motors and Panasonic, and to obtain future trends of technology and other important information. Chen et al. [16] presented the technological S-curves that integrate bibliometric and patent analysis into the Logistic growth curve model for hydrogen energy and fuel cell technologies, and they identified the optimal patent strategy for the fuel cell industry, including PEMFC, solid oxide fuel cells (SOFC), and direct methanol fuel cells (DMFC)/direct alcohol fuel cells (DAFC).

Patents play a key role in fostering innovation and the commercialization of hydrogen production methods and associated technology. Olivo et al. [17] used the patent analysis method to compare the priorities of advanced hydrogen production technology development among China, Japan, South Korea, the European Union, and the United States (US). They observed the scope and competitiveness of these technologies, and the developmental trends of biological hydrogen production technologies. In the research conducted by Lai et al., the differences in biological hydrogen energy fuel cell technologies among Taiwan, the US, and Japan have been compared based on patent and market analysis. The research indicated that Taiwan has put more focus on the R&D of feedstock and biological hydrogen production technology, while the US and Japan have emphasized the development of rear-end application products, and the integration of hydrogen energy and fuel cell applications with other industries [18].

However, the results of these studies based on patent information and patent analysis are mostly statistical, and there have not been any specific results related to application situations or commercialization trends in hydrogen energy and fuel cells. For technology R&D staff, investors, and government personnel in charge of formulating technological and industrial policies, an understanding of specific application situations and commercialization trends will help in the decision making with respect to issues such as investment in technology R&D and technology commercialization strategy. By establishing commercial application scenarios of fermentative hydrogen production from biomass through patent content analysis, this study has attempted to overcome the limitations in patent analysis research on hydrogen energy technologies in addition to the provision of specific application scenarios.

Materials and methods

A typical application of fermentative hydrogen production technology includes three important types of commercial information: type of feedstock source, hydrogen production method/procedure/device, and system application function or product. In this study, prospective patents will first be identified through a patent search procedure before confirmation, and content analysis is conducted manually by experts. The focuses of the analysis include feedstock sources, hydrogen production method/procedure/device, and applications and products involved in all patents. Finally, commercial application scenarios are summarized based on the patent analysis.

The method used in this study includes identifying patents related to fermentative hydrogen production from biomass through patent search and content analysis. These patents will then be categorized into different groups in accordance with the analysis results and the possibility of their individual application. Eventually, the possible commercial application scenarios (Fig. 1) are introduced through the categorization and combination of all patent groups. The specific research methods include patent information search, interpretation of retrieved data, and patent analysis.

Chang et al. [19] reported the correlations of wastewater treatment and hydrogen production (Fig. 1). In the original

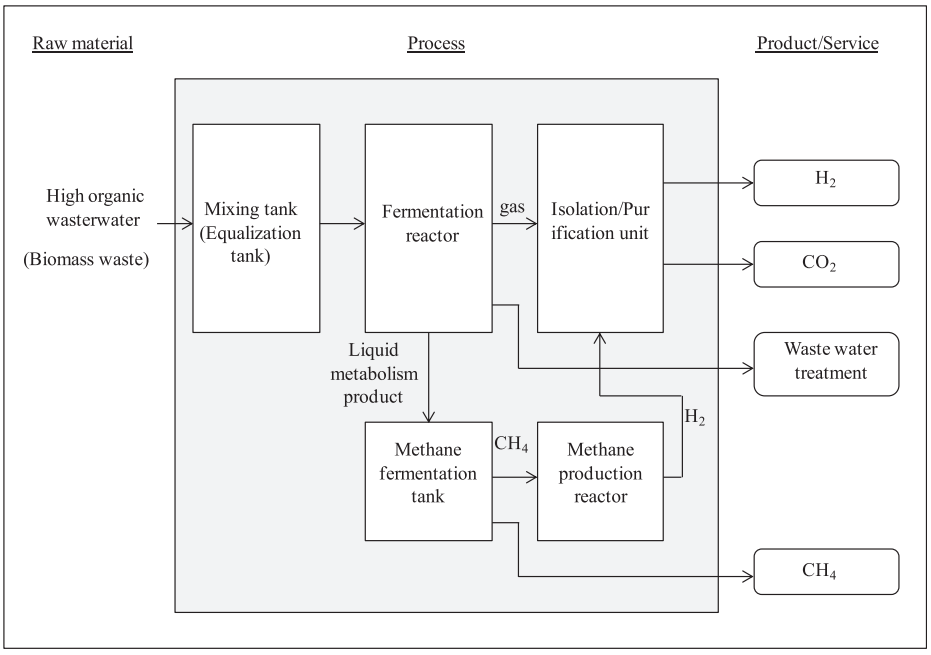

Fig. 1 – Fermentative hydrogen production from biomass/wastewater.

wastewater treatment system, the wastewater flows through an equalization tank, a hydrogen fermentation tank, and a methane fermentation tank. The hydrogen-producing process integrates a hydrogen production system and peripheral equipment with the beverage manufacturer's existing wastewater treatment system to convert wastewater into H_2 and CH_4. This hydrogen production system can be combined with the existing wastewater treatment process.

Results of patent analysis

Patent search and interpretation

Four different keyword combinations were used to conduct searches with respect to claims targeting the content of the United States Patent Office database. This search was conducted in July 2013, and the time range of this search was from 1976 to June 2013. The search results with respect to each keyword combination are presented below:

- "hydrogen" and "fermentation" 390 pieces of data;
- "biomass" and "fermentation" 424 pieces of data;
- "hydrogen" and "wastewater" 1343 pieces of data;
- "hydrogen" and "sewage sludge" 90 pieces of data.

The second step was manual interpretation with respect to these retrieved patents. The content for the interpretation included mainly abstracts and claims of all patents, with help from the patent background, if necessary. The basis for interpretation was to examine whether the patent is related to the use of dark fermentation or anaerobic fermentation technology, and whether or not the main purpose of the process, device, or system included in the patent is for hydrogen production, or if it includes hydrogen in the final products. Based on this principle, patents related to the use of dark fermentation or anaerobic fermentation technology for the production of acid, alcohol, methanol, methane, bio-fuels, or other chemicals were excluded.

Table 1 – The hydrogen production material sources used in all patents.

Hydrogen production material source	US patent
Waste material	
Plant biomass, animal biomass, municipal waste biomass	8377668
Food waste, blackwater, graywater, paper and cardboard, medical waste, wood and plastics, waste fuel and oil	8114663
Organic waste materials	8343749, 8093041, 8003344, 7901916, 7232669, 7083956, 6887692, 5821111
Sewage sludge, landfill material, organic materials	7138046, 6090266
Organic waste, wastewater	8227222, 6860996, 5464539
Waste gases from industrial processes	6340581
Solid biological materials	8343749, 8093041
Biomass containing cellulose	8034592
Decomposing organic matter	7968322
Biomass (did not specify the type of material source)	8420358, 7888085, 7816109, 7575907, 7432091, 7232669, 7083956, 6942998, 5834264, 5821111, 5705374
Manure	6887692
Glucose	5350692, 5350685, 4480035

Note: In accordance with actual patent content, there may be more than one type of hydrogen production material source corresponding to the same patent in this table.

Table 2 – Description and classification of main application technology in each patent.

US patent	Main application technology and description
1. Fermentation hydrogen production procedure or system	
8420358	Method for the combined production of butanol and hydrogen
8377668	Processing biomass
6340581	The method and device for producing useful gas based on biological methods and exhaust.
5464539	The method and device for producing useful gas based on biological methods and exhaust.
4480035	Fermentative hydrogen production using glucose.
2. Hydrogen production by using specific bacteria	
8034592	Using haloalkaliphilic microorganisms for hydrogen production.
8003344	Using *Clostridium* microbes and *Bacillus* microbes as hydrogen production bacteria.
7888085	Using thermophilic, acetogenic, and hydrogen-producing bacteria to enhance the effectiveness of fermentation gas production methods based on a thermophilic anaerobe (such as *Caldicellulosiruptor saccharolyticus*).
7816109	Using hydrogen production bacteria with the hydrogenase gene.
7432091	The hydrogen producing bacteria with better hydrogen producing capability, culturing a microorganism having a formate dehydrogenase gene and a hydrogenase gene under aerobic conditions, culturing the resulting microbial cells under anaerobic conditions.
6942998	Using bacteria from the Order Thermotogales as hydrogen production bacteria.
5834264	Using proteobacteria (such as *Desulfovibrio* sp.
5705374	ATCC 55738 (FOX1)) for anaerobic fermentation hydrogen production.
5350692	Hydrogen producing bacteria, *Clostridium*
5350685	*beijerinckii* Ferm BP-3592 or the anaerobic asporogenic bacterium strain Ferm BP-3593.
3. Fermentation hydrogen production procedure and environmental control	
8343749	Method and apparatus for membrane-based, two-stage gas production from solid biomaterials.
8227222	Method and apparatus for producing hydrogen and microorganism immobilization pellets used in the same.
7901916	The batch fermentation hydrogen production method which can replace continuous fermentation hydrogen production and simplify the system.
7575907	Hydrogen and methane production based on a two-stage approach.
7232669	Enhancing hydrogen production efficiency through specific operating parameters of the hydrogen production procedure.
7083956	Hydrogen production based on a two-stage
6887692	anaerobic hydrogen production method, and the enhancement of hydrogen production efficiency by using a second reaction tank capable of fixing hydrogen production bacteria.
6942998	Hydrogen production through specific environmental conditions.
6860996	Using a preheating treatment to enhance the activity of hydrogen production bacteria in a material source such that the hydrogen production capability can be improved by environmental condition settings.
4. Hydrogen production or device based on a combination of multiple methods	
8114663	Directly using food waste, blackwater, and graywater as the raw materials for dark fermentation hydrogen production; paper and cardboard and medical waste can become raw materials for dark fermentation hydrogen production after steam hydrolysis, and the heat for steam generation can be obtained by burning wood, plastics, waste fuel and oil.
8093041	Hydrogen production based on anaerobic hydrolysis of solid organic waste in combination with dark fermentation and light fermentation procedures.
8034592	The fermentation hydrogen production from the sugar generated by alkaline treatment of cellulose in an acetate solvent with haloalkaliphilic microorganisms as hydrogen producing bacteria.
7138046	Applying anaerobic decomposition to sludge or
6090266	organic waste, mixing the methane-producing bacteria and hydrogen-producing bacteria, and accelerating the reaction by potential difference.
5821111	The method for producing useful gas in combination with gasification and biological procedures.
5. Special fermentative hydrogen production device	
7968322	A string-shaped carrier is installed in the fermentation tank for fixing hydrogen producing bacteria and enhancing hydrogen production efficiency.

Note: In accordance with actual patent content, there may be more than one type of main application technology corresponding to the same patent in this table.

The third step was to analyze the processes cited by those patents after interpretation in accordance with the aforementioned patent content interpretation criteria, in order to identify useful patents that have not been retrieved.

After the patent search and interpretation screening in accordance with the aforementioned procedures, a total of 29 patents were obtained. Among them, only US patent 4480035, which was awarded in 1984, has expired, while the rest were awarded during the time span of 1994–2013.

Patent technology content

In this study, patent technology content has been divided into three categories in accordance with the hydrogen production technology and the actual application procedure: hydrogen production material source, main application technology, and functionality and product. The results of all of the patent technology contents are shown below.

Hydrogen production material source

Of the 29 patents screened in this study, 16 patents use waste material as the hydrogen production feedstock source, while 11 patents did not specify the types of biomass feedstock used. In addition to wastes, other feedstock sources used by the screened patents include solid biological materials, biomass-

containing cellulose, decomposing organic matter, manure, and glucose (see Table 1). Among the patents using wastes as the hydrogen production feedstock source, eight of them use organic waste materials while three use wastewater. That is, the waste material includes mainly organic waste material, organic waste, and wastewater.

Main application technology

In accordance with patent content, the main application technologies used in these 29 patents can be divided into the following five categories (Table 2).

(1) Fermentative hydrogen production procedure or system

The characteristic of this kind of patent is the introduction of the method, procedure, or device for hydrogen production based on dark fermentation or anaerobic fermentation technology. 5 out of the 29 patents belong to this category.

(2) Hydrogen production using specific bacteria

The core technology of this kind of patent is the introduction of a hydrogen production procedure or method based on specific bacteria such as haloalkaliphilic micro-organisms, *Clostridium* and *Bacillus*, *Caldicellulosiruptor saccharolyticus*, and proteobacteria. The purpose is to increase the hydrogen production yield or hydrogen production rate. 10 out of the 29 patents fall into this category.

(3) Fermentation hydrogen production procedure and environmental control

In these patents, specific fermentative hydrogen production procedures or specific methods and statistics for controlling environmental parameters have been proposed to improve hydrogen production yield or hydrogen production rate. 9 out of the 29 patents fall into this category.

(4) Hydrogen production or device based on a combination of multiple

In these patents, a combination of technologies other than dark fermentation or anaerobic fermentation technology has been used to enhance hydrogen production efficiency or expand the application scope of the hydrogen production device or system. 6 out of the 29 patents belong to this category.

(5) Special fermentation hydrogen production device

A special fermentative hydrogen production device design was proposed in US patent 7968322, in which a string-shaped carrier is installed in the fermentation tank to fix hydrogen-producing bacteria and to enhance hydrogen production efficiency.

Function and product

A total of 12 of the 29 patents screened in this study are purely for hydrogen production, while nine of them use wastes as feedstock sources and provide the function of waste treatment in addition to hydrogen production. There is also one patent for producing hydrogen and methane, and two patents for combined waste treatment and production of hydrogen and methane. Finally, there are six patents for producing hydrogen plus useful products other than hydrogen, such as ethanol, butanol, volatile fatty acids, organic acids, alcohols, single cell proteins, salts of organic acids, and other useful gases (Table 3).

Table 3 – Main function and product of each patent.

Function and product	US patent
Hydrogen production only	8227222, 8034592, 7968322, 7816109, 7575907, 7432091, 6942998, 5834264, 5705374, 5350692, 5350684, 4480035
Hydrogen and methane production	7888085
Hydrogen production and waste material treatment	8114663, 8093041, 8003344, 7901916, 7232669, 7083956, 6887692, 6860996, 5464539
Hydrogen and methane production and waste material treatment	7138046, 6090266
Hydrogen and other useful gas or product	
Hydrogen and butanol	8420358
Hydrogen, ethanol, butanol, and other useful products	8377668
Hydrogen, volatile fatty acids, pure water	8114663
Hydrogen, organic acids, alcohols, single cell proteins, and salts of organic acids	6340581
Hydrogen, other useful gases	8343749, 5821111

Note: In accordance with actual patent content, there may be more than one type of application and product corresponding to the same patent in this table.

Commercial application scenarios for patented technology

Summarizing the aforementioned results of patent analysis by content, all types of patents based on value chain (hydrogen production feedstock sources, main application technology, and function and product) were categorized according to the possibility of separate application (Fig. 2).

(1) Hydrogen production feedstock sources based on various attributes can be divided into two categories: waste material (A1) or other types of biomass (A2).
(2) The main application technology based on various attributes can be divided into three categories: hydrogen production using specific bacteria (B1), procedure/method, system, device, procedure, and environmental control related to the hydrogen production process (B2), and hydrogen production or device based on a combination of multiple methods (B3).
(3) Function and product based on various attributes can be divided into two categories: the production of H_2/CH_4 and other useful gases or products (C1), and the function

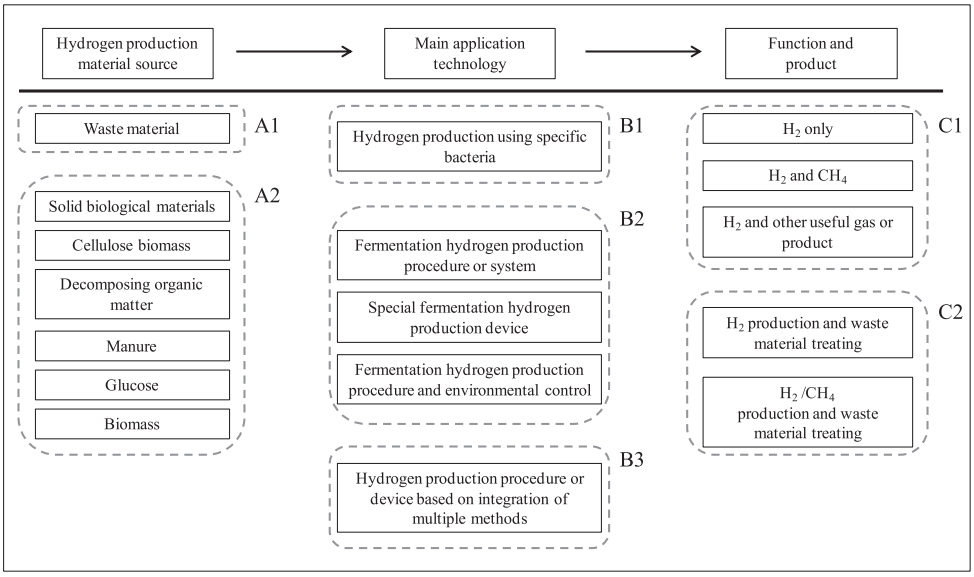

Fig. 2 – Classification of patent groups.

of treatment and reduction of waste and wastewater, in addition to the production of H_2/CH_4 (C2).

The continuous commercialization of fermentative hydrogen production technology is only feasible when its application can lead to sufficient and specific economic benefits. Lee et al. constructed a model of product and market development roadmapping by using technology-driven criteria. To identify possible business opportunities for a specific new technology, one needs to evaluate possible applicable industries, possible products, as well as possible markets [12]. Chesbrough and Rosenbloom [20] showed that the appropriate design of a business model is the most important factor to increase the likelihood of success in commercialization. In the business model design, the first question to consider is, "Who is the new technology or product user, and which new technology or products can create value for the users?"

Therefore, in this study, commercial application scenarios will be constructed based on the following criteria using a combination of patent content: (a) The technology application of an individual patent or a combination of multiple patents must be able to form a specific product or service; (b) the new products or services need to be able to clearly define their potential users; (c) the new products or services need to be able to create a clear value for their users. Thus, in this study, five possible commercial application scenarios have been proposed through the combination and classification of all patent groups, as shown below.

Scenario 1: Based on B1 patent applications, advantageous hydrogen-producing bacteria with high hydrogen production volume and speed obtained from bacteria screening and cultivation have been provided to customers using all kinds of fermentative hydrogen production devices and systems in order to generate profits.

(1) Users: In this scenario, users may belong to one of two categories: the fermentative hydrogen system supplier who needs to match the appropriate hydrogen species for selling fermentative hydrogen systems to end users, or the end user of the fermentative hydrogen system.
(2) Creating value: Firms create value through screening and cultivation of advantageous hydrogen-producing bacteria and supplying them to customers, enabling the customers' fermentative hydrogen production systems to maintain or increase the amount of hydrogen produced, thereby increasing the benefit of the use of the fermentative hydrogen system.

Scenario 2: Based on the integration of A1-B2-C1 patents, H_2/CH_4 or other products with economic value can be produced through a fermentative hydrogen production procedure and device with waste as the material source. In this commercial scenario, there are three possible profit methods: 1) collection, storage, transportation, and sales of all kinds of waste materials; 2) design, manufacture, sales, and maintenance of all kinds of fermentative hydrogen production devices and systems; and 3) production and sales of H_2/CH_4 or other products with economic value.

(1) Users: In this scenario, users are the customers with biomass waste as the source material, and they want to produce energy through fermentative hydrogen production systems, such as public treatment agencies of biomass waste, private contractors, or distributed energy system operation firms.
(2) Creating value: Firms use biomass waste as the source material and use fermentative hydrogen production systems, which can provide clean energy, reduce the cost of the energy supplied, and complete biomass waste treatment.

Scenario 3: Based on the integration of A2-B2-C1 patents, H_2/CH_4 or other products with economic value can be produced through fermentative hydrogen production procedures and devices with biomass as the material source. In this commercial scenario, there are three possible profit methods: 1) collection, storage, transportation, and sales of all kinds of biomass; 2) design, manufacture, sales, and maintenance of all kinds of fermentative hydrogen production devices and systems; and 3) production and sales of H_2/CH_4 or other products with economic value.

(1) Users: In this scenario, the users are customers with biomass as a feedstock source, and they want to produce energy through fermentative hydrogen production systems such as distributed energy system operation firms.
(2) Creating value: Firms use the original low economic value of biomass as a feedstock source and, through fermentative hydrogen production systems, to provide clean energy and reduce the cost of energy supplied.

Scenario 4: Based on the integration of A1-B2-C2 patents, H_2/CH_4 or other products with economic value can be produced through fermentative hydrogen production procedures and devices, with the wastewater to be treated as the feedstock source such that it is also equipped to perform the wastewater treatment. In this commercial scenario, customers can produce, use, and sell H_2/CH_4 or other products with economic value by adding fermentative hydrogen production devices and systems to existing wastewater treatment system, thus enhancing the application value of the original wastewater treatment system.

(1) Users: In this scenario, users may belong to one of two categories: product manufacturers for which the manufacturing process will produce organic wastewater, such as beverage and food factories, and the public institutions or private contractors of organic wastewater treatment.
(2) Creating value: Firms use their original wastewater treatment system, add the necessary fermentative hydrogen production system, and use the wastewater as the feedstock source to produce useable energy. The energy can be used or sold, thereby increasing the overall economic value of the wastewater treatment system.

Scenario 5: Based on the integration of A1/A2-B3-C1 patents, H_2/CH_4 or other products (such as electricity and thermal energy) with economic value can be produced through fermentative hydrogen production procedures and devices and other kinds of energy technologies and devices with waste materials or various biomass materials as the feedstock source. In this commercial scenario, customers can obtain application values and economic benefits through final production applications (H_2, electricity, and thermal energy).

(1) Users: In this scenario, users might be residents of mountain, island, and other remote areas that lack public grids for households, or users with sufficient biomass or biomass waste resources, such as farms or resorts.
(2) Creating value: The households that lack connections to the public grid in remote areas or users with sufficient biomass or biomass waste resources can integrate the solar energy, wind power, fermentative hydrogen production from biomass, and fuel cells. The integrated system can be created with a non-stop operation capacity as an independent power supply system, or to reduce the dependence on the public grid.

Conclusions

Fermentative hydrogen production from biomass can provide clean and sustainable energy supplies with the additional functions of reducing biomass waste and wastewater. Five commercial application scenarios have been established based on the results of patent analysis by content. The results can help R&D personnel, investors, and technological and industrial policy makers in the government with decision making on issues such as investment in relevant technology R&D and technology commercialization strategies.

Technology patents have been identified through a patent search procedure and patent content interpretation based on hydrogen production technologies using dark or anaerobic fermentation with biomass or organics as feedstock sources. They are divided into five patent groups in accordance with the characteristics and patent content for the biomass fermentative hydrogen production technology applications. The following possible commercial application scenarios have been established in accordance with the combinations of patent groups:

(1) Screening and cultivation of hydrogen-producing bacteria with higher hydrogen production yields and production rates for customers using all kinds of fermentative hydrogen production devices and systems.
(2) Production of H_2/CH_4 or other products with economic value through fermentative hydrogen production procedures and devices with waste materials as the feedstock source.
(3) Production of H_2/CH_4 or other products with economic value through fermentative hydrogen production procedures and devices with all kinds of biomass materials as the feedstock sources.
(4) Production of H_2/CH_4 or other products with economic value in combination with wastewater treatment functions through fermentative hydrogen production procedures and devices, with the wastewater to be treated as the feedstock source.
(5) Production of H_2/CH_4 or other products (such as electricity and thermal energy) through fermentative hydrogen production procedures, devices, and other kinds of energy technologies and devices using waste material or all kinds of biomass as the feedstock sources.

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