ENERGY&FUELS

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Energy Fuels, **2008**, 22 (1), 177-181 • DOI: 10.1021/ef700288e • Publication Date (Web): 21 September 2007

Energy & Fuels is published by the American Chemical Society. 1155 Sixteenth
Street N.W., Washington, DC 20036

Energy & Fuels **2008,** *22,* 177–181

Biofuel Economy and Hydrogen Competition[†]

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Received May 28, 2007. Revised Manuscript Received July 23, 2007

This study analyzed how production technology progress and economic structure reformation affect the transition to biofuel or hydrogen economy in Taiwan before 2040. A model, called “Taiwan general equilibrium model—Energy for biofuel and hydrogen (TAIGEM—EBH)”, was the forecast tool, considering as well the role of four new energies, including bioethanol, biodiesel, hydrogen, and fuel cell production industries. When no effort was made to advance the biofuel and hydrogen production technologies, the energy structure in Taiwan will remain almost unchanged over time, with crude oil and coal the primary energy sources up to 2040. With technological advance to reduce production cost, bioethanol will become the dominating renewable energy source, with coal and oil the main primary energy sources as well. Only with a reformed economic structure resembling a developed country, the biofuels and hydrogen economy can be realized in Taiwan.

1. Introduction

Renewable energy sources are developed worldwide, owing to high oil prices and the implementation of the Kyoto Protocol to limit greenhouse gas emission. Obstacles for the transition from petroleum to hydrogen economy include the lack of a reliable and sufficient supply of hydrogen.[1,2] Biofuels, including bioethanol and biodiesel, used as a substitute of petroleum for industrial sectors, are relatively environmentally friendly, energy-independent, less greenhouse-gas-emitting fuels.[3]

Analysis of various economic development scenarios helps decision makers to identify their optimal strategy for achieving biofuel or hydrogen economic targets. This study presents an economy-wide analysis of how technology advance and how reformation in the economic structure can affect the use of biofuel or hydrogen in Taiwan. A model, called “Taiwan general equilibrium model—Energy for biofuel and hydrogen (TAIGEM—EBH)”, is used as the forecast tool. Critical indices, including economic growth rates, energy share, and CO_2 emission rates, were evaluated considering the adverse impact brought by the rising oil price.

2. Model

2.1. Basic Model. The TAIGEM—EBH model was an extended version of the Taiwan general equilibrium model—Energy for hydrogen (TAIGEM—EH), whose details were available elsewhere.[4,5] The TAIGEM—EH is the most comprehensive forecast model available for the economy of Taiwan, which consists of 170 sectors, 6 types of labor, 8 types of margin, and 182 commodities. The input demand for industry production is represented as a five-level nested structure, and the operation of each level is decided independently. The energy composite of the model is comprised of industries of bioethanol, biodiesel, hydrogen, fuel cell, coal products, oil products, natural gas products, and electricity. The power sector of TAIGEM—EBH is modeled as a technology bundle derived from the MEGABARE model,[6] 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. All electricity thus generated is sent to end-users.

The database for the TAIGEM—EH model is presented in the IO table.[7] The supply side includes intermediate and primary input for industries, and the demand side includes an intermediate demand for industries and a final demand for household consumption, government expenditure, investment, net export, and inventory.

Table 1 presents the costs of biofuels, hydrogen, and fuel cell production obtained from a recent survey conducted by the Taiwan Institute of Economic Research. The cost of producing 1 m^3 of hydrogen and 1 L of bioethanol and biodiesel are 1.00, 1.09, and 1.17 USD, respectively. The cost of fuel cell assembly is 10 000 USD/kW.

An energy balance sheet was used to estimate the CO_2 emission matrix from 15 emission commodities, including coal, natural gas, other nonmetallic minerals, gasoline, diesel fuels, aviation fuels, fuel oils, kerosene, lubricants, naphtha, refinery gas, asphalt, other refining products, coal products, and gas. The production of CO_2

[†] Presented at the International Conference on Bioenergy Outlook 2007, Singapore, April 26–27, 2007.

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10.1021/ef700288e CCC: $40.75

Table 1. Cost Share for Different Kinds of Biofuels, Hydrogen, and Fuel Cell Production[a]

	bioethanol		biodiesel		hydrogen		fuel cell	
	input	USD/L	input	USD/L	input	USD/m^3	input	USD/kW
intermediate input	sweet potato	0.53	wasted oil	0.53	biomass and waste	0.17	polymer film	550
	(or sugar cane)	(0.59)	NaOH	0.003	catalyst	0.03	catalyst	775
	(or molasses)	(0.64)	methanol	0.09	electricity	0.03	carbon paper	375
					steam	0.03	gasket	75
							bipolar plate	650
							steelplate	75
							fan	400
							heat exchanger	433.3
primary input	wage	0.16	wage	0.1	wage	0.13	wage	1666.7
	depreciation	0.18	depreciation	0.1	depreciation	0.07	depreciation	666.7
	rent of land	0.17	energy	0.1	rent of land	0.03	rent of land	333.3
	rent of durables	0.25	waste treatment	0.07	rent of durables	0.23	rent of durables	333.3
	interest		test	0.08	interest	0.07	interest	333.3
	profit	0.07	profit	0.1	profit	0.13	profit	
	other cost	0.03	other cost		other cost	0.07	other cost	333.3
	total cost	1.09	total cost	1.17	total cost	1	total cost	10000

[a] Source: survey data by the Taiwan Institute of Economic Research. (Note: Unit USD/L means the cost in U.S. dollars when firms produce biofuels per liter. Unit USD/m^3 means the cost in U.S. dollars when firms produce hydrogen per cubic meter. Unit USD/kW means the cost in U.S. dollars when firms produce fuel cell kilowatt. We use the exchange rate at 1:30 to transform from NTD to USD.

Table 2. Exogenous Shocks for Forecasting Baseline: From 2000 to 2040

macroeconomic variables growth rate (%)	2000	2001	2002	2003	2004	2005	~2006–2040
energy-saving decline rate	−0.60	−0.60	−1.20	−1.20	−1.20	−1.20	−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, and 38.91% in 2005 and was assumed to increase by 3.21% onward up to 2030 based on the high oil price projection of EIA[11] forecast.						
technology bundle	The 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 the WTO in 2002. The tariff rate decline rate was assumed 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 new energies (0.25/0.5), other energy sources (1.0/0.5), primary inputs (1.0/0.5), energy composite (1.6/0.8), and transformation (0.8/0.4).						

is penalized through the carbon tax policy. Clean energy sources, such as hydrogen, which does not emit net CO_2, are encouraged, given cost-saving considerations.

2.2. Model Parameters. The production of biofuels and hydrogen requires intermediate inputs (biomass, energy, etc.) and primary inputs (labor, capital, and machinery). A historical data set for biofuels and hydrogen industries in Taiwan was obtained to prepare the balanced IO table to formulate the supply and demand chains. The survey data on these supply demand chains were collected from gas companies, professional clubs, specialists, and articles. The power generation costs of 10 power generation sectors were obtained from the Taiwan Power Company (TPC).[8,9]

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. The TAIGEM—EBH acquires a historical database of supplies and demands in all sectors of Taiwan. Table 2 presents exogenous shocks in the forecast of the petroleum economy baseline from 2006 to 2040 according to a national economic report provided by Directorate—General of Budget, Accounting, and Statistics (DGBAS),[10] and the results are summarized as follows: (1) The annual growth rate in the number of households is 2% from 2006 to 2040. (2) The energy and productivity efficiency improvement rates are 1.2 and 2.5% annually. (3) The rate of increase of employment is 1%, corresponding to population growth. (4) The CPI is 2% annually. (5) The price of imported crude oil increased by 27.4 and 38.9% in 2004 and 2005, respectively, and will continue to rise at 3.21% annually onward until 2040.[11] (6) The rate of tariff decline will meet WTO regulations until 2010.

2.3. Scenario Design. Taiwan is a developing area. The present scenarios I–III adopted the Keynesian short-run closure for simulat-

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Table 3. Assumptions Made for 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
exogenous variables	wage rate capital	wage rate capital	wage rate capital	employment rate of return
elasticities	CES elasticities of four new energies (0.5), other energy sources (0.5), primary inputs (0.5), energy composite (0.8), and CET transformation (0.4).	CES elasticities of four new energies (0.5), other energy sources (0.5), primary inputs (0.5), energy composite (0.8), and CET transformation (0.4).	CES elasticities of four new energies (0.5), other energy sources (0.5), primary inputs (0.5), energy composite (0.8), and CET transformation (0.4).	CES elasticities of four new energies (0.25), other energy sources (1.0), primary inputs (1.0), energy composite (1.6), and CET transformation (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 10%	technology progress rate at 10%

ing the current situation of Taiwan, while scenario IV adopted neoclassical long-run closure for a developed country (Table 3).

The baseline forecast was conducted over the years 1999–2040, with the energy structure in 2005 presented as follows: crude oil (42.7%), coal (31.2%), natural gas (9.2%), nuclear energy (10.5%), hydropower (1.2%), bioethanol (1.9%), biodiesel (0.7%), hydrogen (0.6%), and fuel cell (2.1%). 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 10% for bioethanol, biodiesel, biohydrogen, and fuel cell technologies. The easiness for substitution of each industry by others, quantified as the elasticities for each industry, were set at 0.5 for coal, oil, bioethanol, biodiesel, natural gas, hydrogen, fuel cell, electricity, and primary inputs composite, 0.8 for energy composite, and 0.8 for CET elasticity, respectively. In scenarios I and II, all parameters were the same as in scenario III but with the technology progress rates reduced to 0 and 5%, respectively. The scenario IV was elucidated by adjusting the economy of Taiwan to an "elastic" one with strong support, such as that in developed countries. The corresponding elasticities were set at 1.0, 1.0, 0.25, 0.25, 1.0, 0.25, 0.25, 1.0, 1.6, and 0.8, respectively. Table 3 outlines of the four studied scenarios.

3. Results and Discussion

3.1. Energy Structure and Macroeconomy: Scenarios I–III. Parts a–c of Figure 1 present changes in the energy structure over time in scenarios I–III, respectively.

In scenario I, where no effort is made to advance the biofuel and hydrogen production technologies, the crude oil share will decline from 40.6% in 2005 to 31.0% in 2040. Because the government of Taiwan adopts "no nuclear power policy", the use of nuclear power declines continuously, with the use of coal increases and peaks at 36.6% in 2034 and the use of natural gas increases monotonically to 16.7% in 2040. The share of fuel cell will peak at about 5% in 2020, while the use of hydrogen will peak at 4.3% in 2032. Afterward, the hydrogen use declines with time. For the biofuel aspect, the use of bioethanol will increase gradually to 7% in 2040. On the contrary, the biodiesel will not play any significant role in Taiwan up to 2040. In this particular scenario, the hydrogen economy will not be realized in the foreseeable future as generally expected.

When biofuels and hydrogen technologies have received moderate or strong support, then the use of crude oil will drop to near 29% by 2040, with the use of coal peaks in 2017–2024, and then reduces to 30.2 and 26.1% in 2040, respectively. Different from scenario I, the use of natural gas will only increase mildly, with the substitution of the drop in oil use by

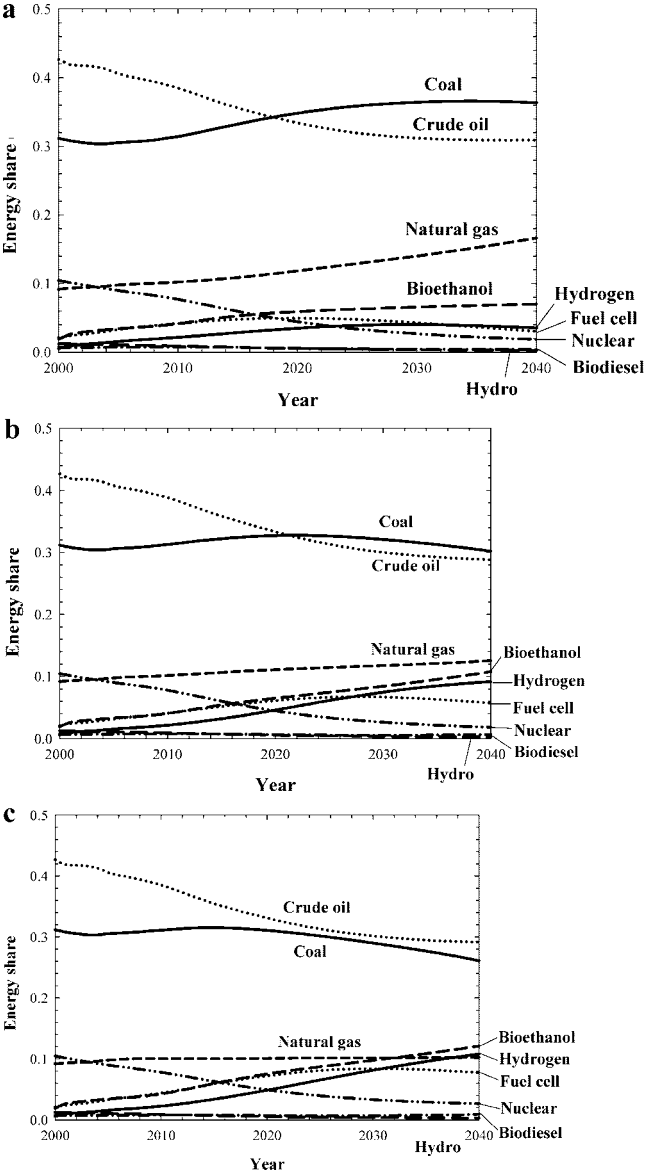

Figure 1. (a) Energy structure in scenario I: existing economic structure with no support. (b) Energy structure in scenario II: existing economic structure with moderate support. (c) Energy structure in scenario III: existing economic structure with strong support.

Table 4. Real GDP Growth Rates (%) under Scenarios I–III

year	scenario I	scenario II	scenario III	II – I	III – I
2006	4.51	4.46	4.38	−0.05	−0.13
2010	4.52	4.35	4.28	−0.17	−0.24
2015	5.36	5.16	5.01	−0.20	−0.35
2020	3.77	4.10	4.45	+0.33	+0.68
2025	3.32	3.82	4.00	+0.50	+0.68
2030	3.07	3.70	3.89	+0.63	+0.82
2035	2.85	3.60	3.88	+0.75	+1.03
2040	2.49	3.42	3.83	+0.93	+1.34

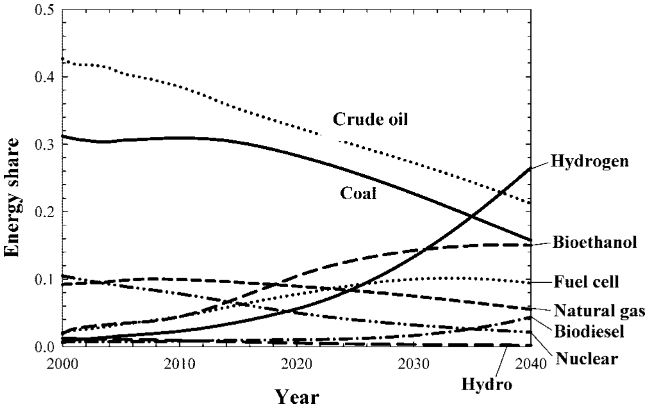

Figure 2. Energy structure in scenario IV. Reformed economic structure with strong support.

bioethanol, hydrogen, and fuel cells. For instance, in scenario III (Figure 1c), the share of bioethanol, hydrogen, and fuel cell will be 12.1, 10.8, and 7.7%, respectively. The use of biodiesel remains low in all cases.

The real GDP growth rate of Taiwan will be lower in scenarios II and III than in scenario I up to 2020, owing to the cost spent for technology advance and infrastructure buildup and depletion of resources commonly used in different industrial sectors (Table 4). Following 2021, the increased use of hydrogen and biofuels will reduce the total CO_2 emission rate, thereby enhancing the GDP growth rate compared to the petroleum-based economy (scenario I).

One main assumed advantage of the biofuel or hydrogen economy is a reduced emission rate of CO_2 (Table 5). In 2005, the total amount of emitted CO_2 in Taiwan is estimated as 243 $\times 10^6$ tons. Without a countermeasure, this emission will increase to 2354 $\times 10^6$ tons by 2040 (scenario I). With strong and moderate effort, the CO_2 emission will be 1949 $\times 10^6$ and 1356 $\times 10^6$ tons, respectively, 17 or 42% lower than that of scenario I in 2040, but is still about 5 times that of 2005. Even with strong effort to advance technologies, the total CO_2 emission rate of Taiwan cannot comply with that set at the Kyoto Protocol.

3.2. Scenario IV: 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 has to be revised. In scenario IV, the economy of Taiwan is considered to be "elastic", similar to those of a developed country (section 2.3).

Figure 2 displays the changes in the energy structure over time in scenario IV. With a reformed economy and a strong effort toward technology progress, the energy share in 2040 will follow: hydrogen (26.5%), crude oil (21.2%), coal (15.7%), bioethanol (15%), fuel cell (10.1%), natural gas (5.5%), and biodiesel (4.3%). The use of all fossil fuels significantly declines, being substituted mainly by hydrogen and bioethanol. Biofuels will dominate in the substituted fuels before 2030 and then hydrogen will take over following 2038, resembling many predictions shown elsewhere. As Table 5 lists, the CO_2 emission rate of scenario IV will be 1175 $\times 10^6$ tons, about 50% of that of scenario I.

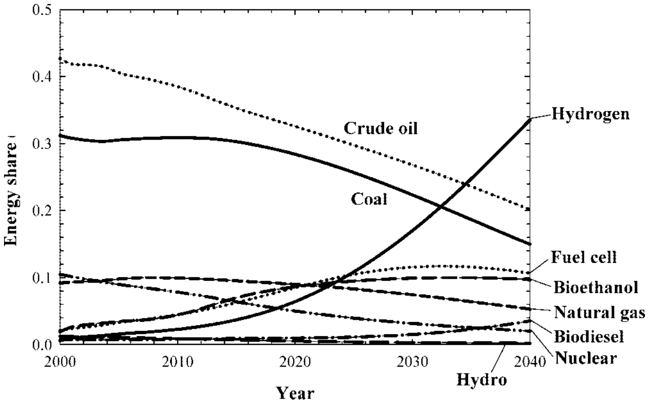

Figure 3. Energy structure in scenario IV with an upper limit of 10% for bioethanol.

3.3. Biofuels and Hydrogen Economy. Unlike the commonly presented trend diagram showing biofuels as a transition energy source from a petroleum to hydrogen economy, the scenarios I–III indicate that the biofuels (bioethanol but not biodiesel) will be more dominating than hydrogen as a substituted energy for fossil fuel in Taiwan. Restated, the incorporation of biofuels delays the transition of a hydrogen economy in Taiwan (if any). Such an occurrence is attributable to the minimal changes needed in infrastructure and credits gained with low cost and CO_2 emission rates with biofuels being added to the existing petroleum-based economy. The mentioned scenarios may be applicable to other developing countries, such as Brazil, that adopt many biofuels as substitutes.

The reformation of the economic structure is to discourage the use of petroleum and strongly encourage the use of biofuels or hydrogen. Therefore, barriers to biofuels and hydrogen or their raw material imports should be removed; biofuels and hydrogen commodity imports should be subsidized; related investments should be made in the biofuels and hydrogen supply chains; a new demand should be created for biofuels and 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 a hydrogen or biofuel economy will not be achievable before 2040 in Taiwan.

Biofuels can be used via most of the existing infrastructure for fossil fuel with greenhouse gas credits and sufficient energy security. Bioethanol uses biomass crops as production input, which can support crop prices for farmers of Taiwan. However, biofuels are not sustainable with the current crop agriculture, owing to nutrient runoff and soil erosion problems.[3] Sweet potato, sugar cane, and molasses are used in Taiwan to produce bioethanol, which is limited by farmland availability and environmental tolerance to the thus yielded adverse effects. According to ref 3, biofuels can substitute up to 10% of the current petroleum consumption in the U.S. if its all corn-planted land was used for biofuel production. Hence, the use of bioethanol in Taiwan should be limited by the available farmlands and the productivity. Moreover, the full use of cellulosic biomass to ethanol needs prehydrolysis with significant energy input. The cost-effective, alternative hydrolysis process is not available at the present stage. A simulation with scenario IV analyzes the constraints imposed by limited farmlands for biofuel crops at an upper limit of 10% for the

Table 5. Carbon Dioxide Emission Amounts under Scenarios I–IV

	CO_2 emission (10^6 tons)						
year	scenario I	scenario II	scenario III	scenario IV	II – I	III – I	IV – I
2006	251	250	250	250	−1	−1	−1
2010	313	293	292	288	−20 (−6%)	−21 (−7%)	−25 (−8%)
2015	485	429	411	394	−56 (−12%)	−74 (−15%)	−91 (−19%)
2020	734	621	559	519	−113 (−15%)	−175 (−24%)	−215 (−29%)
2025	1094	846	718	644	−248 (−23%)	−376 (−34%)	−450 (−41%)
2030	1453	1119	898	783	−334 (−23%)	−555 (−38%)	−670 (−46%)
2035	1867	1478	1120	958	−389 (−21%)	−747 (−40%)	−909 (−49%)
2040	2354	1949	1356	1175	−405 (−17%)	−998 (−42%)	−1179 (−50%)

bioethanol energy share. The results (Figure 3) revealed a similar time course as in scenario IV, except that the hydrogen use will have a bigger share with a limited bioethanol chain.

On the other hand, biodiesel uses waste oil or vegetables oil as raw materials, whose amounts rely on the waste management practice and the oil-plant grains production. The finite supply of raw materials for biodiesel limits its own development.

Therefore, as discussed above, it is not easy for Taiwan to transit to a biofuel- or hydrogen-based economy from the present petroleum-based economy. With reformed economic structure and remarked technology advance, the transition may be thereby realized. However, none of the scenarios studied can comply with the criteria set by the Kyoto Protocol. Restated, Taiwan cannot be affordable to the current living standards regardless of the energy sources depletion. A completely new way of thinking on what kind of life people need to live is needed.

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