Energy Policy 38 (2010) 4604–4616

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

An assessment of exploiting renewable energy sources with concerns of policy and technology

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ARTICLE INFO

Article history:
Received 25 November 2009
Accepted 9 April 2010
Available online 28 April 2010

Keywords:
Renewable energy
Renewable energy policy
Fuzzy analytic hierarchy process

ABSTRACT

In recent years, the Taiwanese government has vigorously promoted the development of renewable energy to engage the challenges of gradual depletion of fossil fuels and oil, as well as the intensification of the greenhouse effect. Since the Sustainable Energy Policy Principles were announced in 2008, Taiwanese government has declared that the development of renewable energy should take into account goals that pertain to energy, the environment, and the economy (3E goals). This study aims to assess the 3E goals and renewable energy sources regulated by the Renewable Energy Development Bill that passed in 2009. The fuzzy analytic hierarchy process (FAHP) is used to resolve the multi-goal problem for achieving our research purposes. That is, this research attempts to reveal the suitable renewable energy sources for the purposes of meeting the 3E policy goals. The results first show that environmental goal is the most important to the development of various renewable energy technologies in Taiwan, followed by the economic and energy goals. Additionally, hydropower, solar energy, and wind energy would be the renewable energy sources utilized in meeting the 3E policy goals.

1. Introduction

In recent years, the exhaustion of fossil fuel and the mitigation of climate changes have become major challenges for governments all over the world. To engage these challenges, many countries are pursuing the research, development, and demonstration of renewable energy sources. As an innovation-oriented island country, Taiwan also seeks renewable energy to engage the challenge of the high incidence of carbon emissions.

Taiwan, a densely populated nation with limited natural resources, imports over 99% of its energy supply (Bureau of Energy of Ministry of Economic Affairs, 2009a). In April 2009, Taiwan National Energy Conference came to the conclusion that due to the geographical limits, Taiwan is not suitable for large scale renewable energy industry. But Taiwan could become the major provider of solar power and wind power equipment in the world. Hence, the development of appropriate renewable energy has become an essential national policy goal for the government. In 2008, Executive Yuan declared that the target share for renewable energy in the total energy supply would reach 8% by the year 2025 (Ministry of Economic Affairs, 2008).

On the other hand, as a medium-sized subtropical island in the Pacific Ocean, Taiwan has enormous potential to develop various renewable energy technologies, such as solar energy, wind power, geothermal energy, hydropower, etc. (Chen et al., 2007a, 2007b). However, a closer look reveals that there are, in fact, multiple goals that the renewable energy policy intends to accomplish. First, from the international view, the International Energy Agency (IEA) (2004) indicates that renewable energy is considered by many policy-makers in IEA member countries to contribute to improving energy security, environmental protection, and economic development (the 3Es). Taking Ireland as an example, Komor and Bazilian (2005) also argue that the numerous drivers and motivators for Irish renewable energy policy can be sorted into energy goal, environmental goal, and economic/industrial goal. Similarly, the Sustainable Energy Policy Principles established by Taiwan's Executive Yuan state that the renewable energy policy should achieve each of the 3E goals as just noted (Ministry of Economic Affairs, 2008).

Several studies have pointed out that specific renewable energy policy goals lead to specific renewable energy sources and technologies (Beccali et al., 2003; Komor and Bazilian, 2005; Önüt et al., 2008). This research aims to assess various renewable energy sources in order to select suitable renewable energy sources for the accomplishment of different policy goals in Taiwan. There are many sophisticated analytical methods available with which to seek optimal solutions for multi-goal problems (Greening and Bernow, 2004). The analytic hierarchy process (AHP) introduced by Saaty (1980) is one of the most

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0301-4215/$ - see front matter
doi:10.1016/j.enpol.2010.04.016

widely used techniques. However, ambiguity and uncertainty often exist among decision-makers' judgment with respect to the problems that they seek to address. Combined with AHP to become known as the fuzzy AHP (FAHP), the fuzzy set theory, therefore, is used to aid in measuring the ambiguity and uncertainty within decision-makers' subjective judgments.

The organization, for the remainder of this research, is as follows: Section 2 briefly illustrates the policy background and the current development of renewable energy in Taiwan. A multi-objective framework is constructed in Section 3 for assessing the renewable energy sources according to Taiwan's policy background and related literature. While Section 4 describes the FAHP method used in this study, the various renewable energy sources are assessed in Section 5 to meet different policy goals. Finally, Section 6 presents the conclusions and policy implications based on the results of Section 5.

2. Renewable energy in Taiwan

The development of renewable energy in Taiwan is currently in the initial stage; related green market mechanisms, such as tradable green certificates, have not been introduced (Wu and Huang, 2006). Even though Taiwan is not a member of the United Nations, the government is now expecting to increase its use of renewable energy for electricity generation. Thus, this section addresses the pressures that Taiwan encounters in order to realize the background and the requirements of Taiwan's energy policy. Moreover, the status quo development of renewable energy is illustrated in this section as well.

2.1. Policy background

Taiwan is a densely populated island with limited natural resources. The energy supply has rapidly increased during the past two decades, along with the dramatic economic growth (Chen et al., 2007a, 2007b). The total energy supply has increased from 51.64 million kiloliters of oil equivalent (KLOE) in 1988 to 142.47 million KLOE in 2008, at an average annual growth rate of 5.21% (Bureau of Energy of Ministry of Economic Affairs, 2009a). In addition to the high dependence on imported energy, Taiwan is particularly dependent on fossil fuel in its energy mix, as shown in Table 1. Such high dependence on fossil fuel has caused Taiwan to rank 17th in the world in terms of CO_2/population emission (International Energy Agency, 2009).

In order to engage the challenge of rapidly increasing global greenhouse gases (GHGs), the United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992, followed by the Kyoto Protocol in 1997 (Bishop, 1997). The European Union has legislated the Directive 2005/32/EC (European Commission, 2005), namely the Directive of Eco-design Requirements of Energy-using Products (EuP), in response to the Kyoto Protocol. Under the EuP directive, product importation will be restricted if the CO_2 emission within production exceeds the regulated standard. Due to the high dependence on exports, Taiwan has to support renewable energy in order to cope with the global trend of green procurement (Huang, 2008).

On the other hand, the indigenous energy price easily fluctuates due to high dependence on imported fossil fuel. Traditional fossil fuel is being gradually depleted. Additionally, the increasing demand from developing countries which also face rapid economic growth, unstable geopolitics, and natural disasters, cause the crude oil price to fluctuate. Thus, the development of indigenous renewable energy sources can decrease the dependence on imported fossil fuel (Bureau of Energy of Ministry of Economic Affairs, 2007).

Moreover, the Sustainable Energy Policy Principles state that the renewable energy policy should take economic development into account (Ministry of Economic Affairs, 2008). According to the National Energy Conference in 2009, the research and development (R&D) of renewable energy technologies and the development of the renewable energy industry should be addressed in the renewable energy policy. Particularly, the development of the renewable energy industry is now regarded as a strategy to create employment and national competitiveness (National Science Council, 2009).

2.2. Renewable energy sources in Taiwan

Due to the deficiency of fossil fuels, Taiwan is seeking renewable energy to engage the previously noted challenges. According to the Renewable Energy Development Bill, which aims to promote the development and utilization of renewable energy and was approved in 2009, renewable energy primarily includes solar energy, biomass energy, geothermal energy, wind energy, ocean energy, and non-pumped storage hydropower (Laws and Regulations Database of The Republic of China, 2009). The current generation capacity and the potential of each renewable energy source in Taiwan are illustrated as follows.

2.2.1. Solar energy

In Taiwan, solar energy is comprised of solar thermal energy and photovoltaics. Based on an estimate of the area of solar collections, the potential of solar energy for heat supply is approximately 1.8 million m^2 (Huang and Yang, 2000). The solar water heater (SWH) is the major application of solar thermal energy in Taiwan (Chen et al., 2007a, 2007b). The energy supply of SWH has contributed 109.5 KLOE in 2008 (Bureau of Energy of Ministry of Economic Affairs, 2009a). The potential for electricity is approximately 12,000 MW in generation capacity and is based on an estimate of the solar photovoltaics settings for residences, commerce, public facilities, and others (Huang and Yang, 2000).

Table 1
Energy supply by resources.
Source: Bureau of Energy of Ministry of Economic Affairs (2009a)

	1988		2008		1988–2008
	KLOE	%	KLOE	%	Average growth rate (%)
Coal	13,683.4	26.50	46,186.7	32.42	6.27
Petroleum	27,225.9	52.72	70,466.7	49.46	4.87
Natural gas	1394.7	2.70	13,420.0	9.42	11.99
Nuclear	8876.6	20.81	11,823.5	8.30	1.44
Hydropower	446.8	1.14	411.6	0.29	−0.41
Solar photovoltaics and wind power	3.0	0.01	56.7	0.04	15.90
Solar thermal	9.8	0.02	109.5	0.08	12.82

Over 385 subsidized systems have been established in Taiwan because of the government's incentive program. Therefore, the total capacity reached 4080 kWp by 2008 (Bureau of Energy of Ministry of Economic Affairs, 2009b).

2.2.2. Biomass energy

Biomass energy is widely used in Taiwan. It includes biogas from animal waste and fuel energy from the burial, gasification, breakdown, and fermentation of household, industrial, and agricultural garbage (Chen et al., 2007a, 2007b). Its potential is estimated to be 2000 MW in generation capacity, based on the biomass investigation in Taiwan, including municipal solid waste (MSW), refuse-derived fuel (RDF), petroleum coke, sugar cane, rice husks, black liquor, scrap tires, paper rejects, and biogas (Huang and Yang, 2000). According to the statistics of the Bureau of Energy, the installed capacity of biomass energy and MSW through 2008 were 116.8 and 622.5 MW, respectively (Bureau of Energy of Ministry of Economic Affairs, 2009a).

2.2.3. Geothermal energy

Taiwan is an island extruded by the Eurasian Plate and the Philippine Sea Plate. Therefore, it has abundant geothermal resources that contain the potential of approximately 1000 MW in generation capacity, according to the investigation of over 26 major geothermal sites in Taiwan (Huang and Yang, 2000). However, most of the geothermal resources in Taiwan are located in remote areas, so the exploitation process is faced with challenges. The economically and technically feasible exploitation is only about 150 MW (Chen et al., 2007a, 2007b). In Taiwan, the main application of geothermal energy is electricity generation. The most promising venture is the Chin-Suei geothermal energy project located in Yi-Lan County, which is developed by the local government by using a build, operate, and transfer method (BOT) for multiple uses of geothermal resources (Bureau of Energy of Ministry of Economic Affairs, 2007).

2.2.4. Wind energy

The potential of wind energy is at least 1000 MW in generation capacity of inshore wind power systems, and a generation capacity of 2000 MW in offshore wind power systems. Such estimates are based on the investigation of numerous sites in Taiwan that have a wind speed of more than 5 m/s (Huang and Yang, 2000; Weng and Lu, 2002). In an attempt to promote wind power generation, in 2000, the Ministry of Economic Affairs initiated a wind demonstration project. The results indicate that the total capacity reached 252.1 MW by 2008, in terms of over 190 established wind power generators (Bureau of Energy of Ministry of Economic Affairs, 2009b).

2.2.5. Ocean energy

The oceans represent a vast and largely untapped source of energy in the form of fluid flow. Approaches to extracting energy from oceans include tidal and wave energy, marine currents, and ocean thermal energy conversion (OTEC). The Kuroshio Current in the northwestern Pacific Ocean, which flows on the eastern coast of Taiwan, has an average speed of 0.9 m/s and carries the potential for 60 GW in generation capacity (Bureau of Energy of Ministry of Economic Affairs, 2007). In addition, the northeast coast of Taiwan and its offshore islands have the potential to generate wave energy. Based on an investigation, the potential generation capacity of OTEC is approximately 30 GW on the eastern and the southern coasts of Taiwan (Bureau of Energy of Ministry of Economic Affairs, 2007). The current development of ocean energy comprises a more detailed investigation of ocean energy distribution, the introduction of ocean energy technologies, and the demonstration of ocean energy generation (Bureau of Energy of Ministry of Economic Affairs, 2007).

2.2.6. Non-pumped storage hydropower

According to an investigation of over 129 rivers in Taiwan, the potential generation capacity for hydropower is approximately 5110 MW (Huang and Yang, 2000). By 2009, the total installed capacity of hydropower in Taiwan reached 1937.9 MW, excluding the pumped storage hydropower of 2602 MW (Bureau of Energy of Ministry of Economic Affairs, 2009a).

3. The assessment framework

As suggested by IEA (2004) and Komor and Bazilian (2005), the goals of a country's renewable energy policy can be categorized into three sorts, including energy goal, environmental goal, and economic/industrial development goal, which echo the 3E policy goals that are declared in Taiwan's Sustainable Energy Policy Principles. By taking into account the Taiwanese context of the renewable energy policy, this study mainly adopts the framework proposed by Komor and Bazilian (2005) to create an assessment structure for Taiwan's renewable energy source (Fig. 1). The following subsections portray the criteria within the three policy goals and a summary is presented in Table 2.

3.1. Energy goal

Taiwan is looking to renewable energy to help it accomplish the energy goal. Based on Taiwan's context and literature review, the assessment of renewable energy sources consider insulation from energy price volatility, security for energy supply, low energy prices, and stability for energy supply, in order to meet this policy goal. The description of each criterion is as follows.

3.1.1. Energy price stability

The prices of traditional fossil fuel are increasingly volatile. They result from influential factors such as increasing demand of rapidly economic growth developing countries, unstable geopolitics, natural disasters, production, and policy matters (Komor and Bazilian, 2005; Bureau of Energy of Ministry of Economic Affairs, 2007; Wang et al., 2009a, 2009b). While Taiwan obtains 38.5%, 28.6%, and 9.8% of its electricity from coal, natural gas, and oil, respectively (Bureau of Energy of Ministry of Economic Affairs, 2009a), the electricity sector has become particularly vulnerable to these price fluctuations. Several studies suggest that the stability of energy cost should be taken into consideration (Mamlook et al., 2001; Liposcak et al., 2006; Begic and Afgan, 2007; Jovanović et al., 2009; Wang et al., 2009a, 2009b). Although Taiwan has an indigenous supply of crude oil and natural gas, the low degree of self-sufficiency does not necessarily eliminate the price fluctuations. Therefore, the development of indigenous renewable energy is essential in preventing energy price fluctuations in international markets.

3.1.2. Security for energy supply

Energy security means consistent availability of sufficient dependent on secure supplies of energy (Asif and Muneer, 2007). The IEA suggests that the development of renewable energy should take energy security into consideration (IEA, 2004). Several researches also argue that energy security is an important criterion for the assessment of renewable energy (Burton and Hubacek, 2007; Lund, 2007; Cai et al., 2009a, 2009b). According to Bureau of Energy statistics, most of Taiwan's electricity is generated from imported fuels including coal, natural gas, oil,

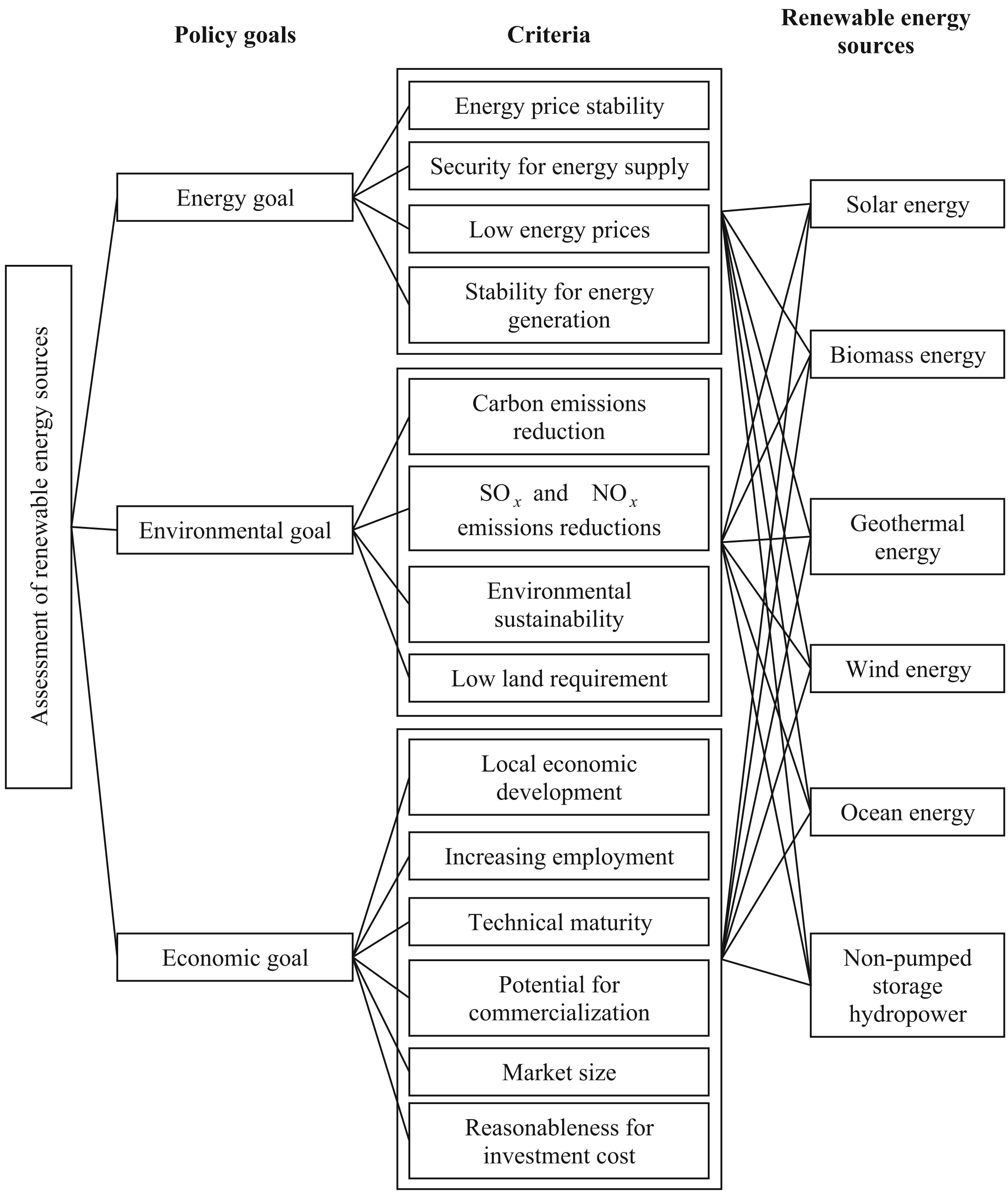

Fig. 1. The assessment model for renewable energy sources in Taiwan.

and nuclear power (Bureau of Energy of Ministry of Economic Affairs, 2009a). Such high imported dependence indicates that Taiwan may be at risk of high exposure to international economic and political price fluctuations. However, such risk can also express the supply shortage in energy (Komor and Bazilian, 2005). Among Taiwan's imported fuels, the supply of natural gas and crude oil is especially affected by the changes in international markets. The exploitation of local renewable energy sources increases the security for energy supply.

3.1.3. Low energy prices

Energy is a fundamental economic input for transportation, industry, agriculture, residents, services, and other sectors. Low energy prices reduce production costs to facilitate economic growth. Additionally, energy is a basic need for heating, cooking, and transportation (Komor and Bazilian, 2005). Maintaining low energy prices is necessary for maintaining the standard of living for residents. However, renewable energy density is so low that energy prices are usually higher than fossil fuels. Thus, in order to maintain residents' basic living standard and national competitiveness, the renewable energy price is suggested to be considered by several studies (Komor and Bazilian, 2005; Shaw and Peteves, 2008).

3.1.4. Stability for energy generation

A common drawback associated with renewable energy is the unpredictable and intermittent output of electric power, particularly in terms of wind and solar energy, which results in the inability to provide all-renewable electricity production in today's society (Hirsch, 2002; Liu and Wang, 2009). In order to realize the

Table 2
The assessment criteria of renewable energy sources.

Policy goal	Criteria	Description	Sources
Energy goal	Energy price stability	The price of final product generated from renewable energy sources is not easily fluctuated	Mamlook et al. (2001), Komor and Bazilian (2005), Liposcak et al. (2006), Begic and Afgan (2007), Bureau of Energy of Ministry of Economic Affairs (2007), Wang et al. (2009a, 2009b), Jovanović et al. (2009)
	Security for energy supply	The consistent availability of sufficient dependent on secure supplies of energy	Komor and Bazilian (2005), Burton and Hubacek (2007), Lund (2007), Cai et al. (2009a, 2009b)
	Low energy prices	The price of final product generated from renewable energy sources is acceptable	Komor and Bazilian (2005), Shaw and Peteves (2008)
	Stability for energy generation	The output generated by renewable energy sources is not easily fluctuated	Gross (2004), Taljan and Gubina (2009), Georgilakis and Katsigiannis (2009)
Environmental goal	Carbon emissions reduction	The extents to which renewable energy sources diminish the emission of CO_2	Diakoulaki and Karangelis (2007), Burton and Hubacek (2007), Chatzimouratidis and Pilavachi (2007), Chatzimouratidis and Pilavachi (2008a), Chatzimouratidis and Pilavachi (2008b), Wang et al. (2008), Wang et al. (2009a, 2009b), Jovanović et al. (2009), Løken et al. (2009), Beccali et al. (2003), Komor and Bazilian (2005)
	SO_x and NO_x emissions reductions	The extents to which renewable energy sources diminish the emission of SO_x and NO_x	Diakoulaki and Karangelis (2007), Begic and Afgan (2007), Chatzimouratidis and Pilavachi (2007), Chatzimouratidis and Pilavachi (2008a), Chatzimouratidis and Pilavachi (2008b), Jovanović et al. (2009), Komor and Bazilian (2005)
	Environmental sustainability	The development meets the needs of the present without compromising the ability of future generations to meet their own needs	World Commission of Environment and Development (1987), Komor and Bazilian (2005)
	Low land requirement	The power plants utilizing renewable energy sources will not occupy large land	Afgan and Carvalho (2002), Beccali et al. (2003), Wang et al. (2008), Chatzimouratidis and Pilavachi (2008a), Chatzimouratidis and Pilavachi (2008b), Wang et al. (2009a, 2009b)
Economic goal	Local economic development	The extents to which renewable energy source can stimulate the domestic economic development	Komor and Bazilian (2005), Williams et al. (2008), Sastresa et al. (2010)
	Increasing employment	The extents to which renewable energy source can create jobs	Haralambopoulos and Polatidis (2003), Beccali et al. (2003), Komor and Bazilian (2005), Erdoğmuş et al. (2006), Madlener et al. (2007), Doukas et al. (2007), Begic and Afgan (2007), Chatzimouratidis and Pilavachi (2008a), Chatzimouratidis and Pilavachi (2008b)
	Technical maturity	The extents to which application of renewable energy sources is technically mature	Beccali et al. (2003), Wang et al. (2008), Huang et al. (2008), Wang et al. (2009a, 2009b)
	Potential for commercialization	The potential of successful commercialization based on assessed renewable energy sources	Lee et al. (2007), Lee et al. (2009)
	Market size	The demand of final products (electricity, gas, fuel, etc.) generated by renewable energy sources	Lee et al. (2007), Lewis and Wiser (2007), Lund (2009)
	Reasonableness for investment cost	The investment cost of renewable energy system is acceptable	Mamlook et al. (2001), Afgan and Carvalho (2002), Liposcak et al. (2006), Diakoulaki and Karangelis (2007), Madlener et al. (2007), Begic and Afgan (2007), Doukas et al. (2007), Jovanović et al. (2009), Wang et al. (2009a, 2009b), Chatzimouratidis and Pilavachi (2009a)

future of all-renewable electricity production, many researches on renewable energy technologies focus on resolving this drawback (Chen et al., 2007a, 2007b; Sørensen, 2007; Moriaty and Honnery, 2007). Owing to the intermittent nature of renewable energy, some studies imply that the stability of electricity output is critical for the development of renewable energy (Gross, 2004; Taljan and Gubina, 2009; Georgilakis and Katsigiannis, 2009). Hence, this study suggests that the stability for energy generation should be considered in the assessment.

3.2. Environmental goal

Renewable energy also allows the Taiwanese government to accomplish the environmental goal. Based on literature review associated with Taiwan's context, the assessment of renewable energy sources should consider carbon emissions reduction, SO_x and NO_x emissions reductions, environmental sustainability, and low land requirements with respect to the environmental goal. Each criterion is illustrated as follows.

3.2.1. Carbon emissions reduction

It is reported that CO_2 contributes 9–26% to the greenhouse effect (Kiehl and Trenberth, 1997; Wang et al., 2009a, 2009b). According to an investigation by the International Energy Agency, Taiwan ranks the 17th in the world in terms of its CO_2/population emission and 20th in terms of its total CO_2 emissions of 276.18 million tons in 2007 (International Energy Agency, 2009). Aggressive action in the energy sector will be necessary if the Taiwanese government is able to successfully clear such a bad reputation. Numerous studies argue that CO_2 emission of renewable energy system is certainly a criterion to assess the renewable energy sources (Diakoulaki and Karangelis, 2007; Burton and Hubacek, 2007; Chatzimouratidis and Pilavachi, 2007, 2008a, 2008b; Wang et al., 2008, 2009a, 2009b; Jovanović et al., 2009; Løken et al., 2009).

3.2.2. SO_x and NO_x emissions reductions

In addition to CO_2, the burning of fossil fuel also emits various compounds that pollute the air. One of the expectations regarding the exploitation of renewable energy is to reduce air pollutant such as SO_x and NO_x (Beccali et al., 2003; Komor and Bazilian, 2005). In addition to air pollution, both SO_x and NO_x lead to acid rain and damage people's health (Wang et al., 2009a, 2009b). The reduction of the emissions of such pollutants is a considerable obstacle to achieving the environmental goal. Therefore, the reduction of SO_x and NO_x emissions is a criterion suggested by many studies (Diakoulaki and Karangelis, 2007; Begic and Afgan, 2007; Chatzimouratidis and Pilavachi, 2007, 2008a, 2008b; Jovanović et al., 2009).

3.2.3. Environmental sustainability

Sustainability is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs as well (World Commission of Environment and Development, 1987). Komor and Bazilian (2005) indicate that in the context of electricity, one interpretation of this definition is to transition away from fossil fuels due to their carbon emissions and their finite supply. Although renewable energy is considered as the substitution of fossil fuels toward the environmental sustainability, the environmental impacts caused by the exploitation of renewable energy should be evaluated according to the following factors: landscape impact, acoustic emissions, electromagnetic interferences, unpleasant odors, and microclimatic changes (Beccali et al., 2003).

3.2.4. Low land requirement

It is important to mention that the amount of energy per unit of land area is small, due to the low energy density of renewable energy (Hirsch, 2002). To obtain the approximate capacity for fossil fuels, the renewable energy sites would need very large areas of converters in order to capture energy. However, human activities are regarded as relevant factors of environmental pressure. A strong demand for land can also cause economic losses, which is proportional to the specific value of a site and the possible alternative needs of the attendant (Beccali et al., 2003). Thus, the land requirement is a matter of great concern found in many studies (Afgan and Carvalho, 2002; Beccali et al., 2003; Wang et al., 2008, 2009a, 2009b; Chatzimouratidis and Pilavachi, 2008a, 2008b).

3.3. Economic goal

The Taiwanese government also expects the renewable energy policy to accomplish the economic goal, particularly in stimulating Taiwan's economic growth and increasing employment (National Science Council, 2009). The evaluating factors for economic goal extracted from related literature should reflect Taiwan's context to facilitate the policy-making in Taiwan. The following subsections clarify the criteria within economic goal.

3.3.1. Local economic development

Taiwan's economic development has relied on the high-tech industry in the past decades. However, today's Taiwanese government expects that the industrial structure can be adjusted to facilitate economic growth by developing renewable energy in the future (National Science Council, 2009). In several studies, the economic benefit contributed by the development of renewable energy is notably highlighted (Komor and Bazilian, 2005; Williams et al., 2008; Sastresa et al., 2010). Therefore, the benefit created by such development should be evaluated in the assessment.

3.3.2. Increasing employment

Due to low economic growth in recent years, the unemployment rate has become a major concern in Taiwan. Creating job opportunities to overcome unemployment is an important consideration which merits inclusion in the renewable energy policy. Numerous studies also indicate that job creation is one of important criteria to evaluate renewable energy projects (Haralambopoulos and Polatidis, 2003; Beccali et al., 2003; Komor and Bazilian, 2005; Erdoğmuş et al., 2006; Madlener et al., 2007; Doukas et al., 2007; Begic and Afgan, 2007; Chatzimouratidis and Pilavachi, 2008a, 2008b). In order to achieve the economic goal, increasing employment is crucial for the assessment of renewable energy in this study.

3.3.3. Technical maturity

Technical maturity is essential for evaluating an applied technology (Beccali et al., 2003; Wang et al., 2008, 2009a, 2009b). Emerging technologies that are more mature have a higher rate of success in terms of their development (Huang et al., 2008). As for renewable energy technologies, Wang et al. (2009a, 2009b) suggest that the following stages can be considered: (1) technologies that are only tested in laboratory; (2) technologies that are only performed in pilot plants, where the demonstrative goal is liked to the experimental one, referring to the operating and technical conditions; (3) technologies that could be still improved; and (4) consolidated technologies, which are close to reaching the theoretical limits of efficiency. Hence, it is necessary to evaluate the maturity of renewable energy technologies for meeting the economic goal in Taiwan's renewable energy policy.

3.3.4. Potential for commercialization

Although there are numerous types of renewable energy, many of them are technically immature and only performed in pilot plants and, thus, cannot be utilized in large scale. Some countries deploy policy measures to facilitate the commercialization of renewable energy technologies to capture competitive position in the global market for domestic renewable energy industry (Hakkila, 2006; Zegers, 2006; Lund, 2009). In order to achieve the economic goal, the potential of commercialization is suggested to be a criterion toward successful utilization of renewable energy by some studies (Lee et al., 2007, 2009).

3.3.5. Market size

Many countries are looking not only to expand their domestic use of renewable energy but also to develop accompanying local renewable energy industries to meet the demand (Lewis and Wiser, 2007). Taiwan's government regards the development of renewable energy industry as a strategy to spur the economic development as well, according to the National Energy Conference in 2009 (National Science Council, 2009). As an emerging industry, the potential market size plays an important role to establish the industrial competitiveness (Lee et al., 2007; Lewis and Wiser, 2007; Lund, 2009). In order to accomplish the economic goal of stimulating economic growth and increasing employment, the potential market size, including those that are domestic as well as international, should be carefully evaluated (Lee et al., 2007). A larger market size attracts more companies that are willing to invest, which is helpful to facilitate the development of related industries.

3.3.6. Reasonableness for investment cost

The investment cost of renewable energy system comprises of all costs relating to: the purchase of mechanical equipment, technological installations, construction of roads and connections to the national grid, engineering services, drilling and other incidental construction work (Wang et al., 2008, 2009a, 2009b). At present, the investment costs, along with the risks of renewable energy, remain high. At the national level, however, the environmental and energy goals have to be evaluated against investment costs in order to determine whether it is more efficient to use renewable energy sources (Lee et al., 2007; Chatzimouratidis and Pilavachi, 2009a). Thus, the investment cost is the most used economic criteria presented in related literature renewable energy assessment (Mamlook et al., 2001; Afgan and Carvalho, 2002;

Liposcak et al., 2006; Diakoulaki and Karangelis, 2007; Madlener et al., 2007; Begic and Afgan, 2007; Doukas et al., 2007; Jovanović et al., 2009; Wang et al., 2009a, 2009b; Chatzimouratidis and Pilavachi, 2009a).

4. Methodology

The analytic hierarchy process (AHP) proposed by Saaty (1980) shows the process of determining the priority of a set of criteria and the relative importance of a multi-criteria decision-making (MCDM) problem among them (Saaty, 1980; Wei et al., 2005; Hu et al., 2009). The primary advantage of AHP is the relative ease with which it conducts multiple criteria and performs qualitative and quantitative data analyses (Meade and Sarkis, 1998; Kahraman et al., 2004). Therefore, several studies have applied AHP during renewable energy planning, such as the utilization of solar energy technologies in Jordan (Elkarni and Mustafa, 1998), sustainable development of rural energy in China (Wang and Feng, 2002), renewable energy planning in Korea (Lee et al., 2007), evaluation of renewable energy plants (Chatzimouratidis and Pilavachi, 2008a, 2009a).

However, AHP is criticized for its inability to reflect the human cognitive process because it does not cope with the uncertainty and ambiguity, which occurs in decision-makers' judgments (Kwong and Bai, 2003; Chan and Kumar, 2007; Lee et al., 2008; Fu et al., 2008). It is difficult to respond to the preference of decision-makers by assigning a specific number. Some techniques are proposed in order to improve the AHP, such as the fuzzy approach (Gupta et al., 1977; Tsaur et al., 1997, 2002; Lee et al., 2008) and the sensitivity analysis (Chatzimouratidis and Pilavachi, 2008b, 2009a). The fuzzy set theory introduced by Zadeh (1965) aims to solve the problems that involve the absence of sharply defined criteria. A commonality among terms of expression, such as "very likely," "probably so," "not very clear," or "rather dangerous," that are often heard in daily life is that they all contain some degree of uncertainty (Tsaur et al., 1997, 2002; Lee et al., 2008). If such inherent uncertainty and imprecision associated with human behavior in decision-making is not taken into account, the results derived from pairwise comparisons process of AHP can be misleading (Deng, 1999). Therefore, the fuzzy analytic hierarchy process (FAHP) uses triangular fuzzy numbers to express the evaluations of decision-makers (Laarhoven and Pedrycz, 1983; Buckley, 1985). The linguistic approach derived from the fuzzy set theory is used to solve such kinds of problem through the use of triangular fuzzy numbers (Gupta et al., 1977; Lee et al., 2008).

In addition to the uncertainty and imprecision caused by human behavior, another type of uncertainty comes from possible external events or scenarios. One may argue that such external uncertainty perplex decision-makers' judgments. Some information can be obtained by asking a set of "what if" questions and determining whether the solution changes to conduct this external uncertainty in a decision-making process (Hahn, 2003). This approach is typically known as sensitivity analysis and broadly applicable to many decision methodologies (Triantaphyllou and Sánchez, 1997; Hahn, 2003). In using AHP with sensitivity analysis, analysts can build scenarios to depict possible circumstances that affect the criteria weights or attributes for each alternative (Erkut and Tarimcilar, 1991; Winebrake and Creswick, 2003).

In this study, the FAHP is mainly employed due to the theme concerns more policy issues in certain time for a country. We therefore feel that the scenario analyses might not possibly add more benefits to the empirical use of the research than the FAHP method might does, in speaking of sorting out different uncertainty problems. However we simply agree that the AHP with a sensitivity analysis should be able to render a very valuable direction for the future researches in various fields to follow.

4.1. Step 1: construct the hierarchical structure

Establish the hierarchical structure with decision elements (i.e., criteria). Next decision-makers are required to express the relative importance of two decision elements in the same level according to a nine-point scale recommended by Saaty (1980). It is then that the data can be collected and formed into pairwise comparison matrices for each of the K decision-makers.

4.2. Step 2: check the consistency

The AHP wishes to find the weights of the criteria, $w_1, \ldots, w_n$, the hierarchical structure constructed in the previous step. A pairwise comparison can be represented by a reciprocal matrix $\boldsymbol{A}$ as

$$\boldsymbol{A} = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{1}$$

where a_{ij} denotes the number indicating the strength of criterion i when compared with criterion j. To ensure that the priority of decision criteria is consistent, the eigenvalues and eigenvectors are calculated using Eq. (1):

$$\mathbf{A} \cdot \mathbf{w} = \lambda_{\max} \cdot \mathbf{w} \tag{2}$$

where $\boldsymbol{w}$ is the eigenvector of the matrix $\boldsymbol{A}$, and $\lambda_{\max}$ is the largest eigenvalue of the matrix $\boldsymbol{A}$. The eigenvector $\boldsymbol{w}$ can be obtained by

$$\mathbf{w} = \left(\prod_{j=1}^{n} a_{ij} \right)^{1/n} \Bigg/ \sum_{i=1}^{n} \left(\prod_{j=1}^{n} a_{ij} \right)^{1/n} \tag{3}$$

where n is the number of criteria being compared in this matrix. The largest eigenvalue $\lambda_{\max}$ of $\boldsymbol{A}$ can be estimated by

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(\mathbf{Aw})_i}{w_i} \tag{4}$$

Table 3
Random index (*RI*).

n	1	2	3	4	5	6	7	8
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41
n	9	10	11	12	13	14	15	
RI	1.45	1.49	1.51	1.53	1.56	1.57	1.59	

Table 4
Triangular fuzzy numbers.

Linguistic variables	Positive triangular fuzzy numbers	Positive reciprocal triangular fuzzy numbers
Extremely strong	(9,9,9)	(1/9,1/9,1/9)
Intermediate	(7,8,9)	(1/9,1/8,1/7)
Very strong	(6,7,8)	(1/8,1/7,1/6)
Intermediate	(5,6,7)	(1/7,1/6,1/5)
Strong	(4,5,6)	(1/6,1/5,1/4)
Intermediate	(3,4,5)	(1/5,1/4,1/3)
Moderately strong	(2,3,4)	(1/4,1/3,1/2)
Intermediate	(1,2,3)	(1/3,1/2,1)
Equally strong	(1,1,1)	(1,1,1)

Then, the consistency index (CI) and the consistency ratio (CR) can be defined, as shown in Eqs. (5) and (6), respectively (Saaty, 1980):

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

where RI represents the random index. The value of RI is the average consistency index of a randomly generated pairwise comparison matrix of a similar size, as shown in Table 3.

4.3. Step 3: construct fuzzy positive matrices

The scores of pairwise comparisons are transformed into linguistic variables, which are represented by a positive triangular fuzzy number, as shown in Table 4. According to Buckley (1985), the definition of the fuzzy positive reciprocal matrix is as follows:

$$\tilde{A}^k = \left[\tilde{a}_{ij}^k\right] \tag{7}$$

where $\tilde{A}^k$ is a fuzzy positive reciprocal matrix of decision maker k, and $\tilde{a}_{ij}^k$ is the relative importance between i and j of the decision criteria. Thus, $\tilde{a}_{ij}^k = 1, \forall i = j$, $\tilde{a}_{ij}^k = 1/a_{ij}^k, \forall i,j = 1,2,\ldots,n$.

4.4. Step 4: calculate fuzzy weights

After synthesizing the decision-makers' pairwise comparison matrices, this study calculates the fuzzy weights according to the Lambda–Max method proposed by Csutora and Buckley (2001). The procedure of the Lambda–Max method is described as follows:

(1) Let $\alpha = 1$ in obtaining the positive matrix of the decision-maker k, $\tilde{A}_m^k = [a_{ijm}]_{n\times n}$, and let $\alpha = 0$ in obtaining the lower bound and upper bound positive matrix of decision-maker k, $\tilde{A}_l^k = [a_{ijl}]_{n\times n}$ and $\tilde{A}_u^k = [a_{iju}]_{n\times n}$, respectively. Using the weight calculating process of AHP, the weight vector can be derived as $W_m^k = [w_{im}^k]$, $W_l^k = [w_{il}^k]$ and $W_u^k = [w_{iu}^k]$, $i = 1,2,\ldots,n$.

(2) In order to minimize the fuzziness of the weight, two constants, M_l^k and M_u^k, are computed using the following equations:

$$M_l^k = \min\left\{\frac{w_{im}^k}{w_{il}^k} \middle| 1 \le i \le n\right\} \tag{8}$$

$$M_u^k = \max\left\{\frac{w_{im}^k}{w_{iu}^k} \middle| 1 \le i \le n\right\} \tag{9}$$

The lower and upper bound of the weight are defined as

$$W_l^{*k} = \left[w_{il}^{*k}\right], \quad w_{il}^{*k} = M_l^k w_{il}^k, \quad i = 1,2,\ldots,n \tag{10}$$

$$W_u^{*k} = \left[w_{iu}^{*k}\right], \quad w_{iu}^{*k} = M_u^k w_{iu}^k, \quad i = 1,2,\ldots,n \tag{11}$$

By computing W_l^{*k}, W_m^k, and W_u^{*k}, the fuzzy weight matrix for decision-maker k can be acquired as $\tilde{W}_i^k = (w_{il}^{*k}, w_{im}^k, w_{iu}^{*k})$, $i = 1,2,\ldots,n$.

4.5. Step 5: integrate the fuzzy weights of each decision maker

The geometric average is applied in order to obtain the aggregate of the fuzzy weights of decision-makers, as in the following equation:

$$\overline{\tilde{W}}_i = \left(\prod_{k=1}^{K} \tilde{W}_i^k\right)^{1/K}, \quad \forall k = 1,2,\ldots,K \tag{12}$$

where $\overline{\tilde{W}}_i$ is the aggregated fuzzy weight of criterion i of K decision-makers, $\tilde{W}_i^k$ is the fuzzy weight of criterion i of decision maker k, and K is the number of decision-makers.

Table 5
Linguistic scales.

Linguistic variables	Corresponding triangular fuzzy number
Very poor	(1,1,3)
Poor	(1,3,5)
Fair	(3,5,7)
Good	(5,7,9)
Very good	(7,9,9)

4.6. Step 6: obtain final ranking of criteria

Based on the equation proposed by Chen (2000), a closeness coefficient defines the ranking order of the decision elements by using the equation listed below:

$$CC_i = \frac{d^-\left(\tilde{W}_i, 0\right)}{d^+\left(\tilde{W}_i, 1\right) + d^-\left(\tilde{W}_i, 0\right)}, \quad i = 1,2,\ldots,n, \quad 0 \le CC_i \le 1 \tag{13}$$

where CC_i is the weight for criterion i. $d^-\left(\tilde{W}_i, 0\right)$ and $d^+\left(\tilde{W}_i, 1\right)$, computed by using Eqs. (14) and (15), are the distance measurements between two fuzzy numbers:

$$d^-\left(\tilde{W}_i, 0\right) = \sqrt{\frac{1}{3}\left[\left(\overline{W}_{il}^* - 0\right)^2 + \left(\overline{W}_{im} - 0\right)^2 + \left(\overline{W}_{iu}^* - 0\right)^2\right]} \tag{14}$$

$$d^+\left(\tilde{W}_i, 1\right) = \sqrt{\frac{1}{3}\left[\left(\overline{W}_{il}^* - 1\right)^2 + \left(\overline{W}_{im} - 1\right)^2 + \left(\overline{W}_{iu}^* - 1\right)^2\right]} \tag{15}$$

4.7. Step 7: assess the renewable energy sources

In this step, the fuzzy theory uses linguistic variables to express experts' subjective judgments in order to reflect the human thinking style in nature. Table 5 illustrates the linguistic variables adopted in this study (Wang et al., 2009a, 2009b), and that experts' judgments are integrated by the geometric average method.

5. Empirical analysis

In this section, the constructed assessment model is used to assess the renewable energy sources that are regulated in the Renewable Energy Development Bill in order to select the suitable renewable energy technologies for Taiwan. The weights of each criteria, which are presented below, are obtained by using FAHP. Moreover, the policy implications are proposed according to the data analysis.

5.1. Data analyses

In order to accomplish the research purpose, this study has invited the experts in Taiwan who are familiar with the status quo development of renewable energy technologies, the market conditions, and the renewable energy policy, to assess the six major renewable energies which are defined in the Renewable

Table 6
The weights on the assessment of renewable energy sources.

Policy goal	Weight	Criteria	Weight within policy goal	Aggregated weight
Energy goal	0.303	Energy price stability	0.164	0.050
		Security for energy supply	0.392	0.119
		Low energy prices	0.141	0.043
		Stability for energy generation	0.319	0.097
Environmental goal	0.377	Carbon emissions reduction	0.322	0.122
		SO_x and NO_x emissions reductions	0.223	0.084
		Environmental sustainability	0.378	0.143
		Low land requirement	0.075	0.028
Economic goal	0.329	Local economic development	0.178	0.059
		Increasing employment	0.123	0.041
		Technical maturity	0.157	0.052
		Potential for commercialization	0.180	0.059
		Market size	0.227	0.075
		Reasonableness for investment cost	0.154	0.051

Table 7
The fuzzy estimation of six renewable energy sources on criteria.

Criteria	Solar energy	Biomass energy	Geothermal energy	Ocean energy	Wind energy	Hydropower
Energy price stability	(2.33,4.55,6.52)	(2.38,4.53,6.57)	(3.39,5.03,7.24)	(2.25,3.76,6.08)	(2.96,4.69,6.90)	(3.66,5.95,7.66)
Security for energy supply	(4.65,6.71,8.45)	(2.96,5.14,7.20)	(3.25,5.36,7.40)	(3.46,5.71,7.66)	(3.18,5.39,7.35)	(4.43,6.61,8.39)
Low energy prices	(1.25,2.33,4.55)	(1.98,4.16,6.21)	(2.94,4.75,6.99)	(2.47,3.93,6.25)	(2.84,4.56,6.75)	(4.25,6.43,8.22)
Stability for energy generation	(3.34,5.47,7.40)	(2.96,5.14,7.20)	(3.32,5.06,7.19)	(2.42,3.84,6.18)	(3.32,5.55,7.50)	(3.39,5.24,7.29)
Carbon emissions reduction	(3.43,5.59,7.40)	(2.28,4.58,6.48)	(3.69,5.32,7.55)	(3.77,5.03,7.34)	(4.69,6.90,8.39)	(4.86,6.90,8.63)
SO_x and NO_x emissions reductions	(3.43,5.59,7.40)	(2.43,3.90,6.12)	(3.69,5.32,7.55)	(3.88,5.13,7.34)	(4.69,6.90,8.39)	(5.36,7.40,8.81)
Environmental sustainability	(4.27,6.34,8.11)	(2.61,4.31,6.48)	(4.19,6.34,8.39)	(3.32,5.06,7.19)	(4.22,6.26,8.28)	(3.90,6.08,7.88)
Low land requirement	(1.65,3.18,5.39)	(1.50,3.34,5.47)	(3.56,5.59,7.61)	(4.85,6.95,8.28)	(1.65,3.82,5.87)	(2.48,4.65,6.71)
Local economic development	(5.07,7.10,8.81)	(2.94,5.21,7.30)	(2.61,3.93,6.21)	(2.78,4.19,6.43)	(3.22,4.96,7.19)	(2.48,4.65,6.71)
Increasing employment	(4.31,6.48,8.39)	(2.96,4.69,6.90)	(2.28,3.66,5.91)	(2.47,3.93,6.25)	(2.70,4.49,6.71)	(1.81,3.63,5.79)
Technical maturity	(4.72,6.76,8.63)	(3.53,5.17,7.40)	(1.65,3.48,5.63)	(1.72,3.27,5.51)	(1.97,3.51,5.79)	(4.53,6.57,8.45)
Potential for commercialization	(4.62,6.80,8.57)	(3.32,5.06,7.19)	(3.05,4.37,6.61)	(2.07,3.56,5.83)	(3.96,6.12,8.05)	(3.68,5.87,7.56)
Market size	(5.92,7.94,9.00)	(4.40,6.44,8.45)	(2.28,4.40,6.44)	(3.41,5.44,7.45)	(4.40,6.44,8.45)	(3.41,5.44,7.45)
Reasonableness for investment cost	(1.00,2.28,4.40)	(2.28,4.40,6.44)	(1.73,3.87,5.92)	(1.32,2.59,4.79)	(2.59,4.79,6.85)	(3.00,5.00,7.00)

Note: The fuzzy value of six renewable energy sources on each criterion is presented in the brackets.

Energy Development Bill. The consistency of the 15 expert questionnaires which have been collected is verified through the use of Step 1, as illustrated in the previous section. As a result, 14 valid questionnaires with values of CI and CR smaller than 0.1 are employed in obtaining the final criteria weights of the assessment framework by adopting Steps 3–6. The empirical results are shown in Table 6.

As presented in Table 6, the environmental goal is the most emphasized policy goal at the present time, and the economic and energy goals rank second and third, respectively. Within the environmental goal, the environmental sustainability and the reduction of carbon emissions are identified as the two most critical criteria with which to evaluate renewable energy sources. Market size, potential for commercialization, and local economic development are identified as the first, second, and third priorities within the economic goal, respectively. The security for energy supply and the stability for energy generation are the two suggested factors within the energy goal with which to evaluate renewable energy sources.

After obtaining the relative weights of each criterion, the renewable energy sources are estimated by using the linguistic variables shown in Table 5 to express the experts' subjective judgments in order to reflect the human thinking style in nature. Experts are required to estimate every renewable energy source for each criterion, and their judgments are later integrated by using the geometric average technique which was suggested by Buckley (1985). The fuzzy estimation of renewable energy sources on each criterion is presented in Table 7. A center of the area defuzzification method is used to determine the optimal non-fuzzy performance (BNP) value of these fuzzy numbers (Opricovic and Tzeng, 2003), and the BNP value is derived by

$$BNP_i = [(UR_i - LR_i) + (MR_i - LR_i)]/3 + LR_i, \quad \forall i \qquad (16)$$

where UR_i, MR_i and LR_i denote the maximum, the middle, and the minimum values of experts' estimations as integrated by the geometric average method, respectively. The BNP values of six renewable energy sources on each criterion are presented in Table 8.

The simple additive weighting method is used to obtain the final score of each renewable energy source. That is, these BNP values multiplied by the weights of each criterion shown in Table 6 to obtain the final evaluation on the six renewable energy sources. For example, the score of solar energy is:

$$\begin{aligned} &4.47 \times 0.050 + 6.61 \times 0.119 + 2.71 \times 0.043 + 5.40 \times 0.097 \\ &\quad + 5.47 \times 0.122 + 5.47 \times 0.084 + 6.24 \times 0.143 + 3.41 \\ &\quad \times 0.028 + 6.99 \times 0.059 + 6.39 \times 0.041 + 6.70 \times 0.052 \\ &\quad + 6.67 \times 0.059 + 7.62 \times 0.075 + 2.56 \times 0.051 = 5.866 \end{aligned}$$

The final evaluation is shown in Table 9. As presented in Table 9, among all six sources, hydropower is the most preferred renewable energy source, followed by solar, wind, geothermal, biomass, and ocean energy.

Table 8
The BNP values of six renewable energy sources on each criterion.

Criteria	Solar energy	Biomass energy	Geothermal energy	Ocean energy	Wind energy	Hydropower
Energy price stability	4.47	4.49	5.22	4.03	4.85	5.76
Security for energy supply	6.61	5.10	5.34	5.61	5.31	6.48
Low energy prices	2.71	4.12	4.90	4.21	4.72	6.30
Stability for energy generation	5.40	5.10	5.19	4.15	5.46	5.31
Carbon emissions reduction	5.47	4.45	5.52	5.38	6.66	6.80
SO_x and NO_x emissions reductions	5.47	4.15	5.52	5.45	6.66	7.19
Environmental sustainability	6.24	4.46	6.31	5.19	6.25	5.95
Low land requirement	3.41	3.44	5.59	6.69	3.78	4.62
Local economic development	6.99	5.15	4.25	4.46	5.12	4.62
Increasing employment	6.39	4.85	3.95	4.21	4.63	3.74
Technical maturity	6.70	5.37	3.59	3.50	3.75	6.52
Potential for commercialization	6.67	5.19	4.67	3.82	6.04	5.70
Market size	7.62	6.43	4.37	5.43	6.43	5.43
Reasonableness for investment cost	2.56	4.37	3.84	2.90	4.74	5.00

Table 9
The ranking of renewable energy sources.

Renewable energy source	Score	Rank
Solar energy	5.866	2
Biomass energy	4.906	5
Geothermal energy	5.190	4
Ocean energy	4.882	6
Wind energy	5.729	3
Hydropower	6.005	1

5.2. *Policy implications*

The result of FAHP indicates that the environmental goal is the most emphasized policy goal at the present time, with the economic and energy goals ranking second and third, respectively. According to the approved Renewable Energy Development Bill of 2009, the major purpose of renewable energy development and popularization is to enhance sustainable development in Taiwan. By complying with the first item of the Renewable Energy Development Bill, the environmental sustainability ranks first within the environmental goal to further accentuate the challenge of the heavy reliance on fossil fuel in Taiwan. Additionally, carbon emissions reduction ranks second within the environmental goal to reflect the excessive CO_2 emissions in Taiwan. The utilization of renewable energy sources, therefore, should focus on their capabilities in facilitating environmentally sustainable development and reduce CO_2 emissions.

As shown in Table 6, market size, the potential for commercialization, and local economic development are identified as the first, second, and third priorities within the economic goal, respectively. The first item of the Renewable Energy Development Bill declares that facilitating the development of related industries should be one of the main purposes of renewable energy exploitation. Renewable energy technologies with larger market size represent more market opportunities for the industries. Similarly, renewable energy technologies with more potential for commercialization mean fewer risks on related technologies and higher market value, a significant factor toward the successful utilization of renewable energy. Finally, according to the empirical analysis, evaluations should be performed to determine whether the utilization of a renewable energy source facilitates local economic development. The renewable energy industry represents an opportunity to stimulate domestic economic development for Taiwan.

According to Table 6, the security of the energy supply and the stability for energy generation are the two suggested measures within the energy goal with which to evaluate renewable energy sources. It is necessary to evaluate the capability of electricity generation in order to decrease the reliance on imported fossil fuel. By reducing the dependency on fossil fuel, the security of the energy supply will be enhanced. Additionally, the unpredictable and intermittent output of electric power is the common drawback that exists in renewable energy, as previously mentioned. Hence, the ability of the renewable energy source to provide more stable electricity production is a significant factor in accomplishing the energy goal.

The assessment results shown in Table 9 suggests that, among all six renewable energy sources, hydropower is the most preferred, followed by solar and wind energy. According to the investigation of hydropower in Taiwan, the technologically feasible capacity is 5110 MW, and it is within the theoretical capacity of 11,727.32 MW (Ministry of Economic Affairs, 1995). At the end of 2008, the total installed capacity of hydropower in Taiwan reached approximately 1937.9 MW, excluding the pumped storage hydropower of 2602 MW (Bureau of Energy of Ministry of Economic Affairs, 2009a). Therefore, approximately 3000 MW are retained for utilization. In addition to accomplishing the goal of eliminating GHGs, hydropower is also more mature than other renewable energy technologies, particularly since the small hydropower (SHP) system is the trend of hydropower utilization due to its friendliness toward the environment (Bureau of Energy of Ministry of Economic Affairs, 2007). Taiwan's government has opened up this market for private sectors to facilitate the establishment of SHP systems. The Renewable Energy Development Bill has defined the non-pumped storage hydropower as renewable energy in order to promote the exploitation of hydropower as well. Compared to other renewable energy sources, SHP offers advantages, such as short set-up time, technical mature, low investment, and operational costs, that can accomplish the energy goal in terms of low-price electricity supply (Chen et al., 2007a, 2007b; Bakis, 2007).

Most parts of Taiwan receive between 1500 and 2200 h of sunshine annually, with as much as 2500 h in the southernmost region. The average solar irradiance in Taiwan is between 716 and 1027 kJ/d m^2. Therefore, solar energy resources are subsequently abundant and capable of providing a practical condition for solar energy utilization (Chen et al., 2007a, 2007b). The application of solar energy consists of solar photovoltaics and solar thermal energy. The SWH is the only commercialized product of solar thermal energy in Taiwan. The solar photovoltaics industry is considered an opportunity to stimulate economic development and increase employment, due to the increasing demand for it in the global market. Hence, the 2009 National Energy Conference has declared and urged development of the solar photovoltaics industry (National Science Council, 2009). Although the utilization of solar energy can accomplish the environmental and economic goals, the rising costs of electricity and intermittent electrical outputs are the weaknesses of solar energy in terms of achieving the energy goal.

In addition to solar photovoltaics, wind energy is another rapidly growing renewable energy technology within the global market. Taiwan's manufacturers can leverage the abundant experience within the precise machinery industry to enter this market and accomplish the economic goal. Although the electricity cost is decreasing with the progress of wind energy technology, wind turbine establishments cause environmental issues in terms of the large areas of land which are required to generate sufficient amounts of electricity. High investment costs of offshore wind power systems are a solution to engage this challenge. Another disadvantage is that wind speed is relatively low from April to September, which is the highest period of electricity consumption each year (Chang et al., 2003). So far, wind energy is not considered a reliable energy source in Taiwan due to the weaknesses mentioned above.

Unlike solar energy and wind power, the application of geothermal energy is not influenced by weather conditions and its stable output can provide a base load for electricity generation (Chen et al., 2007a, 2007b). However, the benefit of geothermal energy is not easily estimated, for it is affected by many factors, such as well drilling and complex geological conditions. For example, the Taiwanese government built an experimental geothermal power station at Chin-Suei, Yi-Lan County, in 1981. However, this experimental power station was closed in 1993, due to its increasing operational costs (Bureau of Energy of Ministry of Economic Affairs, 2007). To utilize geothermal energy, it is crucial to perform further investigations on the geological conditions in Taiwan and find the appropriate locations.

The application of biomass energy in Taiwan includes methane from animal waste and fuel energy derived from the burial, gasification, breakdown, and fermentation of household, industrial, and agricultural refuse (Chen et al., 2007a, 2007b). However, the constant development of biomass is encountering numerous challenges. In this island, there are insufficient amounts of land with which to fulfill the needs for food supply when the crops are used as an energy source. The production costs of energy crops are high because of the limited area of cultivated land in this country. The use of cultivated algae as a biomass crop may provide a solution to the challenge of limited land. Furthermore, it should be noted that non-CO_2 GHG emissions, such as CH_4 and N_2O, which are derived from the incomplete combustion of biomass crops will need to be considered in the energy sector (Bureau of Energy of Ministry of Economic Affairs, 2007; Tsai, 2009).

Ocean energy is the last of the six preferred sources of renewable energy. However, the applications of ocean energy are not technically mature, even though the potential use of ocean energy around Taiwan is enormous. The Kuroshio Current, which flows with steady speed on the eastern coast of Taiwan, will be researched and utilized in the future (Bureau of Energy of Ministry of Economic Affairs, 2007).

6. Concluding remarks

In April 2009, National Energy Conference came to the conclusion that due to the geographical limits, Taiwan is not suitable for large scale renewable energy industry. But Taiwan could become the major provider of solar power and wind power equipment in the world. For the environmental concern with greater importance of carbon emission effects, as an innovation-oriented island country, Taiwan should seek appropriate renewable energy for implementing beneficial energy policy to engage the challenge of the mentioned issues.

The Sustainable Energy Policy Principles that passed in 2008 declare that the development of renewable energy in Taiwan should simultaneously account for energy, environmental, and economic goals (Ministry of Economic Affairs, 2008). To meet various policy goals, every renewable energy source and technology should be carefully reviewed, since each has different features. The purpose of this study aims to assess the six renewable energy sources as defined by the Renewable Energy Bill and, in turn, accomplish energy, environmental, and economic goals in Taiwan. To achieve this research purpose, the construction of the hierarchical model has a basis of the three policy goals, and the six renewable energy sources are defined as the alternatives into this model. The widely used fuzzy analytic hierarchy process is applied to resolve this multi-goal problem in this study.

Empirical analysis suggests that the environmental goal should be the most significant of the 3E policy goals, followed by the economic and energy goals, respectively, while determining the sources of renewable energy. The result has reflected the existing circumstances of the renewable energy policy, in the case of Taiwan, as follows: First, as stated in the Renewable Energy Development Bill, the major purpose of using renewable energy is to reduce GHG emissions. Second, in recent years, as the emerging renewable energy industry has rapidly developed, greater attention has been drawn to the role of stimulating the economic growth in the 2009 National Energy Conference. Finally, most renewable energy sources or technologies have higher costs than fossil fuels, due to the unpredictable and intermittent output of electricity which is caused by inconsistent weather conditions. As a result, to this day the utilization of renewable energy remains auxiliary to fossil fuels.

Furthermore, the determination on renewable energy should try to accomplish the 3E policy goals. This research indicates that hydropower, solar energy, and wind energy are the three suggested renewable energy sources in Taiwan. Thus, it is suggested that the Taiwanese government should focus on the development and utilization of the three renewable energy technologies, particularly the SHP system, solar photovoltaics, and offshore wind energy, based on the analysis in this study. Also it should be noted that hydropower is not emphasized in current promotional measures. In sum, this study suggests that the government should demonstrate and support the utilization of hydropower. Our research outcome is in concord with other studies in similar energy use outlets. Chatzimouratidis and Pilavachi (2008a, 2008b, 2009a, 2009b) who attempt to construct a comprehensive evaluation model of power plant also similarly demonstrate that hydropower, solar photovoltaics and wind energy not only have the highest priority among ten types of power plant but are more stable with regard to criteria weights changes when taking sensitivity analysis into consideration.

By a side note, the deployment of FAHP allows policy-makers to identify the priority of each policy goal in order to determine the resource allocation. The results derived by FAHP represent a synthetic outcome to different aspects. The priority of renewable energy sources shown in this study, therefore, could be a reference for the accomplishment of 3E policy goals.

Decision-makers in a democratic society, however, are faced with the difficulty of deciding which goal to pursue and which form of renewable energy technology to use. It is necessary to explore cause-and-effect scenarios in future studies by using specific policies and, in turn, to derive corresponding renewable energy technologies in order to achieve those goals.

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