行政院國家科學委員會專題研究計畫 成果報告

高效率連續生物污泥厭氧產氫反應器之研究(III)
研究成果報告(完整版)

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計畫主持人：李篤中

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中 華 民 國 95 年 12 月 05 日

行政院國家科學委員會/經濟部能源局
「能源科技學術合作研究計畫」成果報告

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範例

摘要

本計畫第一部份在 AFBR 反應中形成生物膜及團聚顆粒，並比較不同 HRT 及基質濃度下其高效產氫行為。

本計畫第二部份以 TAIGEN-EH 模式探討台灣轉變至氫經濟之可能過程，並討論二氧化碳減量及經濟成長之利基。

關鍵字：生物產氫、經濟分析

Abstract

In the first part of present study, cell immobilization was achieved by formation of biofilm and self-flocculated granules in AFBRs. Process performance with respects to hydrogen production in granule-based reactor and biofilm-based reactor was assessed by varying HRT and substrate concentration simultaneously at a consistent OLR.

In the second part of the present project, an economy-wide analysis was presented based on a model, called “Taiwan General Equilibrium Model-Energy, for hydrogen (TAIGEM-EH)”. The benefits brought by biohydrogen production on hydrogen economy growth and reduced CO_2 emission rates, and the possible, adverse impacts by inertial barriers in energy substitution and oil price rise.

Keywords：biohydrogen production、economic analysis

一、前言

Over the past two decades, anaerobic hydrogen fermentation has attracted worldwide attention [1,2]. This is largely due to the soaring concerns on environmental deterioration and sustainability derived from the utilization of conventional fossil fuels and on the potential of hydrogen as an ideal alternative. Currently, laboratory-scale studies on anaerobic hydrogen fermentation technology are being conducted by a large number of research groups in different countries over the world [3-6]. This technology exhibits positive features in hydrogen production such as high production rate, low energy demand, easy operation and high sustainability. However, it is yet to compete with those thermochemical processes converting hydrogen from fossil fuels in cost, performance, or reliability [7]. As a result, current research of anaerobic hydrogen fermentation has been focused on improving microbial hydrogen conversion rate and unit volumetric production rate. The former could be achieved by screening efficient hydrogen-producing bacteria and optimizing the operational conditions, while the later is substantially influenced by the reactor biomass retention. To achieve such purposes, immobilization processes of hydrogen-producing culture have become most popular and have been developed extensively, due to the elevated biomass retention as compared to suspended-cell systems [8,9].

Recent studies found that favorable immobilized-cell anaerobic hydrogen production systems include upflow anaerobic sludge blanket (UASB) reactor [10], granule-based continuous stirred tank reactor (CSTR) [11], fixed or packed bed reactor [1,12], AFBR [13,14] and tricking biofilter [15]. Overall, these immobilization technologies are mainly based on granulation process or biofilm attachment process. Relatively high unit volumetric production rates were found in these systems as a consequence of the elevated biomass retention. According to reported works, hydrogen production rate was achieved the respective peaks at 7.30 L/L·h in a granular sludge bed reactor [16], 0.25-1.70 L/L·h in fixed bed reactors [1,12,17,18], 0.16-0.28 L/L·h in UASB reactors [9,19], 0.54 L/L·h in a granule-based CSTR [11], 2.32 L/L.h in an anaerobic fluidized bed reactor (AFBR) [14] and 1.01 L/L.h in a thermal trickling biofilter [15]. It is obvious that substantial differences in hydrogen production rate still remains among these immobilized-cell processes, which could be attributed to the difference in the microbial population and the operating conditions. On the other hand, it is likely that the reactor performance is also related to the process characteristics per se, such as reactor and immobilized-cell configurations. However, systematic studies regarding process comparison between granule-based and biofilm-based processes under identical operating conditions have been scarcely reported.

Barriers hindering the transition from petroleum to hydrogen economy in Taiwan include lacking reliable and sufficient supply of hydrogen [16,17]. Fossil fuel, nuclear power and renewable materials could be used for hydrogen production. Biohydrogen was produced from renewable resources using either biological or photobiological manners, which is a clean energy source free of green house effects [18,19]. International Energy Agency commented on this technique as at a position of weak technology strength but of high market potential. Economical analysis on various economic development scenarios can assist decision makers to identify the optimal strategy toward the assigned economic target.

二、研究目的

In the first part of present study, cell immobilization was achieved by formation of biofilm and self-flocculated granules in AFBRs. Process performance with respects to hydrogen production in granule-based reactor and biofilm-based reactor was assessed by varying HRT and substrate concentration simultaneously at a consistent OLR.

In the second part of the present project, an economy-wide analysis on how technology progress as well as the improvement of economic structure can affect the energy structure in 2030 was presented. A model, called "Taiwan General Equilibrium Model-Energy, for hydrogen (TAIGEM-EH)", was the forecast tool to demonstrate the benefits brought by biohydrogen production on hydrogen economy growth and reduced CO_2 emission rates, and the possible, adverse impacts by inertial barriers in energy substitution and oil price rise. The strength of support paid by Government sectors was discussed. biohydrogen production can become a main supply in the transition stage to hydrogen economy in Taiwan.

三、研究方法

3.1. Inoculum and substrate

The granular sludge and biofilm used in the present study were developed by a procedure of acid incubation on the acclimated seed sludge with an initial concentration of 6.14 g-VSS/L which was obtained originally from a local wastewater treatment plant and cultivated for more than two months [2]. Granular activated carbon (GAC) was used as the support medium for biofilm attachment, whose physical characteristics had been described in a previous study [14]. The substrate used for hydrogen fermentation consisted of glucose ranging from 5 g/L to 120 g/L, and nutrients at a constant organic carbon to nutrient ratio as described in previous studies [2,14] throughout the study. Moreover, sodium bicarbonate was added at a concentration of 5 g/L in feed solution.

3.2. Experimental setup and operation

Two identical column reactors, each mounted with a three-phase separator were operated as AFBRs. A schematic diagram of the reactor is shown in Fig. 1. The reactor consisted of a glass tubular section of 40 mm internal diameter and 500 mm height with a conic bottom. An upper section of 80 mm internal diameter and 150 mm length was mounted to minimize carry over of suspended particles into the effluent and also to serve as a gas holder. A 40 mm height fixed-bed of grass beads was located at the conic bottom, serving as a distributor for incoming liquid. Each reactor had a total volume of 1.4 L inclusive of reaction-zone volume of 0.6 L. The column has four sampling ports located at 50, 120, 250 and 400mm above the reactor bottom. These ports were used to extract liquid and bioparticle samples along the reactor. The mixed slurry was recycled through a recycling pump connecting the outlet located at settling section and feed inlet at a constant recycling rate of 200 mL/min. Culture pH in the reactor was controlled at 5.5±0.2 by automatic titration using respective peristaltic pumps connecting to an integrated controller with 4M NaOH and 4M HCl. The reactors were operated at a consistent temperature of 37°C by a heating blanket.

The AFBRs designated as Granule reactor and Biofilm reactor were operated to evaluate reactor performance under the identical conditions. The reactors were run with HRTs of 0.25 h, 0.5 h, 0.75 h, 1 h, 1.5 h, 2 h, 3 h and 0.125 h in series, corresponding to influent glucose concentrations of 10, 20, 30, 40, 60, 80, 120 and 5 g/L to maintain a constant OLR of 40 g-glucose/L·h. The HRT were calculated on the basis of the total reactor volume, while the OLRs were computed from the concentration of glucose loaded to the reactor per unit HRT. Pseudo steady-state conditions at each HRT level were considered attained when the biogas production and glucose conversion rate were relatively consistent within 5% for three consecutive days. Evaluation of the system performance was carried out during the pseudo steady-state conditions.

3.3. Analytical methods

Biogas flow and production were measured using water displacement method, and biogas volume was calibrated to a temperature of 25°C and pressure of 1 atm condition. The biogas composition was analyzed by a gas chromatography (Varian 4900, USA) equipped with a thermal conductivity detector. Hydrogen was analyzed using a Molsieve 5A Plot column with argon as carrier gas set at 60°C; Methane and carbon dioxide were analyzed using a Propac Q column with helium as carrier gas also set at 60°C. Glucose concentration was determined following the phenol-sulfuric acid method reported by Dubois et al. [20]. Measurements of SS and VSS were performed in accordance with the Standard Methods [21].

3.4. Economic model

The TAIGEM-EH considers each industrial sector as a group of inputs domestic and imported commodities, with the choice of up to six levels of labors (and hence salaries), cost of land, capital, energy, and others. The multi-input, multi-output production specification is illustrated by the nested structure shown in Fig. 1. The input demand of industry production is represented with a five-level nested structure, and the decision-making of each level could be independently made. At the top level, commodity composites and a primary-factor composite are combined using a Leontief production function. Consequently, the demand is in direct proportion to the industry activity. At the second level, each commodity composite is represented using a constant elasticity of substitution (CES) function considering the domestic supply and the imported equivalent [40]. The energy and primary-factor composites are a CES aggregation of energy composites and primary-factor composites. At the third level, the primary-factor composite is a CES aggregation of labor, land, and capital, and the energy composite. The energy composite itself is modeled as a CES aggregation of hydrogen, coal products, oil products, natural gas products, and the electricity. At the fourth level, the coal products composite is a CES aggregation of coal and coal products; the oil products composite is a CES aggregation of gasoline, diesel oil, fuel oil, and kerosene; the natural gas products composite is a CES aggregation of refinery gas, gas, and natural gas; and a hydrogen composite, a CES aggregation of biohydrogen, nuclear power (followed by water electrolysis), other renewable resources, and natural gas. At the bottom level the energy composite is a CES aggregation of domestic and imported supplies.

The production of hydrogen needs medium input (such as biomass and/or natural gas as raw materials and nuclear, wind, solar energy sources) and primary inputs (labor, capital, and machine). When hydrogen is produced, the demand side will purchased it from the supply side, including in the medium demand (hydrogen fuel cell, semiconductor, glass, powder metallurgy, and research institutions and universities) and final demand (government, household, export and import, etc). The historical data set for hydrogen related industries in Taiwan was collected for preparing the balanced input-out (IO) table for formulating the hydrogen supply and demand chains. Three major hydrogen-related industries were considered herein: composite hydrogen production, hydrogen fuel cell, and hydrogen fuel cell vehicle. The composite hydrogen production sector was further split into the following four sub-sectors: biohydrogen, nuclear-hydrogen, other renewables-hydrogen, and natural gas hydrogen. The survey data on these supply-demand chains were collected from gas companies, professional clubs, specialists, and articles [43-54]. The power generation cost shares for ten power generation sectors were obtained from Taiwan Power Company (TPC) and from power experts.

We used the energy balance sheet to estimate CO_2 emission matrix from fifteen emission commodities, including coal, natural gas, other non-metallic minerals, gasoline, diesel fuels, aviation fuels, fuel oils, kerosene, lubricants, naphtha, refinery gases, asphalt, other refining products, coal product and gas. The production of CO_2 was discouraged in production/consumption functions with carbon tax. Clean energy source like biohydrogen that does not emit net CO_2 is encouraged by cost saving.

The annual recursion of status of all sectors was simulated. Individual sectors tried to minimize their costs (film agents) owing to production/consumption needs or to maximize their utility efficiency (household agents) owing to budget constraints. The outputs of the model are the “optimal” status achieved by all agents in the economic body at the “demand equals supply” criterion. In simulation, all nonlinear relationships were linearlized to reduce computation efforts [39]. The TAIGEN-EH acquires the historical database for supplies and demands of all sectors in Taiwan. Table 1 lists the exogenous shocks for forecasting the petroleum economy baseline from 2005 to 2030 by DGBAS, references and expert opinions

Taiwan is a developing country. Hence, its resources reallocation is not flexible as a developed country. The nominal wage rate rigidity can not alter labor demand. The corresponding capital accumulation, household consumption, and government expenditure are almost fixed. The corresponding substitution among different resources is hence difficult owing to a rigid economical structure.

The baseline forecast was conducted over year 1999-2030, with the energy structure in 2005 as follows: crude oil (50.0%), coal (33.1%), natural gas (8.0%), nuclear energy (7.3%), hydro-power (1.2%), and hydrogen energy (0.4%). The progress in hydrogen technology is encouraged by the policy of Government and is modeled herein by three levels: no effort (scenario I), medium effort (scenario II), and strong effort (scenario III). In scenario III, owing to the strong efforts by Government sectors, the technology progress rates of biohydrogen, nuclear-hydrogen, and renewable-hydrogen were at 15%, while that for natural gas was zero, while the CES elasticities for biohydrogen, other energy sources, primary inputs, and transformation were 0.5, 0.5, 0.4, and 0.4, respectively. For scenarios II and I, all parameters were the same as in scenario III but with the progress rates reduced from 15% to 5% and 0%, respectively. Table 2 lists the parameters used in further simulation.

四、結果與討論

4.1. Production of hydrogen

Fig. 2 illustrates that the impacts of HRT and glucose concentration on the hydrogen production in Granule reactor and Biofilm reactor at a given OLR of 40 g-glucose/L·h. The biogas produced consisted of hydrogen and carbon dioxide, and was free of methane during the experimental period. Similar level of hydrogen content at each HRT was observed in both Granule reactor and Biofilm reactor as illustrated in Fig. 2. Hydrogen content increased slightly from 38% to 48% of the biogas produced as the HRT increased from 0.25 h to 3 h. These values were much lower than that (60-64%) obtained in reported studies with the same seed sludge [2,22]. It is likely that part of the carbon dioxide was released from sodium bicarbonate when neutralized by organic acids produced during the hydrogen fermentation and hence reduced the associated content of hydrogen gas.

In general, both Granule reactor and Biofilm reactor indicated close performance in hydrogen production. Hydrogen yield and hydrogen production rate increased as the HRT was shortened from 3 h to 0.25 h and decreased substantially with further reduction in HRT to 0.125 h (Fig. 2). While hydrogen yield at a given HRT was comparable for both reactors, a slightly higher hydrogen production rate was found in the Biofilm reactor. The hydrogen yield obtained in both reactors was within a range of 0.4-1.7 mol-H_2/mol-glucose with the maximum yield occurring at a HRT of 0.25 h and a glucose concentration of 10 g/L, in which hydrogen production rate also reached the respective maximum values of 7.6 and 6.6 L-H_2/L·h in Biofilm reactor and Granule reactor. It was noted that a 1.1 L-H_2/L·h increase in hydrogen production rate was achieved in Biofilm reactor under the optimum operating conditions as compared with Granule reactor. This was due to the relatively high glucose conversion rates obtained in Biofilm reactor as shown in Fig. 2. Glucose conversions rate in Biofilm reactor and Granule reactor were determined to be around 80% at HRT ranging between 0.25 h and 1.0 h, corresponding to glucose concentration of 10-40 g/L. Significant decrease in glucose conversion rate was noted when the HRT and glucose concentration reduced to 0.125 h and 5 g/L, at which 44% and 54% of the influent glucose were utilized. Such a decrease in glucose conversion rate was also found when the HRT increased to 3 h, corresponding to an increase in glucose concentration to 120 g/L.

Based on the above observation and on hydrogen yield and hydrogen production rate, the optimal operating HRT and glucose concentration were determined to range between 0.25-0.75 h and 10-30 g/L for Biofilm reactor and Granule reactor, respectively. Shortening the HRT to 0.125 h caused inferior hydrogen fermentation, and a HRT of 0.25 h was considered to be critical for the AFBRs, regardless of biofilm or granule system. This value was at least one-fold lower than the HRT required by other hydrogen production bioreactors at optimum hydrogen production. For examples, Lee et al. [16] found a substantial decrease in hydrogen yield and hydrogen production rate when a granule-based column reactor was operated at a HRT of 0.25 h as compared with the peaks achieved at 0.5 h HRT. Furthermore, it was recognized that the HRT ranged between 1 h and 2 h for other immobilized-cell biosystems, i.e. UASB reactor [19] and packed-bed reactor [12] for optimum hydrogen production. It was speculated that a lower critical HRT obtained was attributed to the good mixing characteristics of bioparticles under fluidization state. On the other hand, while both reactors were operated at a glucose concentration of up to 30 g/L, satisfactory hydrogen production could still be achieved. This implied that critical glucose concentration was around 30 g/L for the present system as significant reduction in hydrogen yield and hydrogen production rate occurred when glucose concentration was further increased to 40 g/L for both reactors. This critical concentration of substrate was in agreement with the reported values for the granule- or biofilm- based processes [8,14]. It was noted that inhibitory concentration of substrate on acidogenic bacteria was estimated to be about 5-6 g-glucose/L in the suspended cultures [23]. These results imply that microorganisms in the biofilm and granule biomass matrix might react more actively under a stressful environment in comparison to the biomass in the form of suspension.

4.2. Biomass retention

Obviously, no apparent difference in hydrogen production between the Granule reactor and Biofilm reactor was reported in the present study. This is largely owing to the relatively consistent and comparable biomass concentration maintained in both reactors as shown in Fig. 3. Furthermore, scanning electron microscope (SEM) images as illustrated in Fig. 4 reveal similar microbial composition, i.e. rod-shaped bacteria predominated on the surface of the biofilm and granules. Biomass concentration in the reaction zone was maintained consistently within the ranges of 61-65 g-VSS/L and 61-66 g-VSS/L at HRTs between 0.125 h to 2 h for the Granule reactor and Biofilm reactor, respectively. Considering the total volume of reactor (1.4 L), overall biomass concentration corresponded to 34.7-36.9 g-VSS/L and 34.3-37.6 g-VSS/L, respectively. This indicated that adding support media in Biofilm reactor did not reduce the biomass retention as compared with the granule-based reactor. Nevertheless, substantial decrease in overall biomass concentration to 23.4 g-VSS/L and 16.8 g-VSS/L was noted in Biofilm reactor and granule reactor, respectively at a HRT of 3 h and a glucose concentration of 120 g/L.

Fig. 5 reveals that proportion of biofilm decreased significantly with an increase of granular biomass in the Biofilm reactor. Because of high cell yield of hydrogen-producing bacteria (0.1 g-VSS/g-glucose, data not shown) and a high OLR (40 g-glucose/L·h) employed, a large amount of biomass (ca. 72-127 g-VSS) was produced daily. Furthermore, it was observed that with the evolution of biofilm, the thickness of biofilm increased significantly and attachment of microorganisms to the support media might become weaker. As a result, biofilm was separated from support media due to particle-particle collision, leaving fragmented biofilm in the reactor. These fragmented biofilm eventually developed into granules which had predominated over biofilm in Biofilm reactor after being operated for 50 days.

4.3. Model prediction

Figures 6a-c show the changes in energy structure over time in scenarios I-III, respectively. When no effort is paid to advance the technology of hydrogen production, the energy structure in Taiwan will have little change over time. The use of crude oil decreases from 50% in 2005 to 45.8% in 2030, mainly owing to the increased oil price and the carbon tax. The use of coal remains almost unchanged, all around 33%. While the use of natural gas increase in amount to take over the decreased amount in crude oil. The share of hydrogen energy remains negligible.

To migrate to hydrogen economy cannot depend sorely on the technology progress. The whole economic structure may need revision. We herein consider a scenario IV on how a more “elastic” economy can affect the evolution in energy structure in Taiwan. In this scenario, the parameters set is the same as scenario III, except for that the while the CES elasticities for biohydrogen, other energy sources, primary inputs, and transformation were 0.25, 1.0, 0.8, and 0.8, respectively. The use of hydrogen shares of crude oil and coal can be reduced to 25.3% and 23.0% in 2030, with hydrogen being the 3rd place energy source (Fig. 6). It is also clear that the use of nuclear energy and of natural gas will increase as well, but will level off in about 2022-2025 and onward. On the contrary, the use of hydrogen is still increasing. It is thereby clear that the transition to hydrogen economy can be achieved before 2040.

The hydrogen production from biohydrogen, nuclear-hydrogen, and renewables-hydrogen will increase in an annual increase rate over time, of

10.5%, 8.5%, and 9.2%, respectively (Table 5). The biohydrogen can be produced cheaper and cleaner than the other two alternatives, hence gaining the higher growth rate. In the meantime, the technology progress also makes the renewable and nuclear energy cheaper, safer and more reliable, hence could keep substituting natural gas as a energy source. Restated, if the biohydrogen were becoming one main player for future hydrogen supplier, its technology progress has to move fast, as a competitor to the other sources. Moreover, it is obvious under the current economic structure it is very difficult to transform from petroleum to hydrogen economy. The production using natural gas remains an important way of producing hydrogen. However, its growth rate is low, compared with other sources that emitted less or no CO_2 as their main advantage.

As shown in Table 6, because of public and private investment in hydrogen R&D, technical progress and larger-scale production, prices of hydrogen will drop. For example, along with technology development and the building up of infrastructure, the price of biohydrogen will keep decreasing around 3.4% to 6.3% in an advanced country with strong efforts, 1.1% to 3.4% with medium efforts, 0.7% to 3.5% in a developed country with strong efforts, and 0.5% to 1.9% with medium efforts. The prices of other renewable and nuclear hydrogen will also decrease but the effects are smaller than biohydrogen. The prices of natural gas are increasing steadily in four scenarios. Results demonstrated that price of hydrogen falls when the price of fossil fuel rises. It makes hydrogen more attractive than fossil fuels, and keep its industrial competition than other energy. According the results we mentioned above, biohydrogen is the most important hydrogen production way in the future because of its lowest price, stable source supply and cost efficiency.

4.3. Summaries

Two AFBRs initially loaded with biofilm and granules were operated for biohydrogen production at a constant OLR of 40 g/L·h, but at varying HRTs (0.125-3 h) and glucose concentrations (5-120 g/L). From the results obtained, the following conclusions can be drawn.

No significant difference in hydrogen production was observed between Biofilm reactor and Granule reactor during the entire period of study. A consistent hydrogen production was achieved in both reactors as the HRT was controlled within the range of 0.25-0.75 h, corresponding to glucose concentrations of 10-30 g/L. The hydrogen yield obtained in both reactors ranged between 0.4 and 1.7 mol-H_2/mol-glucose with the maximum yield occurring at a HRT of 0.25 h and a glucose concentration of 10 g/L, at which hydrogen production rate also reached the respective maximum values of 7.6 and 6.6 L-H_2/L·h in Biofilm reactor and Granule reactor.

Substantial washout of biofilm was noted in Biofilm reactor, in which the biofilm was almost replaced by granules completely without affecting reactor performance during the operation of 50 days. Substantial biomass retention of up to 37 g-VSS/L was achieved in the both reactor.

A dynamic, multi-sectoral, annually recursive, combined top-down and partial bottom-up TAIGEM-EH model compared the advanced and developed economy with strong and medium efforts to hydrogen economy. The model includes four major hydrogen-related industries, biohydrogen, nuclear-hydrogen, other renewable-hydrogen and natural gas hydrogen. Because biohydrogen has many advantages than other methods to produce hydrogen, we focus on the role of hydrogen in hydrogen economy.

五、計畫成果自評

本計畫共發表 SCI 論文三篇、國際會議論文三篇，成果中上。

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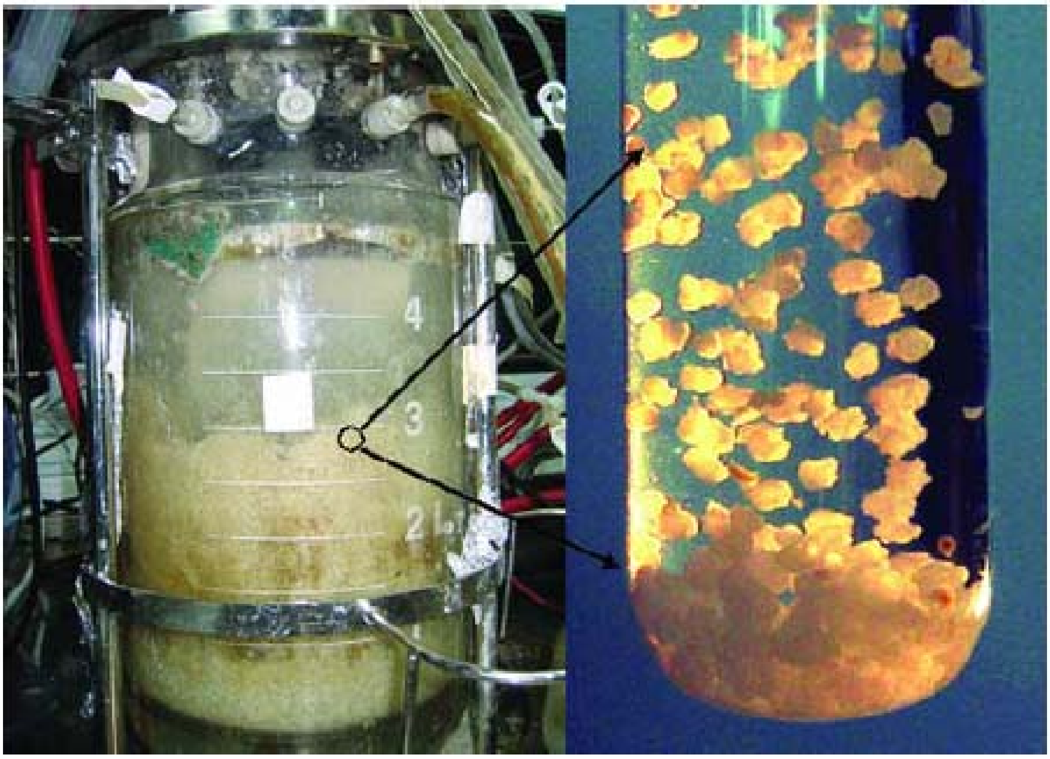

Figure 1 The schematic diagram of the reactor and the formed granules.

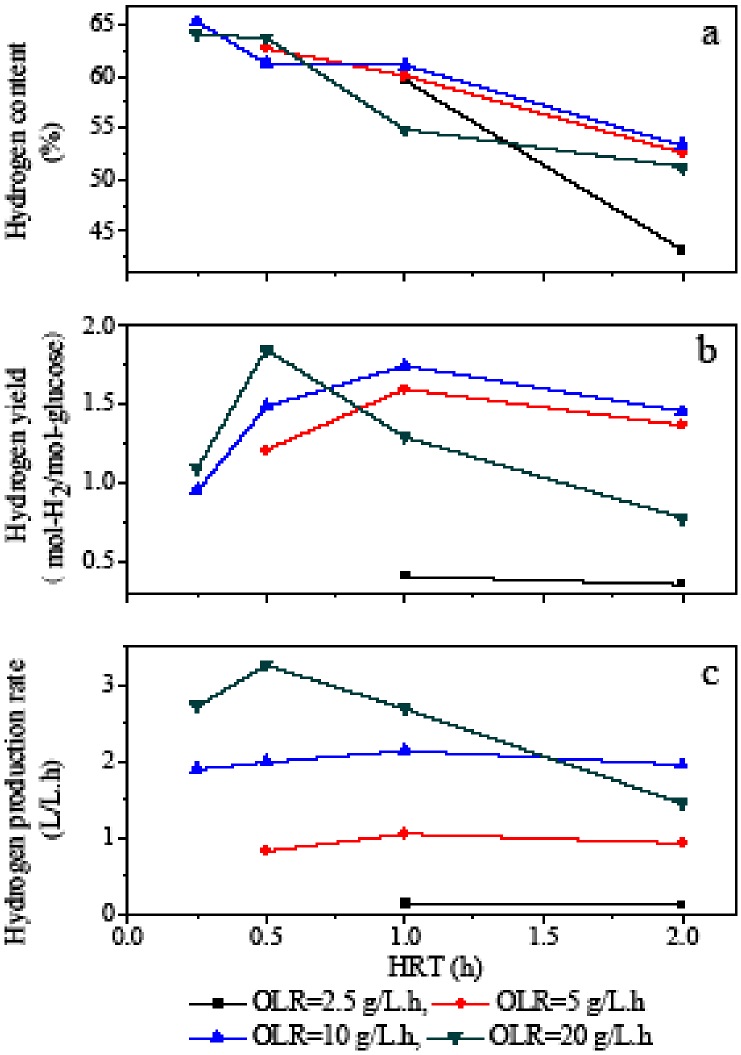

Figure 2. Influence of HRT, influent glucose concentration and resulting OLR on (a) hydrogen content, (b) hydrogen yield, and (c) hydrogen production rate.

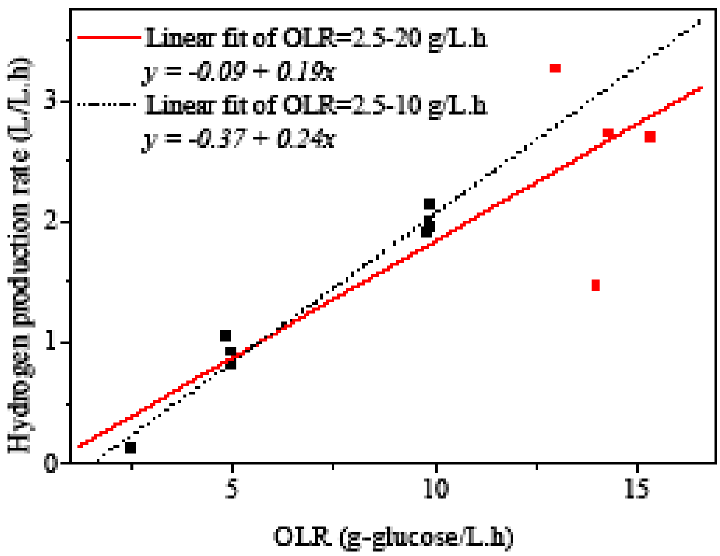

Figure 3. Hydrogen production rate as a function of OLR (solid line, R=0.89 and p<0.0001; dot line, R=0.99 and p<0.0001).

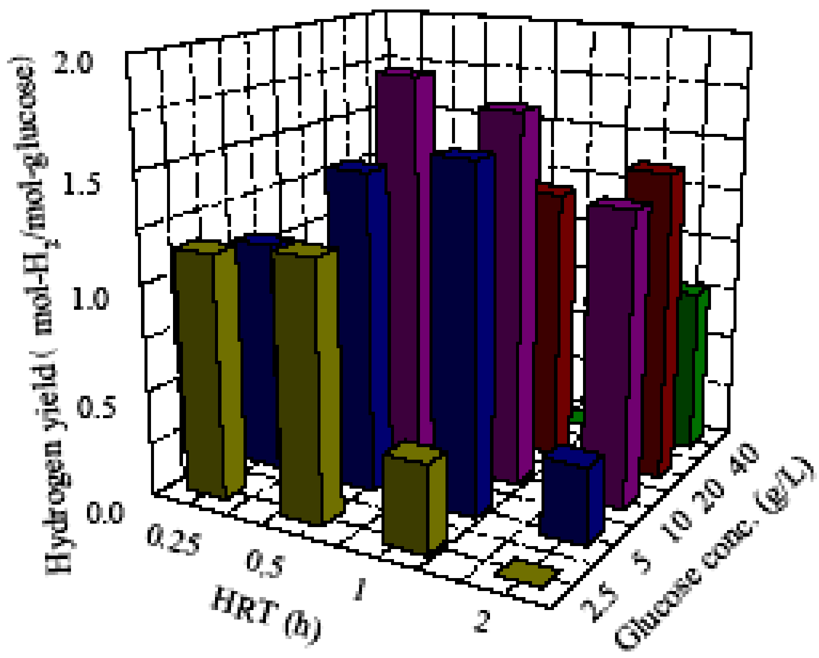

Figure 4. Hydrogen yield with a matrix of HRT and ISC.

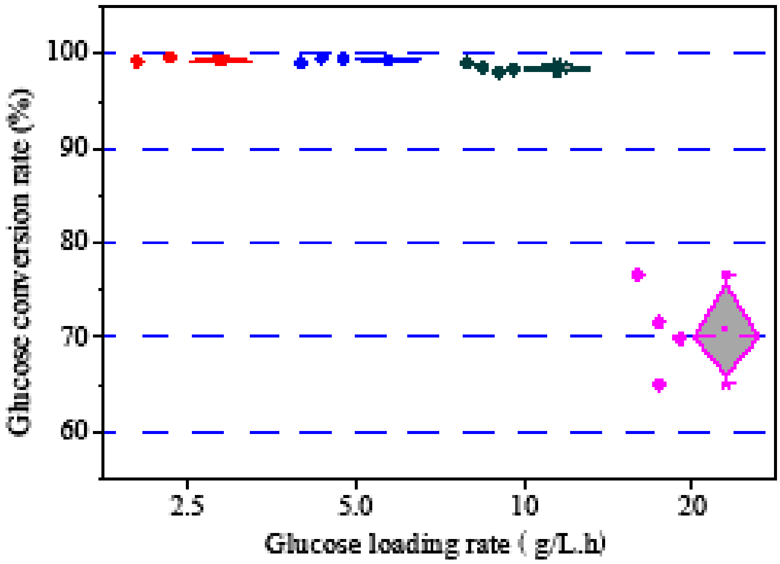

Figure 5. Glucose conversion rate as a function of organic loading rate.

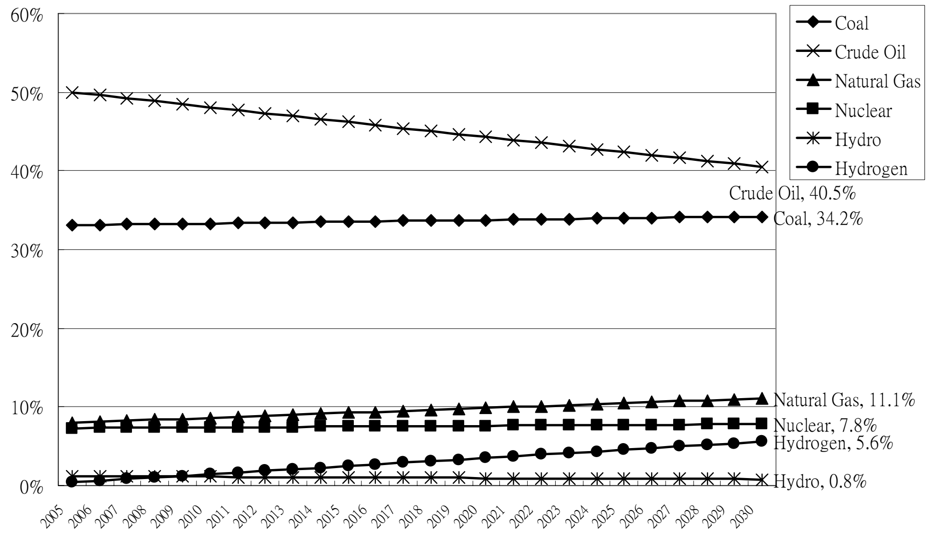

Figure 5   Energy Structure for a developed economy with medium efforts

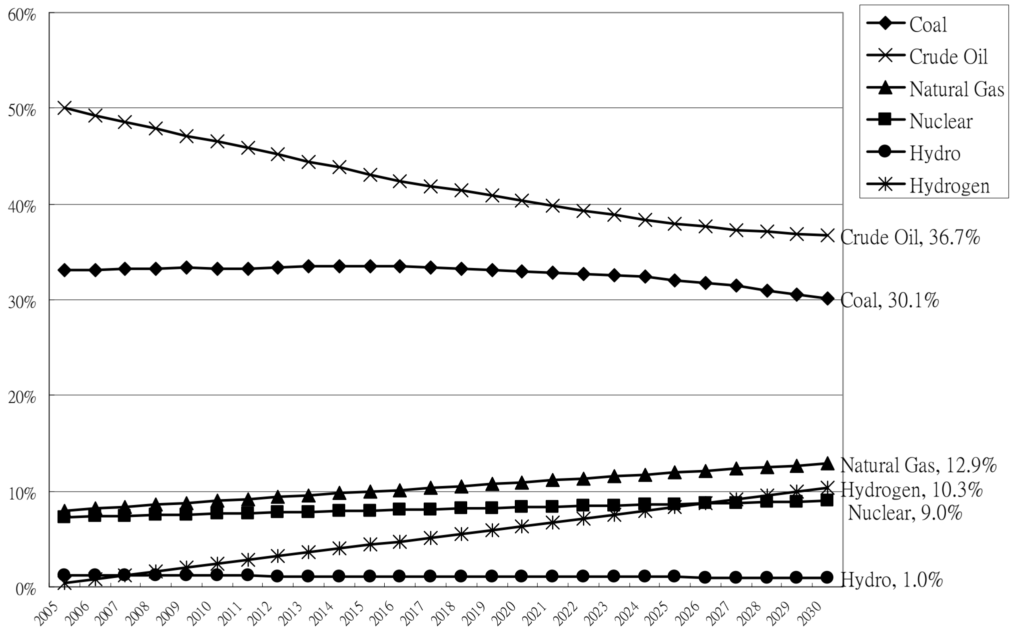

Figure 6. Energy Structure for a developed economy with strong efforts.

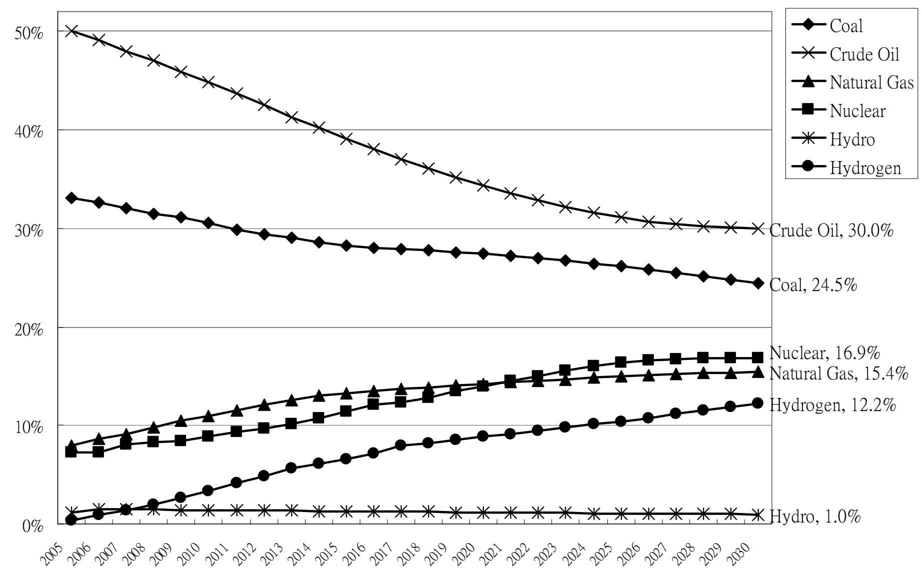

Figure 7. Energy Structure for an advanced economy with medium efforts.

Table 1 Exogenous shocks for forecasting baseline: from 2000 to 2030

Macroeconomic variables growth rate (%)	2000	2001	2002	2003	2004	2005 ~2030
Energy-saving decline rate	-0.60	-0.60	-1.20	-1.20	-1.20	-1.20
Real GDP	5.78	-2.17	3.94	3.33	5.71	endog
Imports	4.54	-13.5	5.71	6.72	18.6	endog.
Household consumption	4.84	1.00	2.07	0.84	3.13	endog.
Export	18.1	-8.08	10.5	10.9	15.3	endog.
Investment	8.38	-21.1	-1.61	-2.05	15.4	endog.
Government expenditure	0.28	-0.55	1.47	0.71	-0.69	endog.
Number of households	2.28	1.80	1.80	1.76	1.75	2.00
Employment Trend	1.20	0.49	1.13	1.07	2.11	1.00
Aggregate price index	-1.80	0.51	-0.89	-2.21	-1.92	endog.
Exchange rate	-5.15	6.00	-1.29	0.49	2.87	endog.
Imports price index (c.i.f.)	-4.62	1.34	-1.25	2.98	8.57	endog.
Exports price index	0.87	0.77	0.32	-0.87	1.61	endog.
Primary factors productivity	endog.	Endog.	endog.	endog.	endog.	-2.50
Consumer price index	endog.	Endog.	endog.	endog.	endog.	2.00
The energy structure	endog.	Endog.	endog.	endog.	endog.	endog
Industrial structure	endog.	endog.	endog.	endog.	endog.	endog
Labor (primary factor) demand	Labor is a CES aggregation of various types of labor forces.					
Price of petroleum	The price of imported petroleum increased by4.96% in 2002, 13.94% in 2003, 27.40% in 2004, 38.91% in 2005, and was assumed to increase by 3.21% onwards up to 2030, based on IEA (2006) forecast.					
Technology bundle	Substitution elasticity of hydro is 0.1, nuclear power 1.0, coal 0.1, oil 0.5, and natural gas 0.5.					
Ascension to WTO	Taiwan joined WTO in 2002. The tariff rate decline rate was assumed to in conformance to WTO rules up to 2010.					
Nuclear-free homeland policy	Taiwan Government adopts “nuclear-free homeland” policy, hence the existing three nuclear plants were assumed to expire before 2015 and the new plant (#4) will commence in 2010.					

Table 2 Cost share for different kinds of hydrogen production

	Natural Gas Steam Reforming		Bio-hydrogen		Nuclear Hydrogen		Other Renewable Hydrogen	
	Input	NT$/m^3	Input	NT$/m^3	Input	NT$/m^3	Input	NT$/m^3
Inter-mediate Input	Natural gas	3	Biomass and waste	5	Nuclear Material	2	Water	4
	Catalyst	1	Catalyst	1	Chemical Material	1		
	Electricity	1	Electricity	1	Electricity	1		
	Steam	1	Steam	1				
Primary Input	Wage	3	Wage	4	Wage	2	Wage	2
	Depre-Ciation	2	Depre-Ciation	2	Depre-ciation	4	Depre-ciation	5
	Rent of Land	1	Rent of Land	1	Rent of Land	1	Rent of Land	5
	Rent of Durables	2	Rent of Durables	7	Rent of Durables	9	Rent of Durables	11
	Interest	1	Interest	2	Interest	2	Interest	3
	Profit	4	Profit	4	Profit	4	Profit	4
	Other Cost	2	Other Cost	2	Other Cost	6	Other Cost	2
	Total Cost	20	Total Cost	30	Total Cost	32	Total Cost	36

Table 3 Hydrogen Economy's Impacts on the Macroeconomy

	I	II	III	I - III	II - III
GDP growth rate					
	Strong	Medium	Baseline	Difference	Difference
2005	4.58	4.64	5.42	-0.84	-0.78
2010	5.45	5.57	6.21	-0.76	-0.64
2015	5.56	5.62	5.98	-0.42	-0.36
2020	5.04	5.16	5.32	-0.28	-0.16
2025	5.24	5.07	5.01	0.23	0.06
2030	5.33	5.08	4.97	0.36	0.11
Unemployment					
	I	II	III	I - III	II - III
	Strong	Medium	Baseline	Difference	Difference
2005	2.84	3.10	3.62	-0.78	-0.52
2010	3.38	3.60	3.82	-0.44	-0.22
2015	3.59	3.70	3.72	-0.13	-0.02
2020	3.47	3.38	3.32	0.15	0.06
2025	3.25	3.16	3.05	0.20	0.11
2030	3.21	3.11	2.97	0.24	0.14
CO_2 emission (10^6 tons)					
	I	II	III	I - III	II - III
	Strong	Medium	Baseline	Difference	Difference
2005	265.6	266.4	266.7	-1.1(-0.4%)	-0.3(-0.1%)
2010	344.6	349.7	352.7	-8.1(-2.3%)	-3.0(-0.9%)
2015	429.8	443.2	448.6	-18.8(-4.2%)	-5.4(-1.2%)
2020	562.9	586.9	596.9	-34.0(-5.7%)	-10.0(-1.7%)
2025	730.1	762.7	778.4	-48.3(-6.2%)	-15.7(-2.0%)
2030	928.9	989.5	1015.2	-86.3(-8.5%)	-25.7(-2.5%)

Table 4 Hydrogen Economy's Impacts on Hydrogen-Related Industry Outputs

year	Strong effort				Medium effort			
	NG Hydrogen	Bio-hydrogen	Nuclear Hydrogen	Other Renewable	NG Hydrogen	Bio-hydrogen	Nuclear Hydrogen	Other Renewable
2005	4.5	2.1	1.1	1.8	1.2	0.3	0.1	0.3
2010	4.8	3.4	1.8	2.9	3.2	0.7	0.3	0.6
2015	5.1	4.2	2.1	3.9	2.1	1.2	0.5	1.0
2020	3.8	5.3	3.2	4.8	2.3	1.4	0.8	1.2
2025	3.2	6.1	3.8	5.5	1.5	1.8	0.9	1.6
2030	2.9	4.3	3.2	4.1	1.3	2.1	1.1	1.9
Ave.	4.1	4.2	2.5	3.8	1.9	1.3	0.6	1.1

Table 5 Hydrogen Economy's Impacts on Prices of Energies

year	Strong effort				Medium effort			
	NG Hydrogen	Bio-hydrogen	Nuclear Hydrogen	Other Renewable	NG Hydrogen	Bio-hydrogen	Nuclear Hydrogen	Other Renewable
2005	4.1	-0.7	-0.4	-0.6	3.2	-0.5	-0.1	-0.3
2010	2.7	-1.9	-1.0	-1.7	2.3	-1.2	-0.4	-0.8
2015	2.4	-2.0	-1.2	-1.8	1.4	-1.5	-0.6	-1.1
2020	2.5	-2.4	-1.3	-2.0	1.5	-1.7	-1.0	-1.4
2025	2.9	-3.5	-1.6	-3.1	1.6	-1.9	-0.9	-1.5
2030	2.7	-3.1	-2.1	-2.8	1.4	-1.8	-1.0	-1.4
Ave.	2.9	-2.3	-1.3	-2.0	1.9	-1.4	-0.7	-1.0