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Cost-benefit analysis of sustainable energy development using life-cycle co-benefits assessment and the system dynamics approach

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HIGHLIGHTS

- The energy policy was assessed using the system dynamics approach.
- A life table approach was presented to estimate averted loss of life expectancy.
- The mortality benefits estimated by VSL and VSLY are found to be similar.
- Economic feasibility of the energy policy for climate change mitigation was presented.

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ABSTRACT

A novel Air Resource Co-benefits model was developed to estimate the social benefits of a Sustainable Energy Policy, involving both renewable energy (RE) and energy efficiency improvements (EEI). The costs and benefits of the policy during 2010–2030 were quantified. A system dynamics model was constructed to simulate the amount of energy saving under the scenario of promoting both RE and EEI. The life-cycle co-reductions of five criteria pollutants (PM_{10}, SO_2, NOx, CO, and ozone) and greenhouse gas are estimated by assuming coal fired as marginal electricity suppliers. Moreover, a concise life table approach was developed to estimate averted years of life lost (YOLL). The results showed that YOLL totaling 0.11–0.21 years (41–78 days) per capita, or premature deaths totaling 126,507–251,169, is expected to be averted during 2010–2030 under the RE plus EEI scenario. Specifically, because of the higher investment cost, the benefit-cost ratio of 1.9–2.1 under the EEI scenario is lower than the 7.2–7.9 under the RE scenario. This difference reveals that RE is more socially beneficial than EEI. The net benefit of the RE and EEI scenarios during 2010–2030 totaled approximately US$ 5,972–6,893 per person or US$ 170–190 per MW h. To summarize, this study presents a new approach to estimate averted YOLL, and finds that the health benefits can justify the compliance costs associated with the Sustainable Energy Policy.

1. Introduction

Increasing environmental burdens on both humans and ecosystems have highlighted issues of climate change and sustainable development and accelerated policy reform and innovation in renewable energy and energy conservation technology [1–5]. Energy consumption in Taiwan increased by 135% from 1990 to 2010, and up to 99.3% of this energy is imported [6]. The energy structure comprised electricity (49%), petroleum (40%), coal (8%), and natural gas (2.5%) in 2010. Taiwan's total greenhouse gases (GHGs) emissions were 258.59 million metric tons of carbon dioxide equivalents ($MtCO_2e$) in 2010, and per capita GHGs emissions were 11.58 tCO_2e, ranking highest in Asia, and far above the world average of 4.38 tCO_2e [7]. Therefore, GHGs reduction is a pressing challenge for Taiwan. Research and development on renewable energy (RE) in the power generation and vehicular transportation industries, generally emphasizes GHGs reduction, and emphasizes energy efficiency improvements (EEI) in the residential, commercial, and industrial sectors. The Intergovernmental Panel on Climate Change (IPCC) reported that both RE and EEI have mitigation (namely GHGs emission abatement) and adaptation (namely reducing vulnerability to impacts of climate change) synergies with climate change [8].

Co-benefit analysis integrates CO_2 reduction with reduction of local criteria air pollutants. The criteria pollutants, include PM_{10}, SO_2, NOx, CO, and ozone, is listing in the Taiwan Air Pollution Control Act. All epidemiological studies of these pollutants have identified as harmful to human health [9–13]. Avoided externalities, or external costs, such as environmental and health damages, achieved through the co-reduction of criteria air pollutants from CO_2 reduction strategies, thus have been widely discussed.

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Nowadays, a variety of co-benefit analyses for CO_2 reductions are performed when setting climate policy [14–23]. The European Commission launched the ExternE project in collaboration with the US Department of Energy since 1991 to assess the external cost of various different fuel cycles [24]. ExternE was the first systematic study to use a bottom-up impact pathway approach (IPA), which helps quantify the environmental impacts and social costs of energy production and consumption. However, the study was limited to renewable energies such as wind, hydro, and biomass fuels.

Various energy models, such as system dynamics (SD) and MARKAL (MARKet ALlocation) models, have been widely adopted to optimize energy deployment for CO_2 emissions reduction scenarios by evaluating their corresponding economic impacts, namely gross domestic product (GDP) loss [25–30]. The SD approach is suitable for modeling dynamic environments, such as ecosystems and human activities, on a muti-dimensional scale with time-dependent variables [31]. SD modeling has been applied for strategic energy planning and policy analysis since the early 1970s, starting with the well-known "Limits to Growth" and WORLD models. The SD software STELLA helps more clearly demonstrate the interactions of the environment and socio-economic variables, and also helps to identify the key factors that significantly alter a dynamic system [32,33]. Some studies have incorporated internalization of externalities in energy system modeling [34–38]. Pietrapertosa et al. (2009) integrated the ExternE, life cycle assessment (LCA), and MARKAL method to comprehensively analyze the external costs of energy systems [39]. Chae and Park (2011) used the Environmental Benefits Mapping and Analysis Program (BenMAP) to perform the first local scale cost-benefit analysis and showed that Integrated Environmental Strategies (IES) outperform air quality management or GHG reduction measures alone [40]. However, these studies regularly applied the IPA to estimate mortality benefits, which are the major portion of human health benefits, and are awaiting verification.

This study thus aims to calculate both premature deaths avoided and the life table approach using the novel Air Resource Co-benefits (ARCoB) model. The main objective of this paper is to conduct a cost-benefit analysis to demonstrate the economic feasibility of the Sustainable Energy Policy Guidelines for climate change mitigation via the following steps: (a) to assess the life-cycle emissions of GHGs and air pollutants associated with electricity generation; (b) to predict changes in the unit costs of electricity generation technologies with the learning curve model; (c) to link the relationships among the renewable energy promotion, energy efficiency improvement, and energy pricing for modeling the evolution of electricity prices and electricity savings with the system dynamics approach; (d) to estimate the reductions of GHGs and air pollutants and evaluate the co-benefits from reduced exposure to air pollutants. The ARCoB model was implemented to evaluate the co-benefits of both RE and EEI improvement over the period 2010–2030. This study is the first cost-benefit analysis evaluating integrated strategies in the energy sector. Based on the positive findings, this methodology is recommended to energy sector authorities and policy-makers.

2. Methods

2.1. Outline and scenarios

Fig. 1 shows the research framework. The Sustainable Energy Policy Guidelines for Taiwan released in June 2008 focus on "clean sourcing" and "conservation", which are represented by renewable energy promotion and energy efficiency improvement, respectively. For evaluating the sustainable energy policy, the reference or business as usual (BAU) scenario was defined as future growth in energy demand being supplied by coal-fired power plants. GHGs and air pollutants emissions from non-renewables, namely coal-fired power plants, are assumed to be reduced by either substitution with renewable energy or reducing electricity generation through energy saving. The electricity generated is calculated by multiplying capacity installed by units of electricity generated. Capacity of coal-fired power plants installed from 2010 to 2019 was forecast by the Bureau of Energy of Taiwan [41]. The capacity growth rate during 2019–2030 was assumed to be the same as during 2010–2019, and was used to predict the growth of coal-fired power plants during 2010–2030, that is the BAU scenario in this study.

2.1.1. The Renewable Energy (RE) scenario

The GHGs reduction scenario involving renewable energy (RE) development was defined as occurring when the growth in installation capacity of coal-fired power plants can be fully replaced by that of RE, assuming the non-dispatchability or intermittency of RE will not affect electricity supply.

In 2011, Taiwan launched the "Million Sunlight Roofs" and "Thousand Wind Mills" projects by subsidizing households and enterprises to install 420 and 1240 megawatt (MW) of photovoltaic (PV) modules by 2015 and 2020 for water heating or power generation, as well as 4200 MW of onshore and offshore windmills by 2025. The growth rate for renewable energy assumed in this study is based on official targets [41]. Table 1 lists the projected capacity of renewable energy during 2010–2030.

To forecast electricity generation during 2010–2030 requires data on capacity installed (Table 1) and electricity generated per kW capacity per year by each category of energy. The unit electricity generated by energy source listed in Table 2 is estimated by dividing annual power generated by capacity installed as of 2010.

2.1.2. The Energy Efficiency Improvements (EEI) scenario

The EEI scenario involved the promotion of energy efficiency, with electricity saved reducing electricity generation from coal-fired power plants during 2010–2030, assuming generation from other sources is unaffected. EEI devices were recommended for the residential, commercial, and industrial sectors, the three main

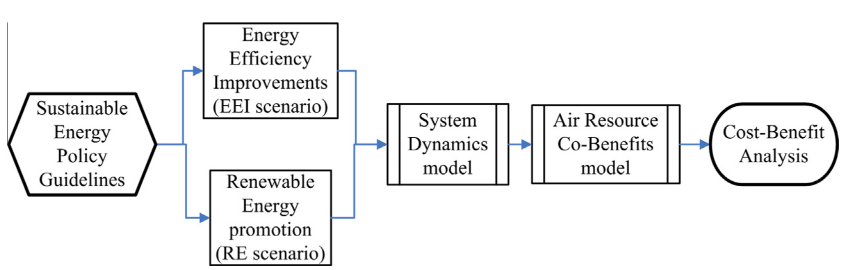

Fig. 1. Research framework.