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Complementarity and substitution of renewable energy in target year energy supply-mix plannin–in the case of Taiwan

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HIGHLIGHTS

- Discuss renewable and non-renewable energy substitution.
- Discuss the complementary among renewable energies.
- The MOLP model achieves goals of economy, environment, energy supply-mix.
- Scenario and sensitivity analyses are for policy support.
- Case of Taiwan supports the applicability and validity.

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ABSTRACT

Renewable energies are eco-friendly and sustainable. However, their development faces two critical issues: the uncontrollable generation variability, and the high levelized cost. These two issues impede the development of renewables substitution for a government from lacking of clearly argument of how to promote renewables substitution, and what is the role of traditional generation resources should play to back up the renewable energies in a target year. This study aims to depict the possibility of the concerned topic from the aspects of economy, security, and environment, taking a top–down viewpoint of policy-making to address an energy supply problem, and proposes an Energy Supply-Mix Model by considering the complimentary and substitution possibilities between renewable and non-renewable energies, and also among the renewable energies. The solution provides an overall assessment of three aspects under the conditions of supply and demand balance, desired generation percentage of renewable energies, and also ensure no shortage in peak-hour demand. Parametric analysis on the carbon tax is particularly conducted for policy making reference.

This study takes Taiwan as a case and performs the scenario analysis according to the recent energy policies. The results have shown that the proposed model can effectively support a decision body for policy formulation.

1. Introduction

Renewable energy substitution has become an increasingly crucial issue over the recent decades. The first oil crisis in 1973 severely affected countries that highly depended on imported energy resources. The overuse of fossil fuels has also resulted in excessive carbon emissions. Therefore, alternative energy resources must be developed to prevent adverse effects on the environment and the economy.

Nuclear power has been regarded as a clean and stable source of electricity. However, the safety of this resource has been questioned after the Fukushima nuclear disaster in 2011. Renewable energies are limitless and comparatively safer than nuclear power, but their intermittency and technical limitations have prevented these energies from being adopted into the energy supply system. Therefore, how to incorporate the renewable energies into energy supply system by complementing the pros and cons of different energy resources is an urgent issue.

As its most critical problem, the operation of renewable energy substitution is influenced by the uncontrollable weather conditions. For example, wind and solar energies are influenced by weather patterns and geographical conditions. In Taiwan, wind power is usually generated from October to March, whereas solar power is usually generated from June to September. Although the

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monthly power output patterns of wind and solar energies are different, the generation of these energies can complement to each other. Such monthly climate variation also shows the shortcomings of conventional yearly-based research on renewable energy substitution. Nonetheless, monthly generation patterns provide better indexes for representing and controlling the generation variability of renewable energies.

Given the properties of generation variability, the monthly power output patterns of renewable energies must be investigated and how non-renewable energies could be complemented and substituted must be prioritized. Therefore, to consider the generation variability of renewable energies and the generation flexibility of non-renewable energies, this study proposes an Energy Supply-Mix model by incorporating the monthly capacity factor of renewable energies in order to achieve economy, security, and environment optimization under the conditions of no power shortage, limited resource availability, and achievement of expected renewable energy generation target ratios.

2. Literature review

Before going on the development of the model, we first review the related research in this section.

2.1. Renewable energies

The U.S. Energy Information Administration (EIA, 2015) has identified biomass, hydropower, geothermal, wind, and solar energies as the most commonly used renewable energies. The renewable energies have been categorized as alternative energies in the opposite to the fossil fuels (Dresselhaus and Tomas, 2001). Although they are much cleaner than fossil fuels in the electricity generation stage, the usage of such energies, especially wind and solar energies, are limited by their generation variability.

Upon the publication of *The Third Industrial Revolution* (Rifkin, 2011), many individuals have considered how renewable energies can affect their future and how these clean energies can be incorporated into the smart electricity grid and storage system. Renewable energies will undoubtedly play a crucial role in the future energy supply system.

In addition, Johansson et al. also suggested that under the *Renewables-Intensive Global Energy Scenario*, renewable energies would account for three-fifth of the world's electricity market until the mid-21st century and would exceed double and triple of their generation ratio in 1985 by 2025 and 2050, respectively. Among them, fuel gas will become a significant back-up energy resource for the intermittent renewables that are incorporated into the grid (Johansson et al., 1992).

Although renewable energies have been recognized as important alternatives for energy supply, the development of renewable energies is affected by the acquired technology and the weather conditions (Mathieson, et al., 2011). Impact of technology changes are often observed from the learning curve. Such changes could be explained by the accumulation experience in production that can be revealed by the cost difference (Bodie, et al., 2005). Furthermore, based on the survey of Maycock (Maycock, 2002) and the report of Strategies Unlimited (Strategies-Unlimited, 2003), Nemet has investigated the factors that affect the experience curve for photovoltaics (Nemet, 2006), and interpreted the learning curve according to the availability of solar and wind energies. Then, the subsidy program was simulated, and the result suggested that the cost of solar energy is more uncertain and the government must monitor such cost dynamics (Nemet, 2009).

The generation variability of specific intermittent renewables, such as solar and wind energies, presents another obstacle. Generation variability generally results from the unstable and uncontrollable nature of weather conditions and can represent the generation intermittency according to capacity factor.Chang and Tu have applied time series method for the power output of Taiwan based on the monthly capacity factor of different areas derived from the collected monthly generation data of wind energy in Taiwan (Chang and Tu, 2007). In the other hand, in Portugal, Moura and Almeida investigated the capacity factor of renewables to determine the electricity generation patterns (Moura and de Almeida, 2010). The studies provide promising approach to coping with the variability.

2.2. Energy supply planning

Decision makers must clarify their standpoint on the energy supply-mix issue before proposing energy plans. The top–down method identified the object of the problem at first, then describes the subsystem. On the other hand, the bottom–up method is used to address the issues at the operational level by identifying the network of the problem background and examining the objective consistency in terms of the operator (Sabatier, 1986).

Over the past few decades, the European Union has been actively addressing issues on renewable energy substitution and provided a top–down planning guidance by the *Directive on Electricity Production from Renewable Energy Sources* (European Union, 2001). An example can be referred to Moura and Almeida of which they applied a multi-objective optimization method to find the complementarity between solar energy and wind energy such that the generation cost, the annual and monthly intermittence, and the peak load can be minimized (Moura and de Almeida, 2010).

By applying the bottom–up approach and adopting the energy flow optimization model, Cormio et al. have investigated the energy flow from the resources to the end users. They also considered the co-generation system of electricity and combined heat and power during the intermediate conversion stage as well as derived the optimal energy generation mix to support the policies for renewable energy substitution (Cormio et al., 2003). In addition, by considering the external cost of environment and health damages, Rafaj and Kypreos have developed a model to examine the technologies in the energy system (Rafaj and Kypreos, 2007).

2.3. Portfolio theory

Developing renewable energies is similar to making an investment decision, in which the expected return and risk must be assessed altogether. The Portfolio Theory describes how rational investors optimize their expected investment returns in the presence of a risk. Awerbuch applied this theory and found that the diversity of the energy mix would lower the risk of the supply system (Awerbuch, 2006). Although the returned cost initially increased, the market mechanism has remained capable of adjusting this problem. Further extension in energy supply planning has been done in energy supply planning, Huang and Wu applied the theory to address the risks of volatile fuel prices and uncertain changes in technology. They also examined the effect of the risk-reverse level on the energy technology portfolio in the context of Taiwan (Huang and Wu, 2008).

The Portfolio Theory shows that the penetration of renewables into the energy supply system will raise concerns about the uncertain technologies and the cost of capacity investment. Renewable energies will become competitive in the market in the long term if policy makers are able to cope with the issue of uncertain technologies.