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Hydrogen economy in Taiwan and biohydrogen

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ABSTRACT

This study analyzed how production technology advances and how economic structure reformation affects transition to a hydrogen economy in Taiwan before 2030. A model, called "Taiwan general equilibrium model-energy, for hydrogen (TAIGEM-EH)", was the forecast tool used to consider steam reforming of natural gas, the biodegradation of biomass and water electrolysis using nuclear power or renewable energies of hydrogen production industries. Owing to increase in the prices of oil and concern for global warming effects, hydrogen will have a 10.3% share in 2030 when demands for hydrogen production could be met if strong technological progress in hydrogen production were made. With reformed economic structure and strong support to progress in production technologies, hydrogen's share can reach 22.1% in 2030 and become the dominating energy source from then onwards. In the four scenarios studied, including developing country with three levels of effort and developed country with strong effort, the biohydrogen production industry can become a main supplier of hydrogen in the market if its technological progress can be competitive to other CO_2-free alternatives.

1. Introduction

Obstacles to the transition from a petroleum to hydrogen economy include the lack of a reliable and sufficient supply of hydrogen [1,2]. The steam reforming of natural gas, the biodegradation of biomass and water electrolysis using nuclear power or renewable energies, herein referred to as NG-H_2, bio-H_2, nuclear-H_2 and renewables-H_2, are used in industrial hydrogen production. Biohydrogen has been produced from biomass using biological and photobiological approaches [3,4] as a clean energy source without greenhouse gas emission [5,6]. The International Energy Agency has commented that biohydrogen is now a weak technology but with high market potential [7].

An analysis of various economic development scenarios can help decision makers identify their optimal strategy for achieving economic targets. This study presents an economy-wide analysis of how technology advances and how an improvement in the economic structure is accelerating Taiwan's transition to a hydrogen economy before 2030. A model, called "Taiwan general equilibrium model-energy, for hydrogen (TAIGEM-EH)", which is derived from ORANI [8] and MONASH [9,10] models by Monash University in Australia, is a dynamic, linearized percentage change forecast tool used especially in the economic evaluation of environment policies. The critical factors that affect economic growth rates, CO_2 emission rates, possible adverse effects of inertial barriers of oil price hikes and difficulty of energy substitution in the present economic structure were discussed.

2. Model

2.1. Basic model

The TAIGEM-EH model has been described elsewhere [11–16]. A brief description of the model, and particularly the role of

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hydrogen production-related industries, is presented as follows.

TAIGEM-EH is the most comprehensive model available for Taiwan's economy, which consists of 170 sectors, six types of labor, eight types of margin and 182 commodities. The assumption of input–output separability for model simplification implies the generalized production function for some industries: $F(\text{inputs}, \text{output}) = 0$ can be written as: $G(\text{inputs}) = \text{Activity} = H(\text{outputs})$. The H function is derived from two nested constant elasticity of transformation (CET) [17] aggregation functions, while the G function is broken into five nested constant elasticity of substitutions (CES) [18]. Each nested CES structure displays the optimization problem that firms choose cheapest input combination to minimize total cost subject to the CES production technology. Each nested CET structure displays the optimization problem that distributors choose optimal output combination to maximize total profit subject to the CET production transformation ratio. CET is identical to CES, except that the transformation parameter in the CET function has an opposite sign to the substitution parameter in the CES function. The nested structure displayed in Fig. 1 shows multi-input and multi-output production specifications. The input demand for industry production is represented as a five-level nested structure, and the operation of each level is decided independently. On the top level, commodity composites and a primary-factor composite are combined using a Leontief production function. Therefore, the demand is directly proportional to the industry activity. On the second level, each commodity composite is represented using a CES function incorporating domestic supply and imported equivalents [19]. The energy and primary-factor composites are CES aggregates of energy composites and primary-factor composites. On the third level, the primary-factor composite is a CES aggregation of labor, land, capital and the energy composite. The energy composite is modeled as a CES aggregate of hydrogen, coal products, oil products, natural gas products and electricity. On the fourth level, the coal product composite is a CES aggregation of coal and coal products; the oil product composite is a CES aggregation of gasoline, diesel oil, fuel oil and kerosene; the natural gas product composite is a CES aggregation of refinery gas, gas and natural gas; and a hydrogen composite is a CES aggregation of NG-H_2, bio-H_2, nuclear-H_2 and renewables-H_2. On the bottom level, energy and hydrogen are a CES aggregation of domestic and imported supplies. In the output level, CET profit maximization behavior demonstrates how industry outputs transform to commodity outputs in the first level, and also presents how a distributor decides to sell a commodity to the local or export market in the second level.

The power sector of TAIGEM-EH is modeled as a technology bundle (Fig. 2) derived from the MEGABARE model developed by Australian Bureau of Agricultural and Resource Economics (ABARE) [20], which is composed of 10 power generation technologies, namely hydro, stream turbine oil, stream turbine coal, stream turbine gas, combined cycle oil, combined cycle gas, gas turbine oil, gas turbine gas, diesel and nuclear. The power sector is able to switch between different power technologies in response to changes in their relative costs through the CES production function. The output of the end-use electricity is a minimized cost behavior subject to a CES aggregate of each electricity technology. All electricity thus generated is sent to end-users.

2.2. Database

The database for TAIGEM-EH model is presented in the IO table [21] (Fig. 3). Column data in the table denote the "supply side" and the row data represent the "demand side". It shows that aggregate supply is equaled to aggregate demand for the entire economy equilibrium. Supply side includes intermediate and primary input for industries, demand side includes intermediate demand for industries and final demand for household consumption, government expenditure, investment and net export.

2.3. Model parameters

The production of hydrogen requires intermediate inputs (such as biomass and/or natural gas as raw materials and nuclear, wind and solar energy sources) and primary inputs (labor, capital and machinery). A historical data set for hydrogen-related industries in Taiwan was obtained to prepare the balanced IO table to formulate hydrogen supply and demand chains. The survey data on these supply–demand chains were collected from gas companies, professional clubs, specialists and articles [22–31]. The relative power generation costs of 10 power generation sectors were obtained from Taiwan Power Company (TPC) [32,33].

The annual recursion of the status of all 170 sectors was simulated. Individual sectors try to minimize their costs (film agents) to meet production/consumption needs or to maximize utility efficiency (household agents) because of budget constraints. The outputs of the model are the "optimal" states of all agents in the economic body of the "demand equals supply" criterion. In the simulation, all nonlinear relationships were linearized to reduce computational effort. The TAIGEM-EH acquires a historical database of supplies and demands in all sectors of Taiwan. Table 1 presents exogenous shocks in the forecast of the petroleum economy baseline from 2006 to 2030 according to a national economic report provided by Directorate-General of Budget, Accounting and Statistics (DGBAS) [34] and the results are summarized as follows.

(1) The annual growth rate in the number of households is 2% from 2006 to 2030, reflecting Taiwan's currently low population growth rate.
(2) The energy and productivity efficiency improvement rates are 1.2% and 2.5% annually, indicating the advantages provided by advances in energy technologies and production technologies.
(3) The rate of increase of employment is 1%, which corresponds to the population growth rate.
(4) The CPI will be 2% annually.
(5) The price of imported petroleum increased by 27.4% in 2004 and by 38.9% in 2005. It will continue to rise at a pace of 3.21% onwards until 2030, based on the high oil price projection of EIA's forecast [35].
(6) The rate of tariff decline meets WTO regulations until 2010.

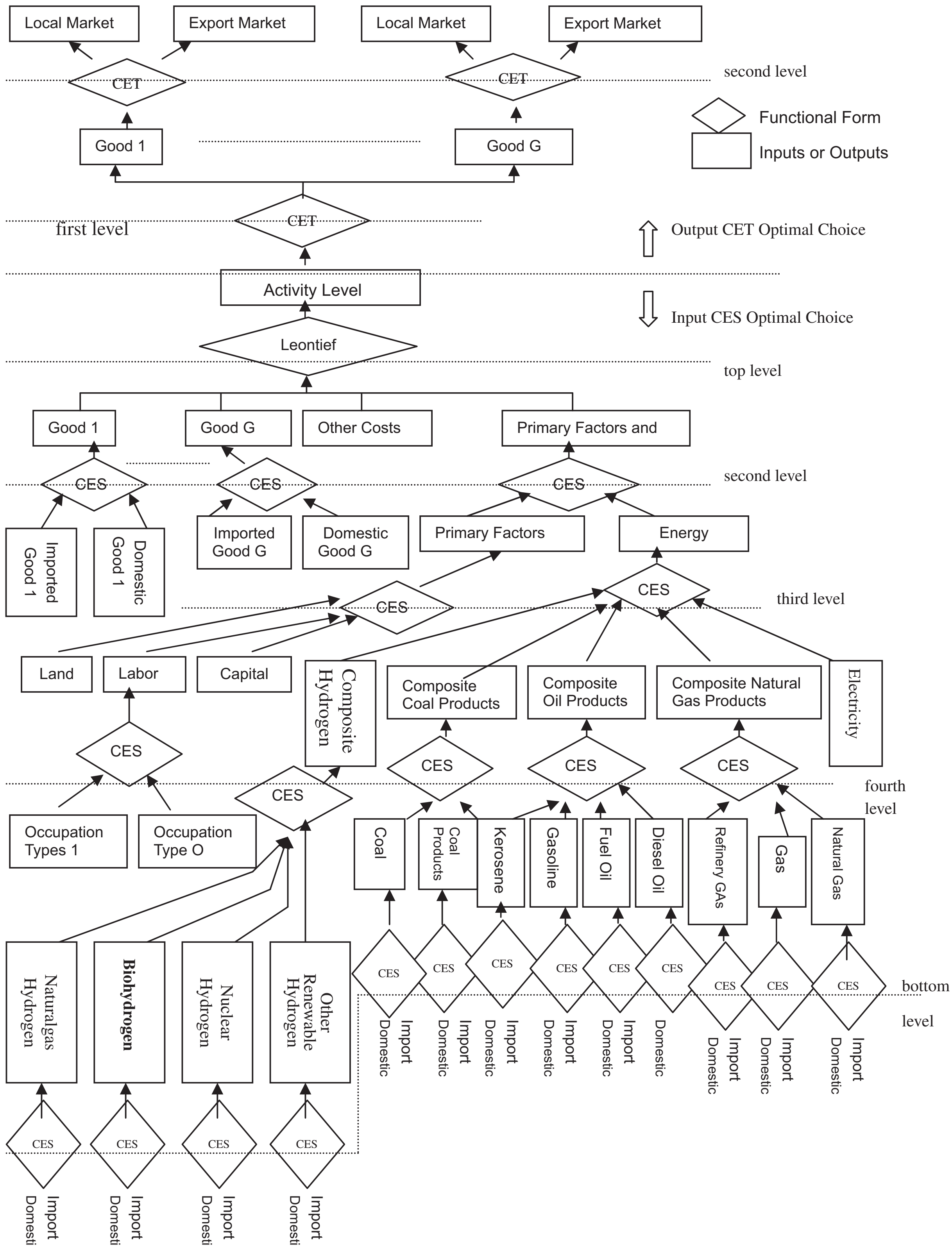

Fig. 1 – Structure of production function: non-electricity sectors.

Table 2 presents the relative costs of various hydrogen production sub-sectors obtained from a recent survey conducted by the Taiwan Institute of Economic Research. The cost of producing hydrogen from natural gas is the lowest among the four sub-sectors, corresponding to its current popularity. The cost of bio-H_2 is lower than those of nuclear-H_2 and renewables-H_2.

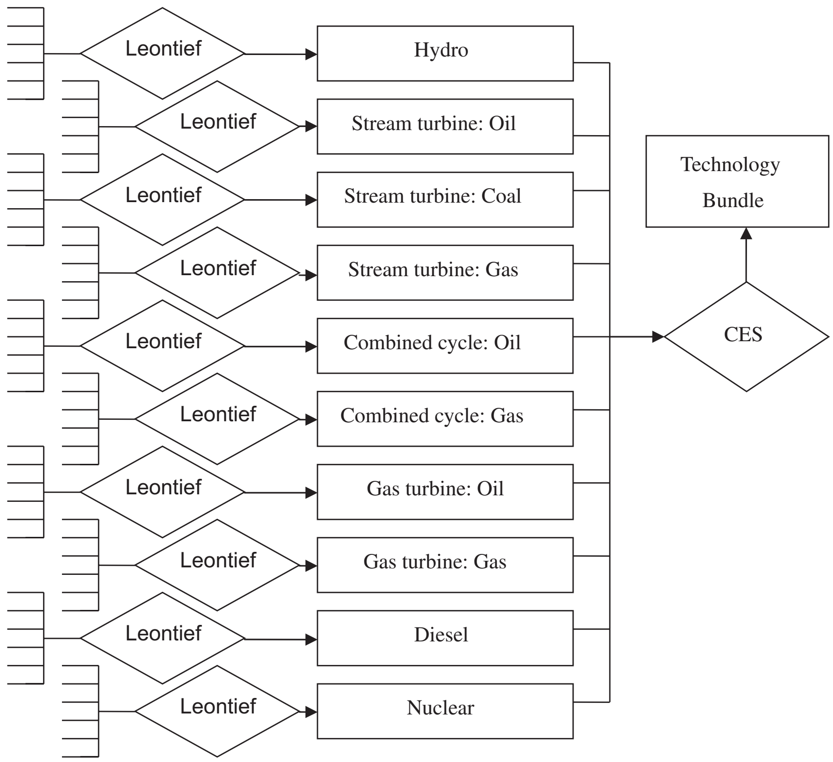

Fig. 2 – The technology bundle of TAIGEM-EH model for electricity sectors.

		Absorb Matrix					
		1	2	3	4	5	6
		Producer	Investor	Household	Export	Government	Inventory
	Dimension	I	1	1	1	1	1
Basic Flow	C×S	***V1BAS***	***V2BAS***	***V3BAS***	***V4BAS***	***V5BAS***	***V6BAS***
Tax	C×S	***V1TAX***	***V2TAX***	***V3TAX***	***V4TAX***	***V5TAX***	
Labor	O	***V1LAB***					
Capital	1	***V1CAP***					
Land	1	***V1LND***					
Other Cost	1	***V1OCT***					

I = Industry
C = Commodity
S = Domestic or Imported
O = Occupation
Bads = commodity emits CO_2

	Producer
Dimension	I
Bads*S	***CO_2 Emission***

Capital	Accumulation
Dimension	1
I	***STOK***

	Production
Dimension	I
C	***MAKE***

	Tariff
Dimension	1
C	***V0TAR***

Fig. 3 – Input–output database for TAIGEM-EH model.

An energy balance sheet was used to estimate a CO_2 emission matrix from 15 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 products and gas. The production of CO_2 is penalized in production/consumption functions through the carbon tax policy. Clean energy sources such as bio-H_2, which does not emit net CO_2, are encouraged given cost saving considerations.

2.4. *Scenario design*

A developed country is in an economic maturity stage; restated, it is classified under the so-called "neo-classical" long-run assumption in economics. A developing country is on the other hand under the "Keynesian" short-run assumption, in that, in the economic growing stage, resource reallocation is not so flexible. Taiwan is a developing country. The present Scenarios I–III adopted the Keynesian short-run closure for simulating the current situation of Taiwan, while

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

Macroeconomic variables growth rate (%)	2000	2001	2002	2003	2004	2005	2006–2030
Energy-saving decline rate	−0.60	−0.60	−1.20	−1.20	−1.20	−1.2	−1.20
Real GDP	5.78	−2.17	3.94	3.33	5.71	4.09	Endog.
Imports	4.54	−13.5	5.71	6.72	18.60	3.90	Endog.
Household consumption	4.84	1.00	2.07	0.84	3.13	4.81	Endog.
Export	18.1	−8.08	10.5	10.9	15.3	4.77	Endog.
Investment	8.38	−21.1	−1.61	−2.05	15.4	−0.43	Endog.
Government expenditure	0.28	−0.55	1.47	0.71	−0.69	1.98	Endog.
Number of households	2.28	1.80	1.80	1.76	1.75	1.57	2.00
Employment trend	1.20	0.49	1.13	1.07	2.11	1.59	1.00
Aggregate price index	−1.80	0.51	−0.89	−2.21	−1.92	−0.70	Endog.
Exchange rate	−5.15	6.00	−1.29	0.49	2.87	3.76	Endog.
Imports price index (c.i.f.)	−4.62	1.34	−1.25	2.98	8.57	2.42	Endog.
Exports price index	0.87	0.77	0.32	−0.87	1.61	−2.45	Endog.
Primary-factors productivity	Endog.	Endog.	Endog.	Endog.	Endog.	Endog.	−2.50
Consumer price index	Endog.	Endog.	Endog.	Endog.	Endog.	Endog.	2.00
The energy structure	Endog.	Endog.	Endog.	Endog.	Endog.	Endog.	Endog.
Industrial structure	Endog.	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 by 4.96% 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 high oil price projection of EIA [35] 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 decline rate was assumed to in conformance to WTO rules up to 2010						
A developed and a developing country elasticities setting	Different CES elasticities are adopted in the simulation: four hydrogen (0.8/0.4), other energy sources (1.0/0.5), primary inputs (0.8/0.4) and transformation (0.8/0.4)						

Source: DBGAS [34] and EIA [35].

Table 2 – Cost share for different kinds of hydrogen production

	Natural gas steam reforming		Biohydrogen		Nuclear hydrogen		Other renewable hydrogen	
	Input	USD/m^3	Input	USD/m^3	Input	USD/m^3	Input	USD/m^3
Inter-mediate input	Natural gas	0.1	Biomass and waste	0.17	Nuclear material	0.07	Water	0.13
	Catalyst	0.03	Catalyst	0.03	Chemical material	0.03		
	Electricity	0.03	Electricity	0.03	Electricity	0.03		
	Steam	0.03	Steam	0.03				
Primary input	Wage	0.1	Wage	0.13	Wage	0.07	Wage	0.07
	Depreciation	0.07	Depreciation	0.07	Depreciation	0.13	Depreciation	0.17
	Rent of land	0.03	Rent of land	0.03	Rent of land	0.03	Rent of land	0.17
	Rent of durables	0.07	Rent of durables	0.23	Rent of durables	0.3	Rent of durables	0.37
	Interest	0.03	Interest	0.07	Interest	0.07	Interest	0.1
	Profit	0.13	Profit	0.13	Profit	0.13	Profit	0.13
	Other cost	0.07	Other cost	0.07	Other cost	0.20	Other cost	0.07
	Total cost	0.67	Total cost	1	Total cost	1.07	Total cost	1.2

Source: Survey data by Taiwan Institute of Economic Research.
Note: Unit USD/m^3 means the cost in US dollars when firms produce hydrogen per cubic meter. We use the exchange rate at 1:30 to transform NTD to USD.

Scenario IV adopted neo-classical long-run closure for a developed country.

The baseline forecast was conducted over the years 1999–2030, with the energy structure in 2005 presented 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%). Advances in hydrogen technology are encouraged by government policies and modeled herein using three levels—no effort (Scenario I), moderate effort (Scenario II) and strong effort (Scenario III). In Scenario III, strong government effort and significant incentives in industrial sectors have led to annual technology advancement rates of NG-H_2, bio-H_2, nuclear-H_2 and renewables-H_2 at 15% (means 15% cost down for hydrogen production). The CES/CET elasticities of bio-H_2, other energy sources, primary inputs and transformation are 0.5, 0.5, 0.4 and 0.4, respectively. In Scenarios I and II, all parameters were the same as in Scenario III, but with the progress rate reduced from 15% to 0% and 5%, respectively. Scenario IV was elucidated by adjusting Taiwan's economy to an "elastic" one with strong support, such as that in developed countries, with CES elasticities of biohydrogen, other energy sources, primary inputs and transformation at 0.25, 1.0, 0.8 and 0.8, respectively. Table 3 gives an outline of these four scenarios.

3. Results and discussion

3.1. Energy structure and macroeconomy: Scenarios I–III

Figs. 4(a)–(c) present changes in the energy structure over time in Scenarios I–III, respectively. Since no effort is made to advance the hydrogen production technology, the energy structure in Taiwan changes little over time. The use of crude oil will decline from 50% in 2005 to 45.8% in 2030, mainly because of increases in oil price and carbon tax. The use of coal will remain roughly constant at around 33%. While the use of natural gas will increase to compensate for the decline in crude oil supply, the entire economy will still be based on fossil fuels, and the importance of hydrogen energy will be negligible.

If hydrogen technology receives moderate or strong support, then the use of crude oil will drop to 40.5% or 36.7%, respectively, by 2030. In particular, the use of coal will be reduced to 30.1% in 2005 according to the value shown in Scenario III because the price of coal will be quite stable. Accordingly, coal will outperform petroleum in the future as the main energy source. With progress in hydrogen production technologies, industrial sectors have incentives to use more hydrogen. In Scenario II, the share of hydrogen will increase to 5.6% in 2030. In Scenario III, the hydrogen share will increase to 10.3%, representing a major increase in hydrogen use, but nothing close to fully replacing crude oil or coal.

The real GDP growth rate of Taiwan will be lower in Scenarios II and III than in Scenario I up to 2025, when support will be instituted to promote advances in the industrial hydrogen technology (Scenarios II and III in Table 3), reflecting the investment made in technological development and infrastructure, as well as the depletion of some commonly used resources in the hydrogen sectors during the transition. After 2021, however, hydrogen will replace some fossil fuels, which will be expensive given a high CO_2 emission rate, yielding a higher GDP growth rate than that of a petroleum-based economy (Scenario I in Table 4).

One of the main assumed advantages of the transition to hydrogen economy is a major decrease in CO_2 emission rate. In 2005, the total amount of emitted CO_2 in Taiwan was estimated to be 266.7×10^6 ton. Without countermeasures, this emission rate will increase to 1015×10^6 ton in 2030. With strong or moderate effort, the CO_2 emission will drop to 929×10^6 or 990×10^6 ton, respectively, or 2.3% or 8.5%. However, this emission amount is still about 3.5 times that of 2005. Restated, even with strong effort to advance technology, the fall in the CO_2 emission rate is limited and not necessarily consistent with the target set by the Kyoto Protocol.

Table 3 – Assumptions for four scenarios' design

	Scenario I	Scenario II	Scenario III	Scenario IV
Economic structure	Developing economic structure	Developing economic structure	Developing economic structure	Developed economic structure
Closure	Keynesian school	Keynesian school	Keynesian school	Classical school
Endogenous Variables	Employment Rate of return	Employment Rate of return	Employment Rate of return	Wage rate Capital stock
Exogenous Variables	Wage rate Capital stock	Wage rate Capital stock	Wage rate Capital stock	Employment Rate of return
Elasticities	CES elasticities of biohydrogen, other energy sources, primary inputs, CET transformation, etc. at. 0.5, 0.5, 0.4 and 0.4	CES elasticities of biohydrogen, other energy sources, primary inputs, CET transformation, etc. at 0.5, 0.5, 0.4 and 0.4	CES elasticities of biohydrogen, other energy sources, primary inputs, CET transformation, etc. at 0.5, 0.5, 0.4 and 0.4	CES elasticities of biohydrogen, other energy sources, primary inputs, CET transformation, etc. at 0.25, 1.0, 0.8 and 0.8
Effort	No effort	Moderate effort	Strong effort	Strong effort
Technology progress rate	Technology progress rate at 0%	Technology progress rate at 5%	Technology progress rate at 15%	Technology progress rate at 15%

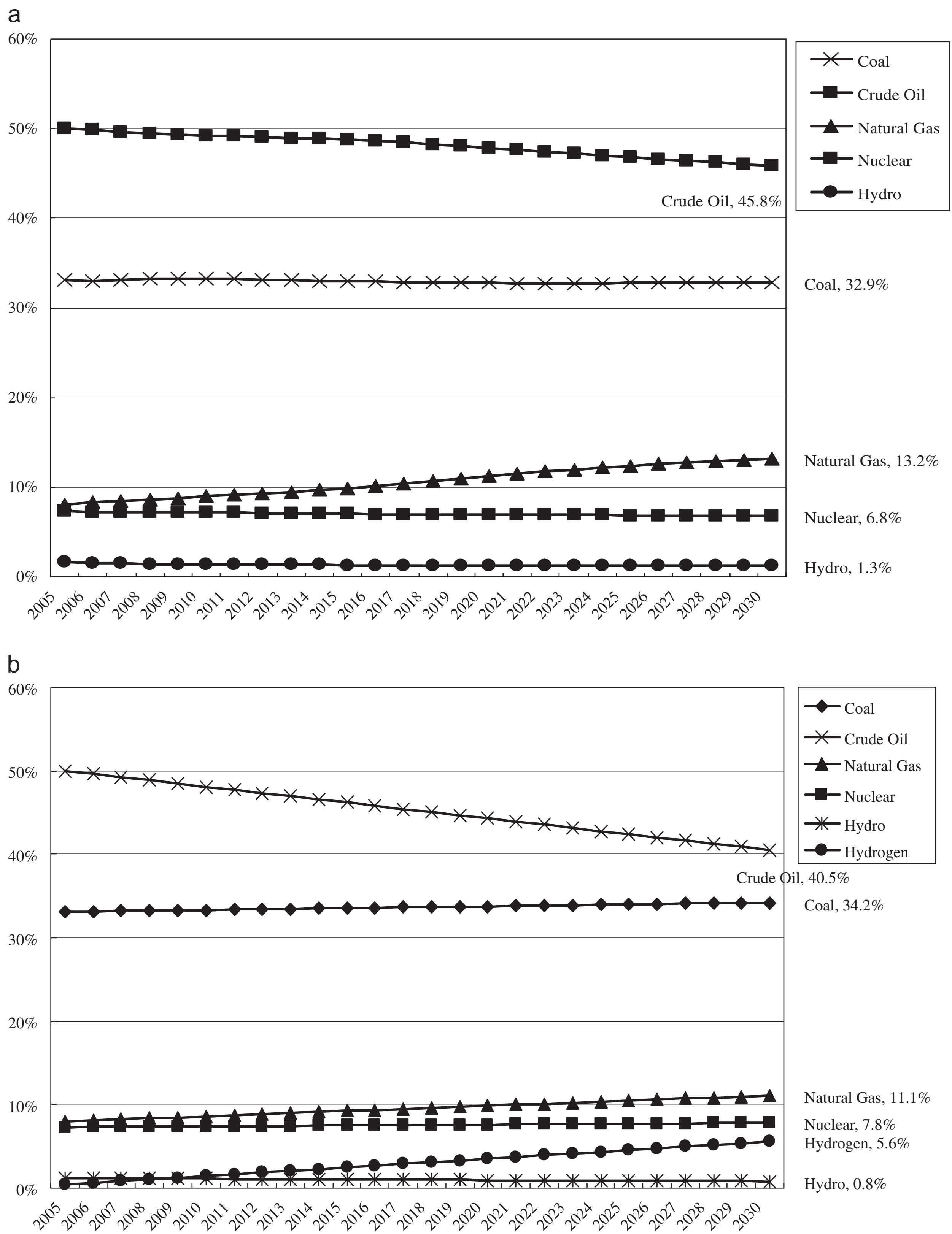

Fig. 4 – (a) Energy structure in Scenario I. Existing economic structure with no support. (b) Energy structure in Scenario II. Existing economic structure with moderate support. (c) Energy structure in Scenario III. Existing economic structure with strong support.

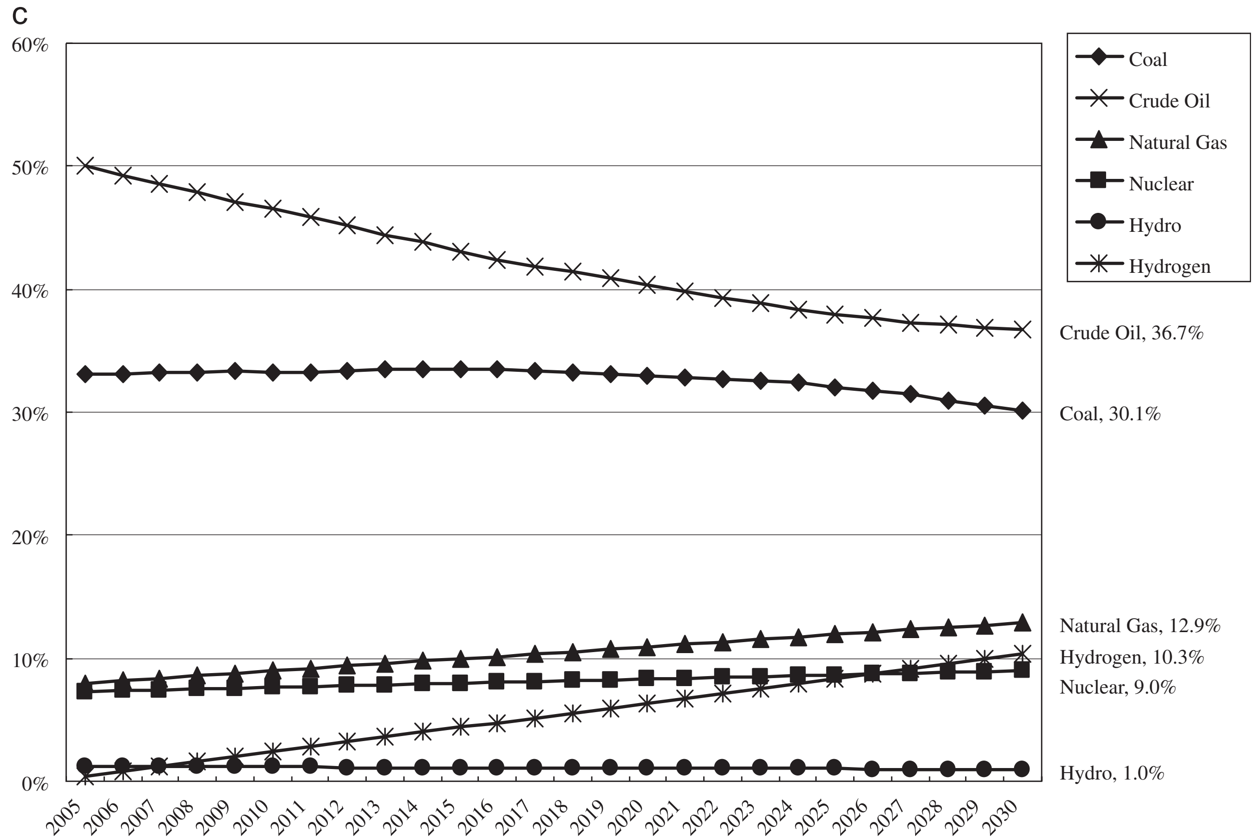

Fig. 4 – (*Continued*)

Table 4 – Real GDP growth rates (%) under Scenarios I–III

Year	Scenario I	Scenario II	Scenario III	II–I	III–I
2006	5.42	4.64	4.58	−0.78	−0.84
2010	6.21	5.57	5.45	−0.64	−0.76
2015	5.98	5.62	5.56	−0.36	−0.42
2020	5.32	5.16	5.04	−0.16	−0.28
2025	5.01	5.07	5.24	+0.06	+0.23
2030	4.97	5.08	5.33	+0.11	+0.36

3.2. *Scenario IV: a reformed economy*

As discussed in Section 3.1, a successful transition to a hydrogen economy cannot be achieved in Taiwan only by promoting technological progress. The economic structure of Taiwan must be completely revised. In Scenario IV, Taiwan's economy is considered to be "elastic"—like those of developed countries. In this scenario, all parameters are as in Scenario III, even though different CES elasticities are adopted in the simulation: biohydrogen (0.25), other energy sources (1.0), primary inputs (0.8) and transformation (0.8). Restated, the fossil fuels (petroleum, coal, natural gas) can be easily replaced with hydrogen. In this scenario, a strong effort is made to ensure a high level of technology progress (15% annually).

Fig. 5 displays the changes in energy structure over time in Scenario IV. With a reformed economy and strong effort, the proportions of crude oil and coal will be reduced to 25.3% and 23.0%, respectively, in 2030, with hydrogen in third place among the six main energy sources. Clearly, the use of nuclear energy and that of natural gas will also increase, leveling off at around 2022–2025 and beyond. In contrast, the use of hydrogen will continue. According Chalk [36], the timeline for hydrogen economy for USA may be realized after 2040. Our results show the trend that hydrogen may be the dominant energy source before 2040, and the transition to a hydrogen economy will thus be successful as Chalk [36] outlines. In Scenario IV the CO_2 emission will drop to 563×10^6 ton or 44.5% compared with Scenario I (Table 5). It means reformation

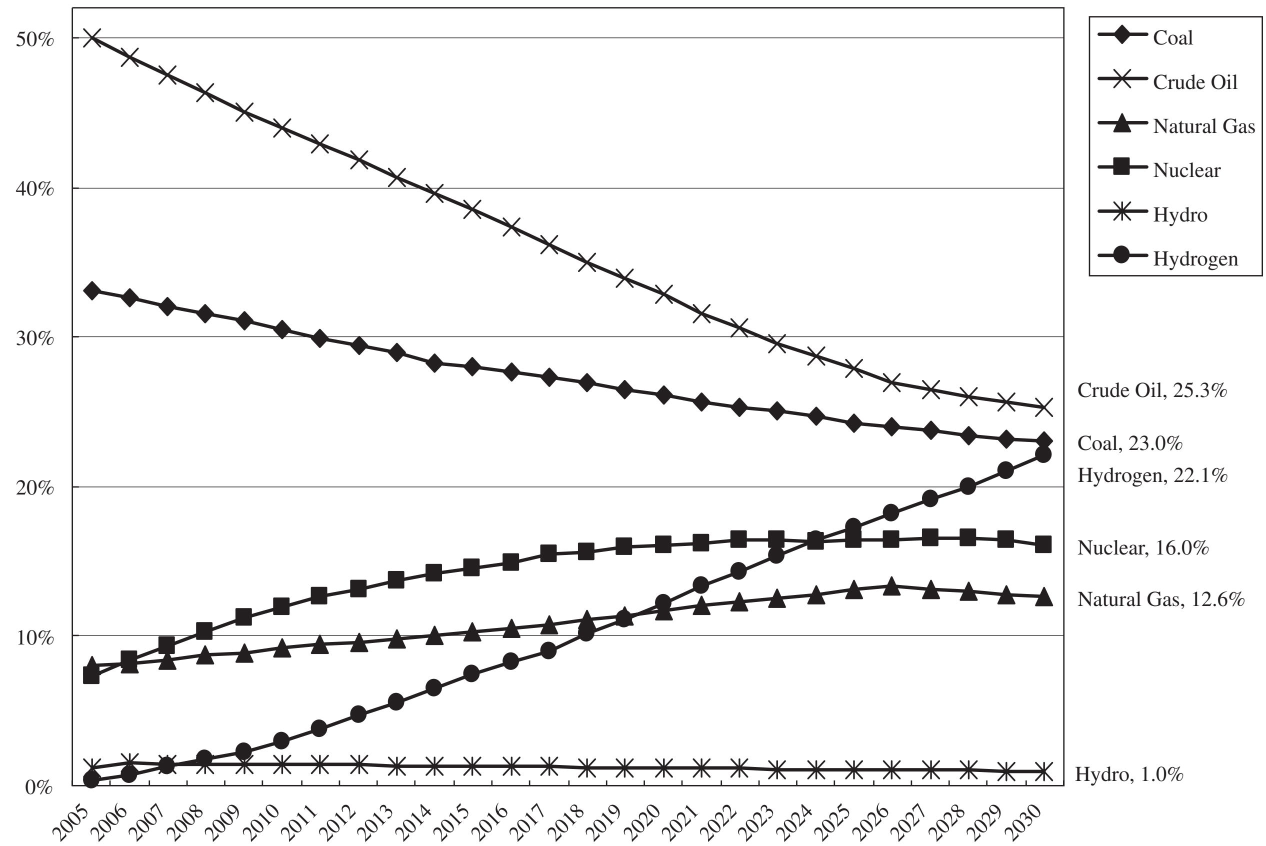

Fig. 5 – Energy structure in Scenario IV. Reformed economic structure with strong support.

Table 5 – Carbon dioxide emission rates under Scenarios I–IV

Year	CO_2 emission (10^6 ton)						
	Scenario I	Scenario II	Scenario III	Scenario IV	II–I	III–I	IV–I
2006	266.7	266.4	265.6	245.2	−0.3 (−0.1%)	−1.1 (−0.4%)	−21.5 (−8.1%)
2010	353	350	345	274	−3.0 (−0.9%)	−8.1 (−2.3%)	−79.2 (−22.5%)
2015	449	443	430	322	−5.4 (−1.2%)	−18.8 (−4.2%)	−127 (−28.3%)
2020	597	587	563	387	−10.0 (−1.7%)	−34.0 (−5.7%)	−210 (−35.2%)
2025	778	763	730	468	−15.7 (−2.0%)	−48.3 (−6.2%)	−311 (−40.0%)
2030	1015	990	929	563	−25.7 (−2.5%)	−86.3 (−8.5%)	−452 (−44.5%)

of economic structure is the key point of the hydrogen economy.

The reformation of the economic structure is to discourage the use of petroleum and strongly encourage the use of hydrogen. Therefore, barriers to hydrogen imports should be removed, hydrogen commodity imports should be subsidized, investments should be made in the hydrogen supply chain, new demand should be created for hydrogen applications, the expansion of petroleum-related industries should be limited and carbon taxes and energy taxes should be levied. Without a complete reformation of the economic structure, the transition to hydrogen economy will not be achievable before 2040.

3.3. *Role of biohydrogen*

In Scenarios II or III, the production rate of hydrogen will initially increase; NG-H_2 will have the highest production rate because of the ease of producing hydrogen using existing facilities whenever needed. However, the NG pathway will be replaced by alternatives in 2010–2015 because of cheaper production costs and the advantage of producing no CO_2 by the other three methods. In Scenario III, the rates of increase of hydrogen production by bio-H_2, nuclear-H_2 and renewables-H_2 will reach 6.1%, 3.8% and 5.5%, respectively, in 2025, with bio-H_2 leading the other two.

Table 6 – Percentage changes of hydrogen industries production under Scenarios II–IV

Year	Scenario II				Scenario III				Scenario IV			
	NG hydrogen	Biohydrogen	Nuclear hydrogen	Other renewable	NG hydrogen	Biohydrogen	Nuclear hydrogen	Other renewable	NG hydrogen	Biohydrogen	Nuclear hydrogen	Other renewable
2006	1.2	0.3	0.1	0.3	4.5	2.1	1.1	1.8	13.4	12.2	10.5	11.3
2010	3.2	0.7	0.3	0.6	4.8	3.4	1.8	2.9	11.2	12.7	11.3	12.1
2015	2.1	1.2	0.5	1.0	5.1	4.2	2.1	3.9	6.3	10.7	9.9	10.2
2020	2.3	1.4	0.8	1.2	3.8	5.3	3.2	4.8	3.4	9.6	8.6	9.1
2025	1.5	1.8	0.9	1.6	3.2	6.1	3.8	5.5	0.4	8.8	7.6	8.5
2030	1.3	2.1	1.1	1.9	2.9	4.3	3.2	4.1	−1.3	8.2	6.3	7.9

Unit: %.

Table 7 – Percentage changes in commodity price of hydrogen-related industries under Scenarios II–IV

Year	Scenario II				Scenario III				Scenario IV			
	NG hydrogen	Biohydrogen	Nuclear hydrogen	Other renewable	NG hydrogen	Biohydrogen	Nuclear hydrogen	Other renewable	NG hydrogen	Biohydrogen	Nuclear hydrogen	Other renewable
2006	3.2	−0.5	−0.1	−0.3	4.1	−0.7	−0.4	−0.6	12.8	−3.4	−1.9	−2.1
2010	2.3	−1.2	−0.4	−0.8	2.7	−1.9	−1.0	−1.7	3.2	−5.4	−5.0	−4.3
2015	1.4	−1.5	−0.6	−1.1	2.4	−2.0	−1.2	−1.8	2.5	−5.0	−5.5	−6.7
2020	1.5	−1.7	−1.0	−1.4	2.5	−2.4	−1.3	−2.0	2.3	−4.7	−5.1	−5.3
2025	1.6	−1.9	−0.9	−1.5	2.9	−3.5	−1.6	−3.1	3.1	−6.1	−5.6	−5.0
2030	1.4	−1.8	−1.0	−1.4	2.7	−3.1	−2.1	−2.8	3.7	−6.3	−6.0	−6.2

Unit: %.

In Scenario IV, with a reformed economy, hydrogen can easily replace fossil fuels, markedly increasing the hydrogen production rate (Fig. 5). As Table 6 indicates, without delay, the increase in all hydrogen production sub-sectors will exceed 10%, with NG-H_2 ranking first (as expected). However, since progress in production technologies is assumed to be significant, the productions of hydrogen using other sub-sectors all increase to a high level. Then, the rate of increase declines over time. In 2030, production through NG-H_2 begins to drop, while the growth through bio-H_2, nuclear-H_2 and renewables-H_2 will be 8.2%, 6.3% and 7.9%, respectively, in 2030.

Table 7 presents changes in energy prices in Scenarios II–IV. The prices of natural gas continue to increase over time, reflecting the increase in the prices of fossil fuels. However, the prices of bio-H_2, nuclear-H_2 and renewables-H_2 drop over time, reaching 6.3%, 6.0% and 6.2% of those in 2030.

Clearly, in all scenarios, all hydrogen production sub-sectors without CO_2 emission contribute almost equally to the hydrogen production sector, since advances in their corresponding technologies are the same over time. Restated, when petroleum runs out and CO_2 emission becomes a major environmental concern, production in all hydrogen sub-sectors will start compensating for the demand–supply gap of fossil fuels. However, in later stages of development, the competition among bio-H_2 and nuclear-H_2 and renewables-H_2 determines their role in the hydrogen economy from 2040. Reduction in costs due to technological progress will be essential toward phasing out non-competitive players in the field.

4. Summary

This study presents an economy-wide analysis of how technology advances and how an improvement in the economic structure is accelerating Taiwan's transition to a hydrogen economy before 2030. We utilized a model, called "Taiwan general equilibrium model-energy, for hydrogen (TAIGEM-EH)", as the forecast tool to evaluate the critical factors that affect the economic growth rates, CO_2 emission rates and the possible, adverse effects of inertial barriers of increases in the price of oil and the difficulty of energy substitution in the present economic structure.

Simulation results showed that, when no effort is made to advance the hydrogen production technology, the energy structure in Taiwan will remain almost unchanged over time, with crude oil and coal the primary energy sources up to 2030. When the hydrogen production technology receives moderate or strong support, then the use of crude oil will drop to 40.5% or 36.7%, respectively, by 2030, the corresponding share of hydrogen will increase to 5.6% or 10.3% and the reduction in CO_2 emission rate will be merely 2.3% or 8.5%. Taiwan cannot achieve a successful transition to the hydrogen economy by solely relying on advances in hydrogen production technology. Scenario IV shows that the CO_2 emission rate will drop to 563×10^6 ton or 44.5% compared with Scenario I, revealing the main benefits that Taiwan will obtain by transforming into a hydrogen economy. Reformation of economic structure together with a strong support for hydrogen technology progress is shown to be essential toward accomplishing a transition to the hydrogen economy.

Among hydrogen production technologies, natural gas dominates the initial stage because of the ease in expanding existing facilities. From 2010 to 2015 and onwards, the production pathway of producing no CO_2 becomes dominating. When petroleum runs out and CO_2 emission becomes a major environmental concern, all hydrogen production sub-sectors will be utilized initially to compensate for the demand–supply gap of fossil fuels. However, in the later development stages, the competition among bio-H_2 and nuclear-H_2 and renewables-H_2 determines their role in the hydrogen economy from 2040. Reduction in costs due to technological progress will be essential toward phasing out non-competitive players in the field. Scenario IV predicts that a successful transition to the hydrogen economy requires not only a substantial reduction of hydrogen production cost, but also a reformation of Taiwan's economic structure. Scenario IV also shows that the cost of hydrogen should down to an incredible low level (with 15% cost down in Table 8). It means that the hydrogen should not be a major energy in the world

Table 8 – Cost down effect in three kinds of hydrogen production

	2010	2015	2020	2025	2030
Strong effort (15% cost down)					
Bio-H_2	0.444	0.197	0.087	0.039	0.017
Nuclear-H_2	0.473	0.210	0.093	0.041	0.018
Renewables-H_2	0.532	0.236	0.105	0.047	0.021
Median effort (5% cost down)					
Bio-H_2	0.774	0.599	0.463	0.358	0.277
Nuclear-H_2	0.825	0.639	0.494	0.382	0.296
Renewables-H_2	0.929	0.718	0.556	0.43	0.333

Unit: USD/m^3.

energy market in the next 20–30 years. It reminds us that hydrogen is a suitable alternative energy but it still has a long way to go. We should develop different kinds of alternative energies to try to replace fossil fuels, not only hydrogen.

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