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The analysis of renewable energy policies for the Taiwan Penghu island administrative region

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ABSTRACT

Taiwan dependents on thermal power for 70% of its total energy supply. The high consumption of fossil fuel increases the carbon dioxide (CO_2) emissions and consequently causes global warming and climate change. Thus, Taiwan has proposed new regulations and measures such as "The Framework for Sustainable Energy Policy – An Energy Saving and Carbon Reduction Action Plan"and" The Master Plan of Energy Conservation and Carbon Mitigation" for domestic carbon reduction. These regulations indicate that the urgency to promote renewable energy to the public to achieve sizable reduction of CO_2 emissions. The objective of this paper is to develop a cost–benefit evaluation methodology based on system dynamics (SD) modelling for any given administrative region to evaluate renewable energy policies. This research develops specific SD models with causal feedback loops to assess the effectiveness of policies and the corresponding benefits for solar energy carbon reduction. The solar energy applications on Taiwan's largest island, Penghu, are used to demonstrate the proposed methodology. The SD approaches and the evaluation of the results serve as a reference to promote solar energy in the other regions with reduced costs and reliability.

Contents

1. Introduction

Global industrialization increases consumption of energy sources (such as coal, petroleum, and natural gas) as well as the emissions of greenhouse gases. The Intergovernmental Panel on Climate Change claims that global warming is directly linked to greenhouse gases [1]. In order to reduce these emissions, many treaties have been formulated such as the United Nations Framework Convention on Climate Change set during the United Nations Conference on Environment and Development in 1992. Further, the Kyoto Protocol was adopted to reinforce legal restrains at the Third Conference of the Parties to the 1997 United Nations in climate change conventions [2]. The major feature of the Kyoto Protocol is to set binding targets for industrialized countries to reduce greenhouse gases emissions and mitigate climate change.

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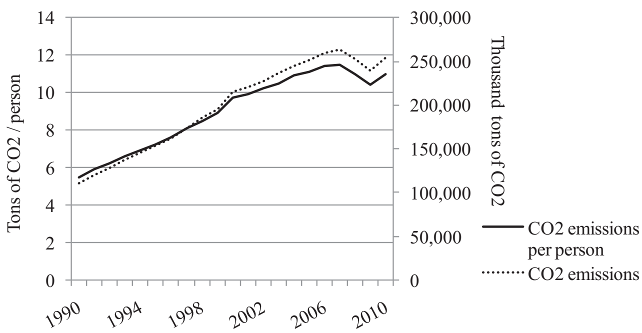

Fig. 1. Taiwan CO_2 emission trends [10].

This protocol prescribes six categories of gases, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6). Until 2010, 191 nations have signed and are committed to reduce overall emissions by at least 5% below 1990 levels before 2012. In addition, the Asia Pacific Economic Cooperation (APEC) nations have reaffirmed the UN climate change commitment and set forth seven arguments and five actions to reduce global carbon emissions during APEC meeting in Sydney in 2007 [3].

Many countries seek renewable energy sources and promote effective policies to reduce greenhouse gases and carbon emissions by utilizing solar energy products and energy saving applications in households. Nonetheless, renewable energy can only be successfully adopted when they are promoted with sufficient incentives to end-users and are cost effective to governments. The objective of this paper is to develop a formal cost–benefit analysis methodology, considering both qualitative and quantitative factors, to evaluate the feasibility of renewable (e.g., solar) energy policies. System dynamics (SD) is a methodology used to describe and analyze dynamical behaviour in the real world [4]. In this research, the SD model with causal feedback loops evaluates scenarios for the proposed solar energy policies. The causal feedback loops describe the relationship between dynamic factors, such as solar energy incentive programs, impacts on the economy, and the effects of carbon emissions. The study uses the case of Penghu County (Taiwan's largest island) as a low carbon island incubator and development project to analyze the costs and related effects of the policy scenarios and evaluate the time varying impacts of the proposed solar energy strategies.

The paper is organized in the following sections. Section 2 describes the related background and research literature, including carbon emissions trends, solar energy development in Taiwan, and the overall low carbon region SD approach. Section 3 presents a benefit evaluation methodology based on system dynamics for solar energy policy. A detailed case study for the Penghu Low Carbon Island project is presented in Section 4. Finally, the conclusions are drawn in Section 5.

2. Literature review

In this section, the literatures related to our study are divided into three parts including carbon emissions trends, solar energy development in Taiwan, low carbon regions, and the systems dynamics approach.

2.1. Carbon emissions trend and solar energy development in Taiwan

The CO_2 emissions and the average CO_2 emissions per person in Taiwan have increased from 1990 to 2010 as shown in Fig. 1. Taiwan is highly dependent on thermal power which accounts for 70% of total primary energy supply. The other carbon-free fuels contribute 30% of the energy supply including nuclear power (16%), hydropower (14%), and wind power (less than 1%) [5]. The energy statistics show that the Taiwan government will need to actively and effectively promote renewable energy adoption to reduce CO_2 emissions. Solar energy, one of the cleanest renewable energy sources, is to be promoted through various policies and incentive programs across Taiwan. The prices of solar system modules have declined 5% per year which has accelerated the promotion, popularity, and adoption of these systems [6]. The solar energy industry is roughly divided into the photovoltaic (PV) industry subsector and the solar thermal industry subsector [7]. Related research shows that the top five photovoltaic-producing countries are Japan, China, Germany, Taiwan, and the United States [8]. In addition, the manufacturing processes of the solar energy industry are similar to the thin film transistor liquid crystal display (TFT-LCD), light-emitting diode (LED), and semiconductor industries which are mature industries for low-cost mass production in Taiwan. Therefore, Taiwan is a very suitable location to develop and promote solar energy applications for the public infrastructure (green transportation, solar street lighting) and domestic applications (water heating, solar power generation) [9].

2.2. Low carbon region

The concept of low a carbon region is an economy which does not depend highly on the combustion of fossil fuels. In addition, it combines the 3Es concept of energy, economic development, and environment to build the low carbon society [11]. Therefore, many countries have focused on developing low carbon islands as an experimental attempt to test renewable energy sources and lower CO_2 emissions in a controlled pilot-plant type setting. The low carbon island has also been called the zero carbon island, the renewable energy island, and the sustainable energy island. Some interesting low carbon island projects are well known, such as Gokceada Islands in Turkey [12], Kinmen Island in Taiwan [13], Dodecanese Islands in Greece [14], Samso Island in Denmark [15], and Yakushima Island in Japan [16].

When promoting a renewable energy policy in an administrative region, it is critical to assess the potential benefit and efficiency of the project. Biberacher et al. [17] have proposed a top–down evaluation approach for renewable energy policy which is divided into three steps, including theoretical potential (sunshine or topography), technical potential (efficiency or accessibility), and realizable potential (legislation, cost, or acceptance). Since renewable energy technologies are becoming technically mature and cost effective, many renewable evaluation projects have been initiated. Jaber et al. [18] used fuzzy theory and the analytic hierarchy process (AHP) method to evaluate the benefits and costs between traditional and renewable energy power generation for decision makers. Celiktas and Kocar [19] applied a quadratic helix approach to select suitable renewable energy policies that included experts' opinions about policy, market, technology, and society levels. D'Agosto and Ribeiro [20] proposed a life cycle inventory approach to analyze the carbon emissions of the fuel fossil and renewable energy, and evaluated the benefits of renewable energy. Lee and Shin [21] established an option based renewable energy policy evaluation model and estimated the fluctuation of generated electricity costs between fuel fossil and renewable energy. Oikonomou et al. [22] combined techno economic modelling and multi-criteria approaches to evaluate renewable policy decision making. The evaluation aspects included cost, degree of energy dependence, and carbon emission reduction.

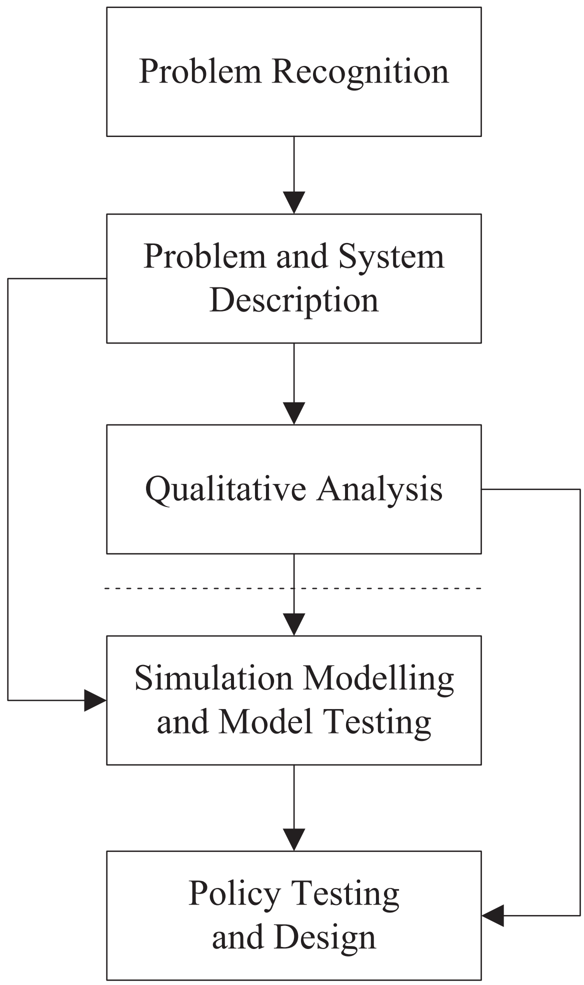

Fig. 2. System dynamics procedure [23].

2.3. System dynamics approach

The system dynamics approach is used to describe and model the activities of the complex systems over time. SD utilizes the various control factors of the system and observes how the system reacts and behaves to trends. Therefore, SD can be used to assist decision making when target systems are complex and dynamic. Coyle [23] has proposed a basic procedure of applying SD as depicted in Fig. 2. The procedure is divided into five stages, including problem recognition, problem understanding and system description, qualitative analysis, simulation modelling, and policy testing and design. After defining the problem, it is important to determine the participants and their interests. The causal feedback loop diagram is used to describe the system. The qualitative analysis stage observes the causal feedback loop diagram and organizes the detailed factors of the problem. The analyst can revise and correct the SD model through discussion with domain experts. The analyst also can execute additional simulation models for alternative scenarios.

The analyst will need to test the model's reliability and validity. Policy testing and design is the final stage used to evaluate the system simulation outcome and plan appropriate policies. The most important parts of the system dynamics procedure are the causal feedback loops and the SD model construction. In general, the causal feedback loops are classified as qualitative analysis. The SD model construction and simulation are classified as quantitative models [24].

Some researches have utilized SD to assess environmental [25] and CO_2 emissions [26] issues. Jin et al. [27] developed a dynamic ecological footprint forecasting platform to support policy making for urban sustainability improvement. Han and Hayashi [28] studied inter-city passenger transport in China as a case and developed a system dynamics model for policy assessment and CO_2 mitigation potential. Trappey et al. [29] proposed a cost analysis methodology which integrates economic input–output life cycle assessment and SD to reduce CO_2 emissions in a mass customization environment.

3. Benefit analysis of renewable energy for administrative regions

This research proposes a benefit evaluation method for an administrative region to analyze the effectiveness of the proposed renewable energy policies. Since these issues are broad and the corresponding variables change rapidly, the SD approach is used to estimate the results of the policy in the region. Fig. 3 shows the analysis processes of the benefit evaluation methodology for renewable energy policies which are divided into three steps including the administrative region carbon emissions analysis, the renewable energy policies SD model, and the renewable energy policies benefit analysis.

For the administrative region carbon emissions analysis step, it is necessary to identify the target problem (CO_2 emissions reduction and costs) and policy (the target renewable energy and its benefit). Afterward, the current administrative region's CO_2 emission policy is depicted as an as-is model. This paper uses Taiwan's average CO_2 emissions per person to estimate the CO_2 emissions status for a given regional population. Subsequently, the to-be model is constructed according to the government's renewable energy policies which include solar, wind, geothermal, tidal or hydropower.

After the first step, the SD approach is used to estimate whether the results of the to-be model are beneficial or not. The procedures of the second step have two sub-parts including causal feedback loops and SD model construction. The causal feedback loop diagrams are used to identify the relationships between related variables (the renewable policies, impacts of economy, and effects of CO_2 emissions) and determine the causal relations in the system. Afterward, the SD model is constructed to simulate the extent of the renewable energy policy variation. The contents of the target policy are converted into related variables and relationship formulas as system inputs in the SD model. The interaction rules such as time delay functions and if–then–else rules between variables and relationships are formularized.

For the renewable energy policies benefit analysis step, the detailed policy scenarios are designed. The candidate scenarios in the administrative region are listed and simulated according to different system inputs and assumptions. The SD simulation results such as unequal carbon emissions and policy expenses help decision makers evaluate the costs and effects of carbon reduction. Furthermore, the simulation reveals the time varying impacts of proposed renewable energy strategies.

4. Case study: solar energy implementation for Penghu Island

Taiwan's Penghu Low Carbon Island project serves as the case study to verify the proposed methodology. The Penghu Islands are an archipelago off the Western coast of Taiwan. The archipelago forms Penghu County and the government decided to promote a Low Carbon Island project to enhance local economic development. This project combines local features with solar energy, wind power, LED illumination, green buildings, and resource recycling

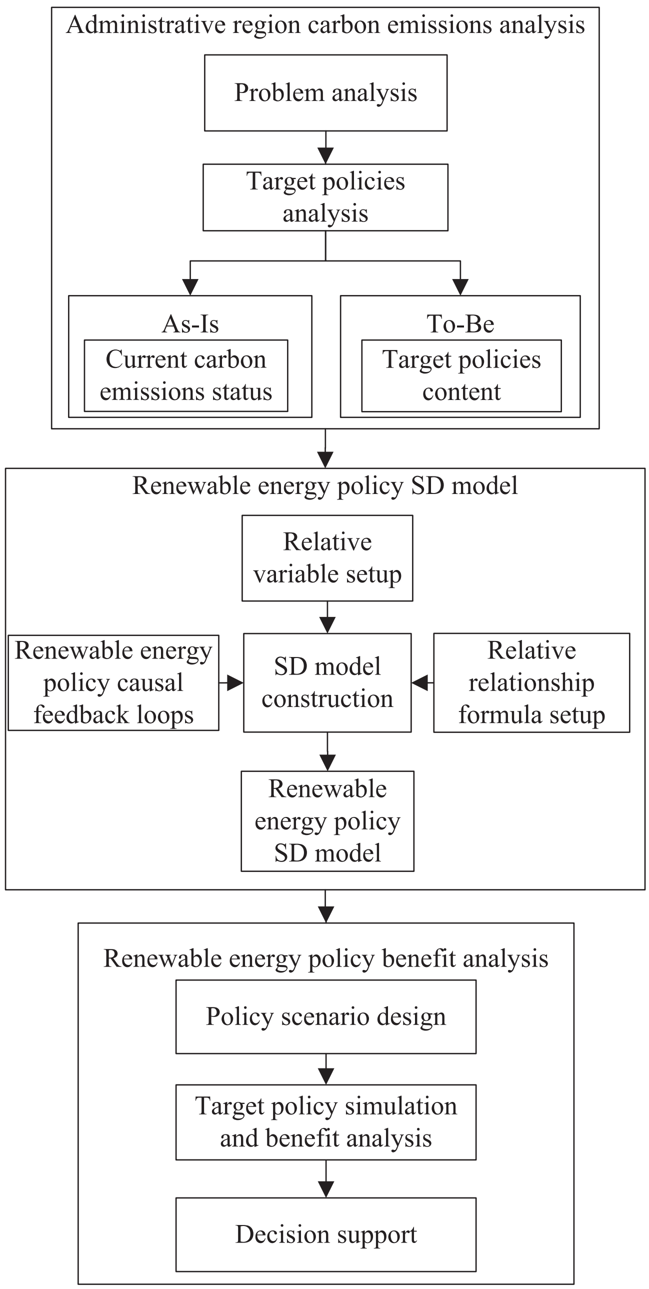

Fig. 3. Renewable energy benefit analysis processes.

facilities to create a clean energy-saving environment. The project focuses on renewable energy substitution, solar energy policy, and CO_2 emissions reduction.

4.1. Penghu Island's current carbon emissions and renewable energy policy

Before implementing the renewable energy policy, a rough estimate of the regional carbon emissions on Penghu Island were derived and are positively correlated with current energy uses. The current carbon emissions on Penghu Island are estimated using the following formula.

Regional carbon emissions per year (local population part) = regional population × personal carbon emissions per year × proportion of regional sectors

According to a statistical report in 2009 [30], Penghu Island had 96,210 residents and the personal carbon emission in Taiwan was about 10.4 tons [5]. Therefore, there are about 1,000,000 tons of CO_2 emitted from Penghu Island per year. The industry structure of Penghu area focuses on fishery, agriculture, and tourism, which is very different from the main island of Taiwan. The Ministry of Economic Affairs (MOEA) statistics show that Taiwan's industry sector contributes 46% and the service sector contributes 14% of the total carbon emissions. In order to evaluate accurate carbon emissions for Penghu Island, the carbon emissions produced from the industry and service sectors need to be estimated. Likewise, carbon emission from tourist electricity demand will be seasonally effected. According to the statistical reports from related government organizations, the tourist population in Penghu Island reached 561,303 people in 2010 [31] and the number of travel days are 2.8 [32]. The current carbon emissions produced by the tourist population in Penghu Island are estimated using the following formula.

Regional carbon emissions per year (tourist population part) = tourist population × (travel days/365) × personal carbon emission per year × Proportion of regional sectorsTherefore, the appropriate carbon emissions on Penghu Island are obtained from the sum of the local population and the average tourist population per year. For simplicity of statistical analysis, the seasonal factors are not considered in the initial models. For the Penghu low carbon island project, Taiwan plans to promote the utilization of solar-energy products, including PV systems and solar water heating systems. Further building construction will use integrated photovoltaic (BIPV) applications to boost the total installation capacity to 1.5 megawatt (MW). In addition, the government provided a 50% subsidy to encourage residents to install solar water heating systems on new or existing houses. The installation capacity goal for solar water heating systems was set to reach 1000 household units covering an area of 6400 square meters during the period from 2011 to 2015. In order to evaluate the long-term effect of carbon emission reduction, this research uses a long-term policy scenario to model the extended the installation schedule ranging from year 2011 to year 2025. The different policy scenarios are described in the following section.

4.2. SD model construction

This research focuses on the cost–benefit evaluation of solar renewable policy execution. The SD system inputs include PV systems and solar water heating systems. The SD system outputs are the reduction volume of carbon emissions and the cost of policy implementation. The causal feedback loops of the model are to be used to estimate the causal relationships between related variables, directions of variable actions, and the system boundaries of the whole system [33]. Fig. 4 shows that the causal feedback loops considers the solar application policies of Penghu Island and describes the relationship between the renewable policies and the impact on carbon emissions.

The carbon emissions are mostly produced from the population using electricity on Penghu Island. In order to control carbon emissions, Penghu Island's government promoted solar energy policies to reduce CO_2 emissions. In Fig. 4, the causal feedback loops are balanced and then converge over a period of time. These results help determine whether the renewable energy policies are suitable for Penghu Island to achieve a stable carbon emissions balance. The key variables in the causal feedback loops are described as follows:

(1) Population using electricity in Penghu Island: This variable changes due to the variation of the local and tourist populations on Penghu Island. The carbon emissions are represented by this variable.

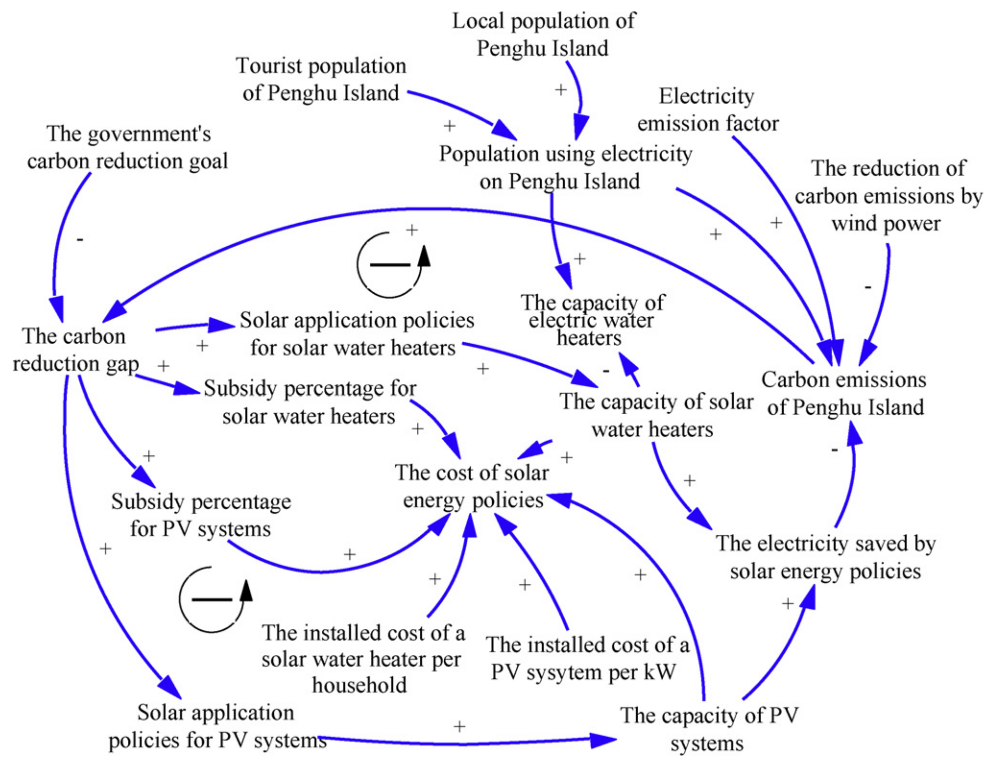

Fig. 4. The causal feedback loops representing the renewable energy policies.

(2) The carbon reduction gap: This variable is the difference between the government's carbon reduction target and the actual carbon emissions of Penghu Island.
(3) The capacity of electric water heaters: The capacity of electric water heaters vary with the sales and incentive promotion of solar water heaters.
(4) The electricity saved by solar energy policies: This variable represents the surplus power generation saved through the utilization of the solar energy application including PV systems and solar water heaters.
(5) Carbon emissions of Penghu Island: This variable varies with the population using electricity and the electricity emission factor.
(6) The cost of solar energy policies: This variable is affected by solar application subsidy policies, the installation costs of solar systems, and the capacity of solar systems.

According to the above-mentioned causal feedback loop variables, the SD model is constructed to evaluate the solar energy policies. The SD model includes stocks, flows, connectors, and auxiliaries. There are three stocks in the SD model for solar energy policies, including the capacity of the electric water heater, the capacity of solar water heaters, and the capacity of PV systems. The development status of the solar energy policies are evaluated by the variation of stocks and their flows in the SD model. For example, the capacity of an electric water heater is a stock influenced by the population using electricity. Fig. 5 shows the SD model for solar policies used to analyze the required implementation costs and the related effects of CO_2 reduction through simulation. The key variables and stocks in the SD mode are described as follows:

(1) Population using electricity on Penghu Island: the population is divided into the local population and the tourist population and the values are derived from government's statistical reports.
(2) Carbon emissions of Penghu Island: carbon emissions are caused by the population using electricity on Penghu Island and calculated by multiplying the population using electricity by the carbon emission factor.
(3) The capacity of solar water heaters: the government executes the solar energy policy to reduce CO_2 emissions. The increased use of solar water heaters matches the capacity of the solar application policies. This research assumes that the depreciation period of the solar water heater is 20 years.
(4) The capacity of PV systems: the increased number of PV systems matches the capacity of the solar energy policies. This research assumes that the depreciation period of the PV system is 20 years.
(5) The cost of solar energy policies uses the equation below:
 The cost of solar energy policies = the number of increased PV systems × subsidy percentage of PV systems × the installed cost of PV systems per kilowatt (kW) + The number of increased solar water heaters × subsidy percentage of solar water heaters × the installed cost of solar water heaters per household
(6) The electricity saved by solar water heaters is estimated using the equation below:
 The electricity saved by solar water heaters = [(heat energy output of solar water heaters/thermal and electricity conversion factor)/thermal efficiency] × 365 days × the capacity of the solar water heaters
(7) The electricity saved by PV systems is estimated using the following equation:
 The electricity saved by PV systems = the capacity of PV systems × solar radiation × overall design coefficient × 365 days
(8) The carbon reduction gap is calculated by carbon emissions on Penghu Island minus the government's carbon reduction goal. If the value is negative, then the target is achieved according to value.
(9) Planning the installation capacity of PV systems is used to simulate the benefit and cost of the PV systems.
(10) Planning the installation capacity of solar water heaters is used to simulate the benefit and cost of the solar water heaters.

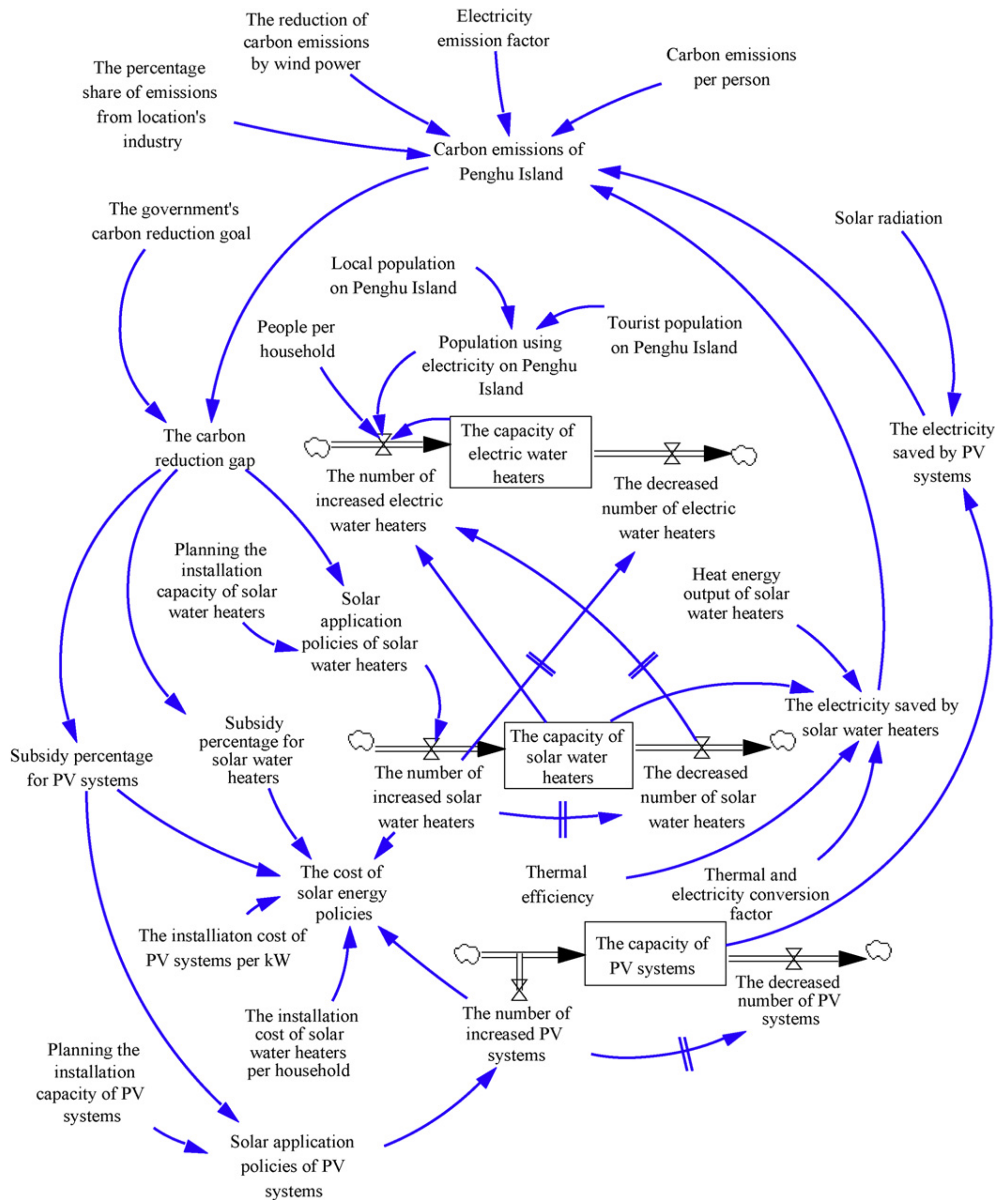

Fig. 5. The SD model solar application policies.

(11) The carbon reduction from wind power is the most expensive but is the greatest source of carbon reduction on Penghu Island. The government has thus promoted 96 MW wind power units. This research assumes the depreciation period of each wind power unit is 20 years.

For the SD model construction step, the value of related parameters and the equations of the relationship formulas are established before running the simulation. Table 1 shows the parameters and relationship for the proposed solar application policies.

4.3. Solar application policies simulation results

Four different policy scenarios are designed and run as shown in Table 2. The simulation results of the four policy scenarios are discussed including the power saved from solar water heaters, power saved from PV systems, the reduction of carbon emissions on Penghu Island, and the costs of the solar application policies.

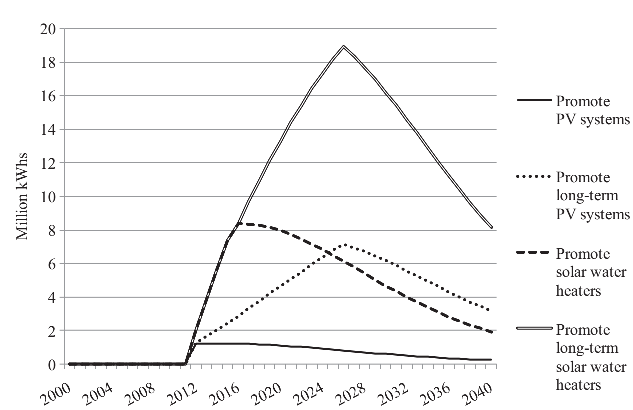

Fig. 6. Electricity saved by installing solar water heaters and PV systems using different promotion periods.

Table 1
The SD model parameters and relationship for the solar application policies.

Parameters and related variables	Value or relationship
The average number of travel days in 2009	2.8 days
Electric emission factor	0.623 kg-CO_2/kilowatt hour (kWh)
Carbon emissions per person	10.4 ton-CO_2/person
People per household on Penghu Island	2.83 people/household
The installation cost of solar water heaters	NTD 18,000/square meter
Thermal and electricity conversion factor	1 kW = 862 kCal
Average solar radiation on Penghu Island	3.2 kWh/square meter
PV system installation cost	NTD 250,000/kW
Carbon emissions per person	The statistical data from the Ministry of Economic Affairs (MOEA) in 1990–2010
The carbon reduction gap	The carbon emissions on Penghu Island – The government's carbon reduction target
Planning installation capacity for solar water heaters and PV systems	These two value are the input variables and represent different scenarios
Solar application policies for solar water heaters	If a carbon reduction gap exists, the government continues to promote solar water heaters
Solar application policies of PV systems	If a carbon reduction gap exists, the government continues to promote PV systems
Subsidy percentage for solar water heaters	50%
Subsidy percentage for PV systems	100%
The increased number of solar water heaters	This value is equal to the planned installation capacity for solar water heaters
The decreased number of solar water heaters	This value matches the quantity of equipment depreciated for solar water heaters
The increased number of PV systems	This value is equal to the planned installation capacity for PV systems
The decreased number of PV systems	This value matches the quantity of equipment depreciated for PV systems

Fig. 6 shows the simulation results for electricity saved by installation of solar water heaters and PV systems. Scenarios 1 and 2 do not promote the solar application policies, thus, their simulation values are zero. Scenario 3 yields the highest electricity savings in 2016 which reaches 8.4 million kilowatt hour (kWh) for solar water heaters. Since the implementation schedule of scenario 3 is five years and considers the depreciation of equipment, the electricity saved using solar water heaters begins to drop after 2017. In scenario 4, the electricity saved is highest in 2026 and reaches 19 million kWh. The electricity savings from the utilization of PV systems are similar to the savings from solar water heaters. Scenario 3 yields the highest electricity saving in 2012 and reaches 1.22 million kWh. In scenario 4, the electricity savings are highest in 2026 which reach 7.14 million kWh.

Table 2
The policy scenarios for the solar application SD model.

No.	Scenario	Contents and goal
1	Before promoting the renewable energy policy	Benchmark current carbon emissions on Penghu Island.
2	Promote wind power policies	Observe the carbon emissions variation on Penghu Island resulting from the promotion of wind power energy policies.
3	Promote solar application policies	Install the PV and solar water heating systems gradually from 2011 to 2015.
4	Promote long-term solar application policies	Install the PV and solar water heating systems gradually from 2011 to 2025.

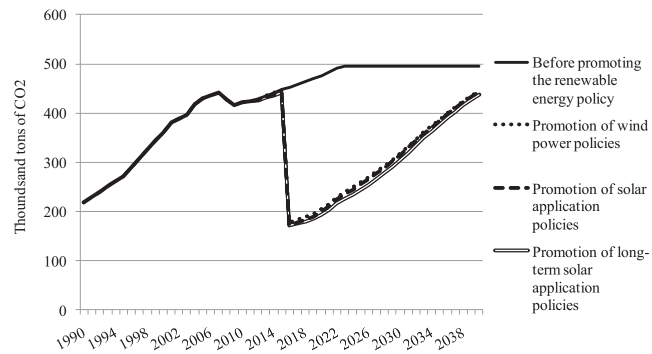

Fig. 7. Different scenarios for reducing carbon emissions on Penghu Island.

As shown in Fig. 7, the carbon emissions on Penghu Island are simulated for the decision maker to evaluate the effects of different policy scenarios. Scenario 1 benchmarks carbon emissions on Penghu Island without promoting any renewable energy policies. The carbon emissions represent a long-term growth of up to 500 thousand tons in the long term. However, the carbon emissions trend towards stability in 2023. In scenario 2, the wind power policies cause a large carbon reduction with carbon emissions reaching a low of 178 thousand tons in 2016. In scenarios 3 and 4, the carbon emissions are reduced year by year during the promotion period of the solar application policies. However, the variations of carbon emissions are relatively lower than the wind power policies. The simulation result shows that scenario 3 has the highest carbon reduction (6 thousand tons) in 2016 and scenario 4 has the highest carbon reduction (16.3 thousand tons) in 2026.

The costs of solar application policies are shown in Fig. 8. In scenario 3, the maximum annual cost of the solar applications policies is NTD 388 million in 2011. The total costs reach NTD 432 million during the promotion period from 2011 to 2015. Scenario 4 shows that the required implementation costs of solar applications policies on Penghu Island during the long-term promotion period from 2011 to 2025. Because of longer promotion period, the maximum annual cost (NTD 634 million) and the total costs (NTD 2647 million) are higher than scenario 3.

Table 3 summarizes the simulation results for the four scenarios. Although the benefits of solar energy policies are lower than wind power policies, carbon reduction will likely need an aggregation of policy approaches. In addition, the performance and cost of the solar applications are limited to current R&D and manufacturing technologies. If the power conversion efficiency can be enhanced and solar application equipment costs can be lowered, then new and more effective solutions can be derived.

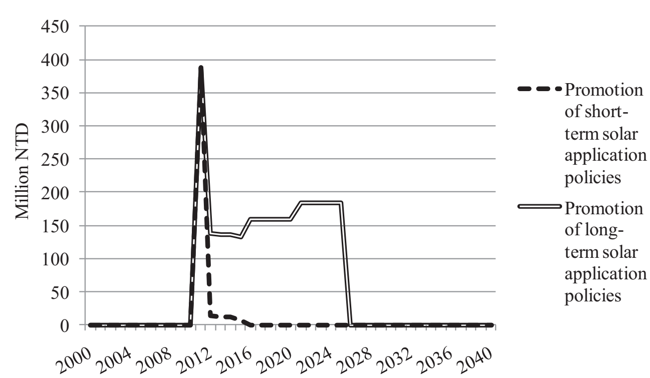

Fig. 8. The comparative costs of solar application policies for short-term and long-term promotions.

Table 3
The summary of simulation results.

No.	Scenario	Explanation
1	Before promoting the renewable energy policy	This scenario is used to observe and benchmark the carbon emissions on Penghu Island before promoting any policies. The carbon emissions on Penghu Island represent a long-term trend of towards stability in 2023 where carbon emissions reach 500 thousand tons.
2	Promote wind power policies	This scenario observes carbon emissions variation on Penghu island when promoting wind power policies. The simulation results show that the wind power policies cause a huge carbon reduction. In 2016, the carbon reduction reaches the highest level of 275 thousand tons of CO_2.
3	Promote solar application policies	This scenario plans scheduled implementation from 2011 to 2015 for installing solar applications. The effects of carbon reduction appear gradually from 2012. During the year 2016, the carbon reduction is highest and reaches 6 thousand tons of CO_2. The maximum annual cost of solar applications policies is NTD 388 millions in 2011 and the total costs are NTD 432 millions.
4	Promote long-term solar application policies	This scenario plans a long-term scheduled implementation from 2011 to 2025. The carbon reduction is highest in 2026 and reaches 16.3 thousand tons of CO_2. The maximum annual cost of solar applications policies is NTD 634 million in 2011 and the total costs are NTD 2647 million.

5. Conclusion

This research provides a systematic cost-benefit evaluation methodology to assess the results of renewable energy policies promotion applied to a controlled administrative island region. SD models with causal feedback loop diagrams are constructed to reveal the relationships between the dynamic factors, the effects of policies, and the costs of carbon emissions reduction. This research uses Taiwan Penghu Island as the case study and designs different policy scenarios to the simulate outcomes. The simulation results show that the promotion of the solar energy policies can restrain and mitigate the carbon emissions on Penghu Island. Future work will include other alternatives, combine renewable energy policies, and also consider invisible benefits such as environmental image enhancement.

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