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Analysis of Energy Policy Effects on 2050 Renewable Energy Target of Taiwan Using Systemic Dynamics Modeling

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Abstract Due to the increasingly severe impact of extreme weather conditions caused by the climate change, countries around the world have taken measures to reduce greenhouse gas emissions, with the use of renewable energy being one of the primary pathways. Feed-in tariff (FIT) and renewable portfolio standard (RPS) policies along with the regulation of renewable energy certificates (RECs) are common policies promoting the development of renewables. Taiwan has implemented FIT since 2010 and introduced a domestic REC scheme (T-RECs) to liberalize the renewables electricity market in 2017. In the study, system dynamics is conducted to investigate renewable energy development and gain a better understanding of the renewable energy growth in its capacity in Taiwan. Through the analysis, we summarize the key factors influencing the installed capacity including FIT decline rates, initial T-REC pricing and the policy strength. The challenges caused by these key factors for the development of renewables are discussed.

Keywords Feed-in tariff, Renewable energy certificates, System dynamics, Taiwan 2050 net zero emissions goal, Energy policy

I. Introduction

International efforts to reduce greenhouse gas emissions have led countries worldwide to facilitate the renewable energy development through the implementation of renewable energy policies, including feed-in tariff (FIT) schemes and renewable portfolio standards (RPS) (Harvey, Orvis and Rissman, 2018; Chuang, Lien, Roche, Liao and Den, 2019). Moreover, large enterprises and supply chains voluntarily increase their use of renewable energy. Taiwan

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has adopted the FIT scheme since 2010 and introduced a renewable energy certificate (REC) trading platform in 2017. The promotion of renewable energy is crucial not only for mitigating climate change but also for Taiwan energy security, given its heavy dependence on imported energy sources.

FIT is a government-based long-term electricity purchase contract provided to renewable energy generators to incentivize the development of renewable energy (Harvey, Orvis and Rissman, 2018). The FIT scheme provides a stable price throughout the contract period, stabilizing investment risks but potentially limiting market competition. This policy may include construction subsidies and other economic incentives to encourage long-term investments by renewable energy developers. Many countries, such as Germany, Association of Southeast Asian Nations (ASEAN) countries and Taiwan, have implemented FIT, but the implementation methods and rates vary based on each country's renewable energy development status (Chuang, Lien, Roche, Liao and Den, 2019). In 2010, the Taiwan government passed the "Renewable Energy Development Act" and implemented the FIT scheme (Legislative Yuan, 2010) where a fixed rate is set for a contract period of 20 years.

The RPS scheme is a government-mandated policy aimed at promoting the development of renewable energy (Zuo, Zhao, Zhang and Zhou, 2019). The policy is often in cooperation with REC scheme to facilitate the management in liberalized markets. The primary objective of RPS is to promote the long-term development of renewable energy in the liberalized market without the need for government subsidies. In many countries' policy planning, RPS is often seen as a complement to FIT policies. Countries such as the United States, China and South Korea utilize RPS as a tool for renewable energy development (Harvey, Orvis and Rissman, 2018). In contrast to many countries where non-renewable energy suppliers bear the primary obligation for RPS, Taiwan assigns major consumers of electricity as the main obligors (Gao, Fan and Chen, 2020). According to the regulation, electricity consumers with a contracted capacity of 5,000 kW or more are responsible for 10% of their total electricity consumption by renewable energy (Ministry of Economic Affairs R.O.C. (Taiwan), 2020).

The RECs are tools used to certify the use of renewable energy (Chuang, Lien, Den, Iskandar and Liao, 2018). In general, for every thousand kilowatt-hours (MWh) of electricity generated from renewable sources, one REC is issued. These RECs are freely tradable, and the purchase of one REC is equivalent to utilizing one MWh of renewable energy. Taiwan established the National Renewable Energy Certificate Center and began issuing Taiwan renewable energy certificates (T-RECs) in 2017 (National Renewable Energy Certification Center, Taiwan, 2022; Chuang, Lien, Den, Iskandar and Liao, 2018). The trading volume of T-RECs has steadily increased in recent years, primarily influenced by the requirement of international supply chains and regulations.

It is evident that the policy plays a key role in the development of renewables. For example, studies have suggested that FIT and RPS should be viewed as complementary policy tools rather than competing ones (Gabrielli, Aboutalebi and Sansavini, 2022). In a policy mix, FIT can act as an initial driving force, while RPS can be introduced in the later stages of the renewable energy market development (Zhao, Li and Zhou, 2020; Dong, Yu, Chang, Zhou and Sang, 2022). The level of enforcement, stringency and rigor with which a policy is implemented is critical. In the case of climate and environmental policies, the policy strength typically indicates how forcefully measures are applied to achieve desired outcomes, such as promoting renewable energy adoption.

Doan, Vu and Le (2022) examined the case of Vietnam renewable energy policy in Ninh Thuan Province and assessed its policy strength (Doan, Vu and Le, 2022). The evaluation was based on the Energy Indicator for Sustainable Development (EISD) and the United Nations Sustainable Development indicators, both released by the International Atomic Energy Agency (IAEA). The scoring criteria included aspects such as socio-economic development, construction of renewable energy infrastructure, greenhouse gas emissions reduction, energy security and stability, and the well-being impact on various societal strata. Ultimately, the policy strength is calculated using the Human Development Index (HDI) from the United Nations Development Programme (UNDP). The scoring results are used to quantify the clarity of the policy, which reflects the strength of the policy's implementation.

In Taiwan, the renewable energy installed capacity increased from 3,197 MW in 2010 to 11,610 MW in 2021. The proportion of electricity generated from renewable sources rose from 3.49 to 5.99%. (Ministry of Economic Affairs R.O.C. (Taiwan), 2023). In response to the climate change, the achievement of 2050 net zero emissions is not only a government policy but has also been legislated as a law in Taiwan where the government announced the "Taiwan 2050 Net Zero Transition Key Strategic Action Plan," which set targets of 20, 31, and 40-80 GW by 2025, 2030, and 2050, respectively, for solar PV power installed capacity. The goal of offshore wind power installed capacity is to reach 5.6, 13.1 and 40-55 GW by 2025, 2030 and 2050, respectively (Executive Yuan National Sustainable Development Commission, 2022). However, there remains a lack of appropriate evaluation to determine whether the government's measures can achieve the proposed goal.

The system dynamics (SD) approach was first developed by Forrester in MIT, USA (Forrester, 1961) and has been widely applied to investigate complicated systems with multi-sectors involved the interconnection among sectors such as renewables (Hsu, 2012; Zhang, Zhao, Ling, Ren, Liang and Liu, 2017; Liu, Zheng, Yi and Yuan, 2020; Loh and Bellam, 2024). For example, Zhang et al. studied the development and constraints of biomass energy in the Chinese market under FIT and RPS schemes by the SD method (Zhang, Zhao, Ling, Ren, Liang and Liu, 2017). They noted that the competitiveness of the market influences the adaptability of different policies and argued that, given the significant demand in China's biomass energy market, RPS policies are more suitable for a competitive market environment. In addition, increasing the level of marketization in the renewable energy sector can further promote the growth of renewable energy installation capacity and investment returns (Zhou, Zhao and Xu, 2022). Furthermore, studies have suggested that setting REC prices within a reasonable range is crucial for effectively driving the development of renewable energy (Zhao, Ren, Zang and Wan, 2018).

In this study, SD is conducted to investigate the effect of FIT and T-REC price on the impact of the 2050 renewable energy target of Taiwan. Indeed, extensive studies have applied a wide array of approaches to evaluate the carbon emissions reduction including mathematical and economic model analysis and dynamic system analysis. For instance, the MARKet and Allocation (MARKAL) energy engineering model was used to simulate the carbon reduction scenarios and low-carbon development scenarios for Taiwan up to 2050, with the aim of minimizing the total cost of climate mitigation. This study considered categories including power generation, industry, households, services, and transportation (Tsai & Chang, 2015). Shaw et al. (2020) used the energy-environment-economy global macroeconomic model (E3ME) to examine the reduction effects of FIT and carbon taxes on the carbon emissions reduction in Taiwan. Their study suggested the carbon tax is far more effective than FIT in terms of carbon emissions reduction (Shaw, Fu, Lin and Huang, 2020). However, Taiwan does not employ the measure of carbon tax. To the best of our knowledge, this is the first paper to address the co-opetition of FIT and REC schemes on the 2050 renewable energy target in Taiwan as the net zero emissions policy announced.

The objectives of the study are aimed to comprehensively exploring the interrelationships among FIT scheme, REC scheme, regulatory quotas, corporate demand, and national renewable energy goals in the renewable energy market. Specific objectives include: (1) to analyze the causal framework of Taiwan's renewable energy market and leverage existing data and market operation mechanisms to assess whether the national renewable energy goals can be achieved by 2050, and (2) to investigate the impact of FIT decline rates, T-REC prices, and policy strength on the renewables capacity target by various scenario simulations. A framework involved a causal loop diagram for the Taiwanese renewable energy market based on the identified cause-and-effect relationships is constructed. Relevant data on the development of renewable energy both domestically and internationally is collected.

II. Methodology

1. Assessment of Policy Strength

The policy strength is evaluated based on 17 scoring criteria, namely, socialization of renewable energy investment, foreign investment in renewable energy, home reception of renewable energy, installation of renewable energy in public non-profit administrative units, employment of local labor, commercialization of renewable energy, contribution of renewable energy to GDP, increase the proportion of renewable energy installed capacity in the national level, improvement of land utilization, development of potential sites, improvement of novel technologies, and effective coordination and communication with institutions around the development sites (Doan, Vu and Le, 2022).

In the study, the renewable energy policy document developed by the Taiwan government is evaluate to determine the policy rating scale based on the method proposed by Doan et al. (Doan, Vu and Le, 2022), including timeliness, meeting the target, effectiveness, feasibility, and economic efficiency, and the scoring criteria are shown in Table 1. The scoring results are used to quantify the clarity of the policy, which reflects the strength of the policy's implementation. While this assessment is not representative of all levels of policy implementation, it can be used as a reference indicator of policy strength. Accordingly, as the policy guideline of Taiwan is "Taiwan 2050 Net Zero Transition Key Strategic Action Plan", we determined the policy strength of renewables to be scored 0.35. The detailed scoring method is given in the supplementary materials I.

Table 1. Scoring criteria for policy strength

Policy strength	Scoring criteria
0-0.25	very low
0.25-0.5	low
0.5-0.65	average
0.65-0.85	high
exceed 0.85	very high

2. System Dynamics Modeling

A causal loop diagram (CLD) conducted by Vensim software is conceptualized and constructed by integrating three energy sources (PV solar energy, onshore wind power and offshore wind power) into the renewable electricity market with the policies implemented in Taiwan as shown in Figure 1. Table 2 summarizes the cause-and-effect relationships for various subsystems shown in Figure 1. The time frame of the model is defined from 2020 to 2025. The qualitative CLD is then transformed to its corresponding stock and flow diagram (SFD) for quantitative modeling (Bala, Arshad and Noh, 2017). Figure 2 shows the SFD for FIT subsystem derived based on the CLD shown in Figure 1. Detail SDF models and corresponding formula to qualify the CLD model are given in the supplementary materials II.

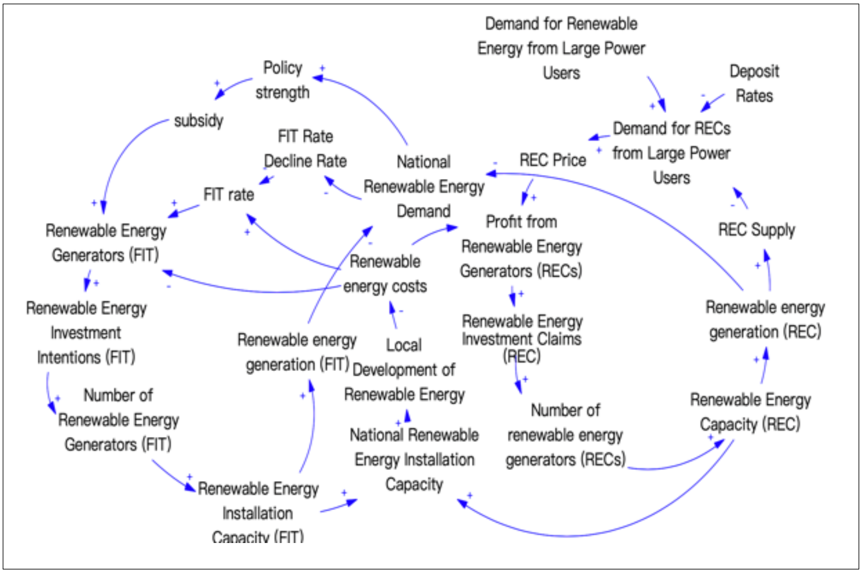

Figure 1. An Overall Causal-Loop Diagram Model

Table 2. The subsystems of the CLD model

Subsystem		loops
FIT Subsystem	Supply and demand for FIT price system	National renewable energy demand→ (-) FIT rate decline rate → (-) FIT rate → (+) renewable energy generators (FIT) → (+) renewable energy Investment intentions (FIT) → (+) number of renewable energy generators (FIT) → (+) renewable energy installed capacity (FIT) → (+) renewable energy generation (FIT) → (-) national renewable energy demand
	Investment system	Renewable energy Installed capacity (FIT) → (+) national renewable energy installation capacity→ (+) local development of renewable energy → (-) renewable energy cost→ (+) FIT rate→ (+) renewable energy generators (FIT) → (+) renewable energy investment intentions (FIT)→ (+) number of renewable energy generators (FIT) → (+) renewable energy generation (FIT) → (-) national renewable energy demand→ (-) FIT rate decline rate → (-) FIT rate → (+) renewable energy generators (FIT) Cost of renewable energy → (-) FIT rate → (+) profit from renewable energy generators (FIT) renewable energy cost→ (-) profit from renewable energy generators (FIT)
	Policy strength system	National renewable energy demand → (+) policy strength → (+) subsidy → (+) profit of renewable energy generators (FIT)
REC Subsystem	Supply and demand for REC price system	Demand for renewable energy from large power users → (+) demand for REC from large power users→ (+) REC price → (+) profit from renewable energy generators (RECs) → (+) renewable energy investment intentions→ (+) number of renewable energy generators (REC) → (+) renewable energy capacity (REC) → (+) renewable energy generation (REC) → (+) REC supply → (-) demand for REC from large power users Substitute fee rate → (-) demand for REC from large power users
	Investment system	Renewable energy capacity (REC) → (+) national renewable energy installation capacity→ (+) local development of renewable energy → (-) renewable energy cost→ (-) profit from renewable energy generators (RECs) → (+) renewable energy investment intentions→ (+) number of renewable energy generators (REC) → (+) renewable energy capacity (REC) Renewable energy Cost→ (-) profit from renewable energy generators (REC)

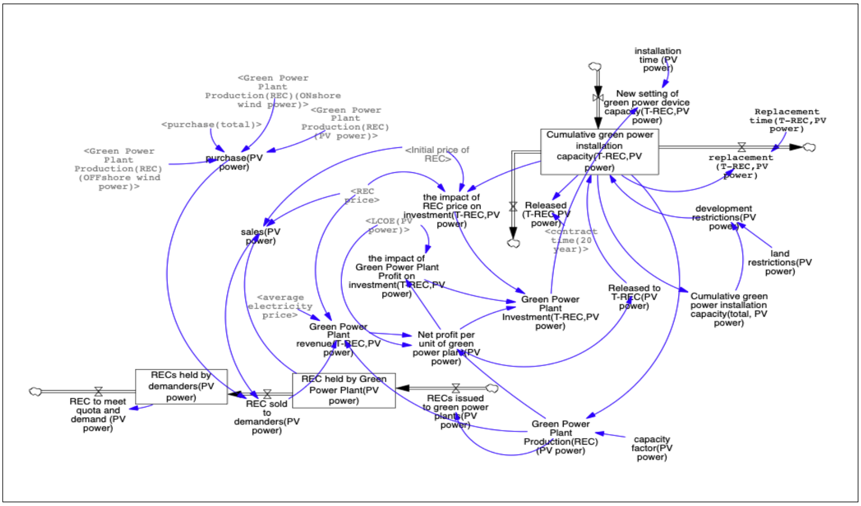

Figure 2. An Example of SFD for the REC Subsystem Derived Based on the CLD Shown in Figure 1

As shown in Figure 1, the system is a profit-driven renewable energy market, all around revenues and costs. On this basis, the impact of various policy schemes is incorporated into the measurement of the levelized cost of energy (LCOE). LCOE is widely used to compare the cost of various technologies for electricity generation. LCOE is assessed by the economic lifetime energy cost and the lifetime electricity production (Shen, Chen, Qiu, Hayward, Sayeef, Osman, Meng and Dong, 2020). The FIT and REC schemes illustrate the way of renewable energy acquiring revenue, and the cost will greatly affect the choice of energy types by renewable energy industry. We have sorted out the data of construction cost, operation and maintenance cost, and annual power generation (annual electricity sales) to calculate LCOE:

$$LCOE = \frac{[(\text{Actual initial setup cost})\times CRF + O\&M\ cost]}{Annual\ electricity\ sales} \quad (1)$$

Where O&M cost is the operation and maintain cost, capital recovery factor (CRF) is the ratio of a constant annuity to the present value of receiving that annuity over a set period of time.

Model validation is successfully confirmed by using a unit conformance test, behavior reproducibility test, and extreme behavior test in the study. The built-in unit consistency test function of Vesim was used to perform the unit consistency test, and the results showed no unit misplacement. The assumptions of the model include:

1. Only three energy sources are considered: solar, onshore wind and offshore wind.
2. The policy score is considered only based on the policy clarity under our best knowledge.
3. No interference occurs during the period of the implementation of all policies.
4. The capacity of the renewable energy device is only increased or decreased on the basis of supply and demand.

III. Results and Discussion

1. Baseline Scenario

A baseline scenario developed in the study is to simulate a system most likely to reflect the current situation of renewable energy development in Taiwan in order to evaluate the outcome in achieving the targets. Therefore, the parameters used primarily is based on the data provided by the government document. For data that cannot be obtained from government document, historical domestic data is firstly collected while the international data is applied secondly. The system simulates various scenarios on different FIT rate reduction rates, T-REC benchmark prices and policy strength. Table 3 shows the basic parameters of baseline scenario for various renewables based on current policies. The FIT decline rate is set based on Liu's study (2008) while a detail description of the T-REC price setting is given in the following subsection 3.

Table 3. Parameters of the baseline scenario

Parameters	PV solar energy	Onshore wind	Offshore wind
FIT decline rate per year (%)	8%	1%	1%
T-REC initial price (USD/ MWh)	3.3	3.3	3.3
Policy strength	0.352	0.352	0.352

The national renewable energy target is given at 5.4, 30 and 60% by 2020, 2030 and 2050, respectively. As shown in Figure 3, onshore wind power, PV solar power, and offshore wind power reaches their targets in 2025, 2028, and 2049, respectively, based on the baseline scenario conditions. After achieving targets, onshore wind and PV solar power tend to experience decreasing FIT rates and lower replacement costs for equipment. This may be attributed to the FIT price is linked to the LCOE. When the target installed capacity is achieved, the LCOE price decreases, which in turn causes the FIT rates and O&M cost to decrease. T-REC prices initially rise due to supply shortages and peak at about 30 USD during 2038-2040 (Figure 4). However, a decline of the renewable energy prices occurred after FIT subsidy balanced with grid equity that loses its competitive advantage and leads to stabilize the T-REC price at around 10 USD per certificate after 2045. In addition, the stabilization of T-REC pricing is dependent on the sufficient supply of the offshore wind power, which is consistent with the projection shown in Figure 3.

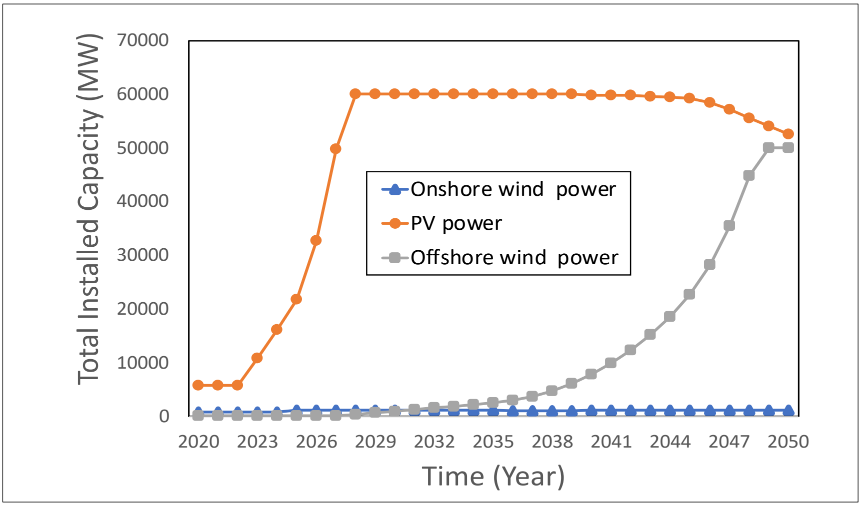

Figure 3. Total Installed Capacity of Different Renewable Powers Under the Baseline Scenario

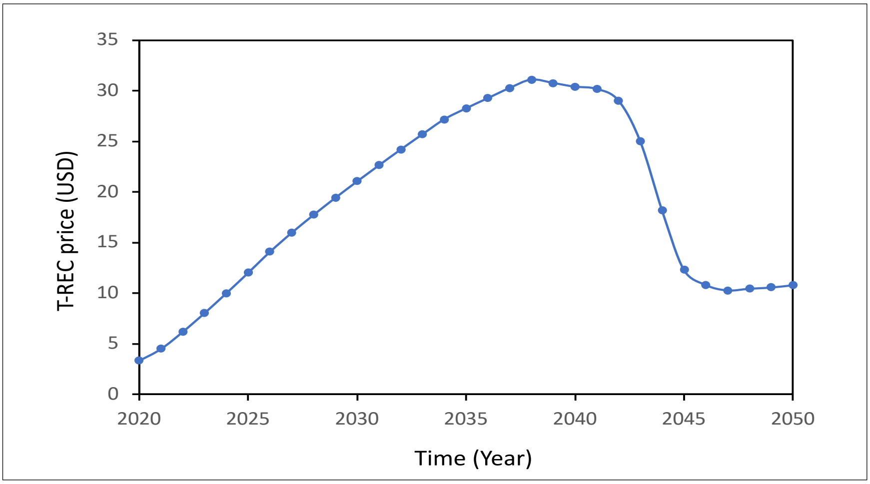

Figure 4. The Change of T-REC Price for Renewables Under the Baseline Scenario

2. Impact of FIT Rates on the RE Capacity and T-REC Price

As discussion above, the baseline scenario conditions are capable of achieving the energy policy goal in Taiwan; thus, the study is conducted to further explore the impact of enhancing the FIT decline rates on the renewable capacity. The increasing in FIT decline rates tends to accelerate the phase-out of the FIT scheme that may provide insights into the optimalization of FIT rates to reduce the financial burden caused by the subsidy of FIT. In the study, the decline rate is set to approximately twice as high as the baseline rate. Here, two scenarios are simulated: (1) baseline scenario and (2) the 15% FIT decline rate per year. It should be noticed that the FIT decline rate is significantly enhanced from 1% to 15% for both onshore and offshore wind power.

Figure 5 shows the simulation results for onshore wind power, PV solar energy and offshore wind power under two different scenarios. As shown in Figure 5a, though a noticeable fluctuation of the installed capacity may occur for the onshore wind power, it is evident that the onshore wind power ultimately reaches its target capacity even under the high FIT decline rate. This is attributed to the onshore wind power has already been achieved the grid parity in Taiwan. The grid parity is defined as a point where renewable energy source can generate power at a LCOE less than or equal to the cost of obtaining power from the conventional power grid (Adeyemi-Kayode, Misra, Maskeliunas and Damasevicius, 2023). In other words, the onshore wind power should no longer be protected by FIT. In fact, the development of the onshore wind power shows its competitiveness in price that has attracted significantly more attention for corporates in Taiwan.

However, a severe impact on the achievement of the target capacity by enhancing the FIT decline rate is observed for both solar PV power and offshore wind power as shown in Figure 5b and Figure 5c, respectively. Solar PV power still requires the support of FIT to achieve its target while the accelerated FIT phase-out leads to only 41 GW of installed capacity (Figure 5b). Moreover, the offshore wind power highly depends on FIT, which is understandable because the offshore wind power is a capital and technology intensive industry (Santhakumar, Heuberger-Austin, Meerman and Faaij, 2023) where Taiwan extremely relies on the foreign companies. However, it should be noticed that the development of offshore wind power only has a very short period of time in Taiwan; thus, the historical domestic data used to calibrate the model is limited. Meanwhile, a strong demand from large consumers of renewables may shake up the market by bringing in the corporate power purchase agreement (CPPA) to compete with FIT in Taiwan (Aswani & Sajith, 2024). Therefore, a further investigation is certainly needed to better understand the comprehensive development of offshore wind power in Taiwan.

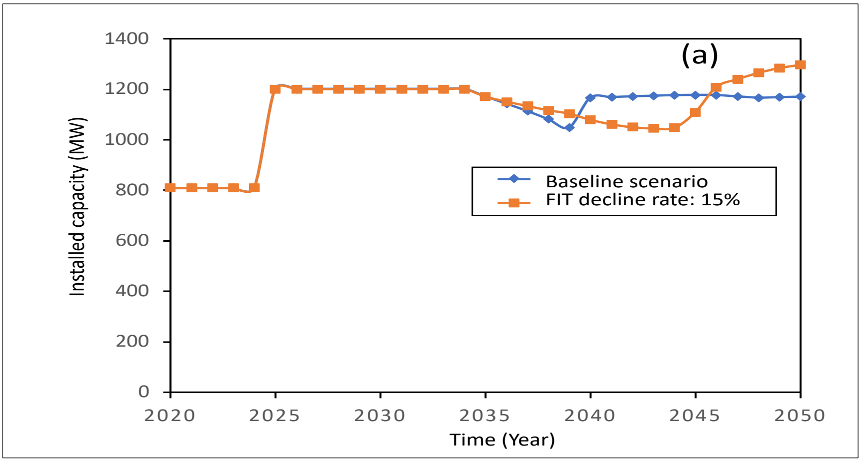

Figure 5a. Total Installed Capacity of Onshore Wind Power Impacted by FIT Policy

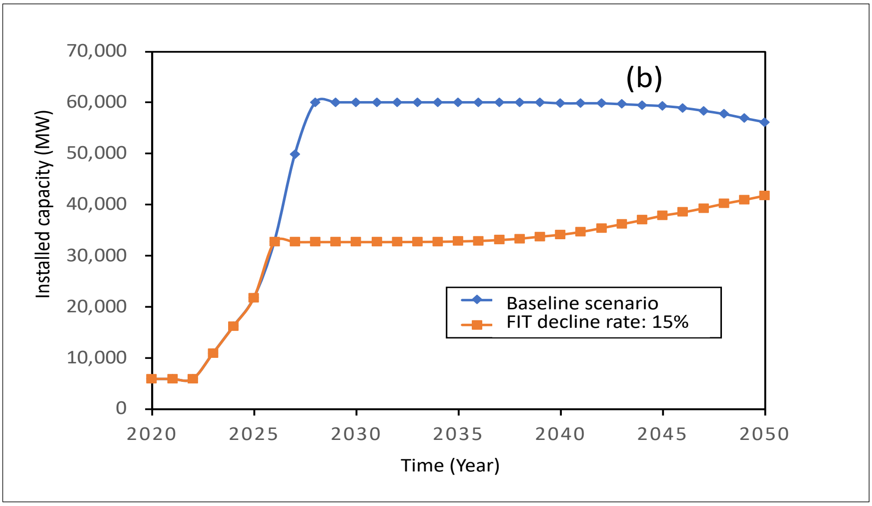

Figure 5b. Total Installed Capacity of PV Solar Power Impacted by FIT Policy

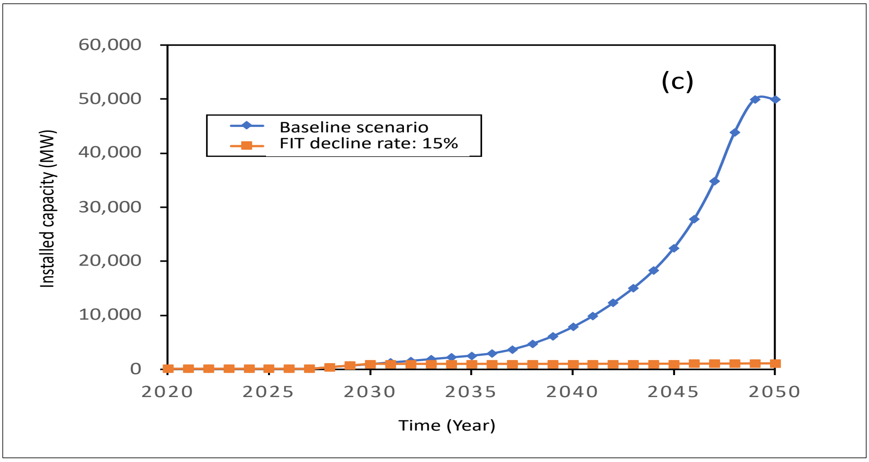

Figure 5c. Total Installed Capacity of Offshore Wind Power Impacted by FIT Policy

3. Impact of Initial Price of T-REC on the RE Capacity and Final T-REC Price

As a new market for REC trading in Taiwan, the initial price of T-REC is dependent of many factors while the value of T-REC eventually is determined by the free trading mechanism in the market. In this study, initial T-REC price is inevitably simulated within a hypothetical range owing to the lack of public statistics on the price of T-REC in Taiwan. The initial price of T-REC is set based on a benchmark of the mature REC market price referent including the international renewable energy certificate (I-REC) and guarantees of origin (GO) (Wimmers & Madlener, 2023; Jati, Ab Manan, Marukatat, Matussin and Phung, 2023). Three different initial prices used for T-REC are: (1) 3.3 USD/ MWh, (2) 16.7 USD /MWh, and (3) 33.3 USD / MWh.

Table 4. Effect of different initial T-REC price on the installed capacity for various renewables

Simulation		PV solar power	Onshore wind power	Offshore wind power
	Target capacity	60 GW	12 MW	50 GW
3.3 USD		56.1 GW	12.35 MW	50 GW
16.7 USD		57.3 GW	12.02 MW	50 GW
33.3 USD		56.1 GW	11.79 MW	50 GW

As shown in Table 4, the initial T-REC price has minimal impact on the development of onshore wind, solar, and offshore wind installed capacities. The highest initial T-REC price (33.3 USD) only causes a slightly decrease in the projected installed capacity, which accounts for about 93% completion rate of the PV solar power. External factors such as unmet market demand, regulations, and international initiatives may lead to supply shortages, thus driving up T-REC prices. However, the trend and scale of T-REC prices vary depending on their initial price levels (Figure 6). Excessively high prices may become unaffordable for obligated entities. Therefore, regulatory mechanisms may be needed to balance the achievement of renewable energy goals with cost considerations for all parties involved.

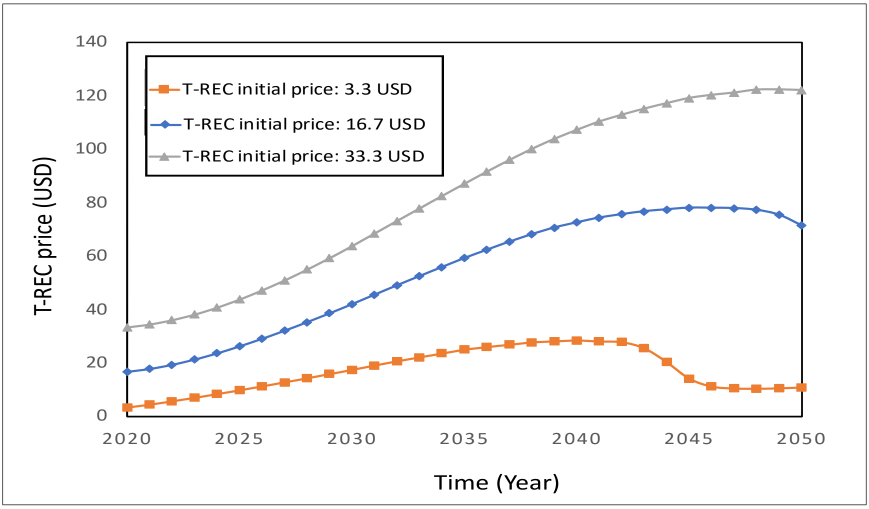

Figure 6. T-REC Pricing Under Different Initial Price Setting

4. Different Policy Strengths

Policy strength affects FIT promotion and investment confidence. As shown in the method section, the policy clarity is used to score the policy strength based on Doan, Vu and Le (2022) scoring criteria. The simulations examined here include (1) low policy strength of 0 (very low) (2) baseline scenario and (3) high policy strength 0.9.

The impact of policy strength on the onshore wind power is nearly neglectable as shown in Figure 7a. The baseline scenario with policy strength of 0.35 exhibits the same projection path as the high policy strength of 0.9. Even without the policy support, the target capacity of onshore wind power still be achievable. This is because the grid parity has been achieved for onshore wind power in Taiwan. Solar and offshore wind power, however, require strong policy support to quickly achieve renewable energy targets. As shown in Figure 7b, the high policy strength leading to rapid growth to reach the target capacity while the increase in installed capacity of PV solar power is much slower and reaches 40,000 MW at 2035 and the capacity slowly increases to about 48,000 MW by 2050 under the low policy strength. This result demonstrates that minimal policy support results in significantly reduced growth in PV solar power capacity over time. Nevertheless, a slow increase in installed capacity during 2035-2050 may be attributed to the decrease of the installation cost of PV solar power that offers competitive prices in the liberalized renewable electricity market in Taiwan.

The policy strength is a highly sensitive factor for offshore wind power. Figure 7c indicates that the low policy strength leads to minimal growth in offshore wind capacity, underscoring the necessity of policy support to realize significant increases in offshore wind power. In contrast, both high and moderate policy intensities result in substantial offshore wind capacity by 2050, although higher policy strength achieves this growth slightly earlier. The simulation concludes that the low policy strength could lead to delays or even failure to achieve targets, especially for offshore wind power. Trends among these different renewables indicate that a certain policy support is needed to achieve grid parity for renewables before the technology is mature and fully integrated into the liberalized electricity market.

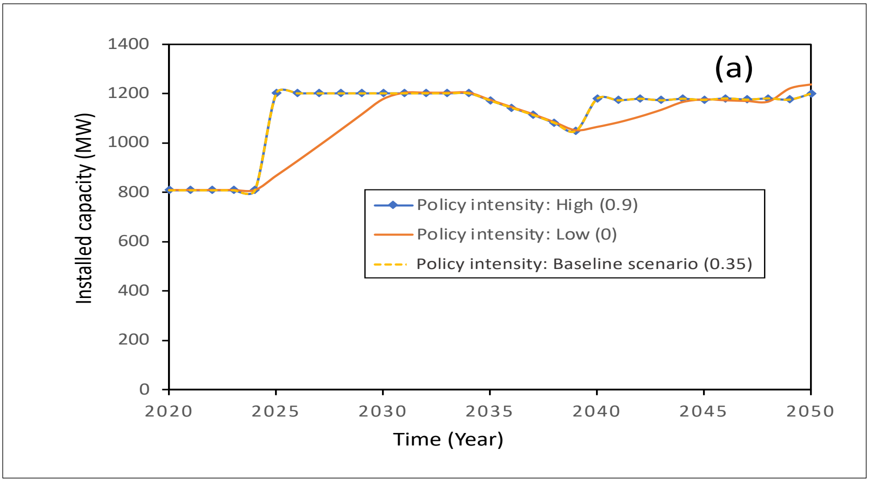

Figure 7a. Total Installed Capacity of Onshore Wind Power Under Different Policy Strengths

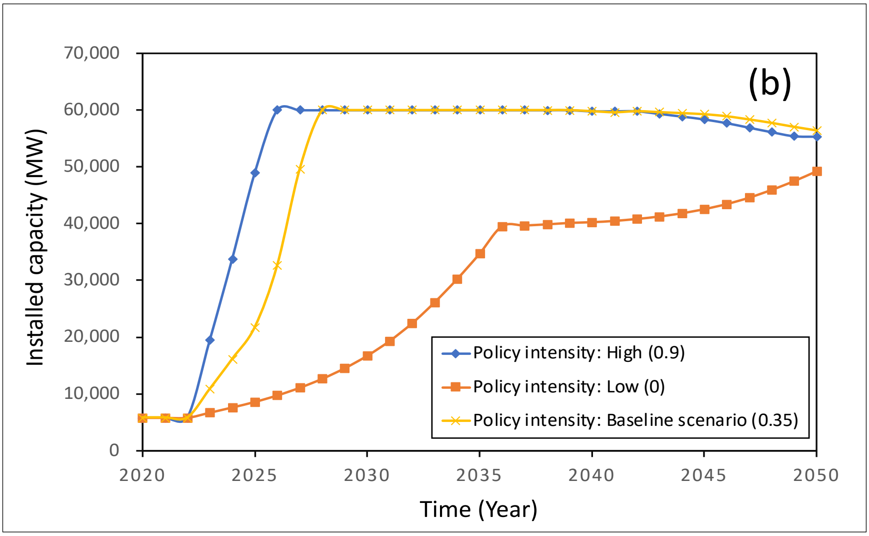

Figure 7b. Total Installed Capacity of PV Solar Power Under Different Policy Strengths

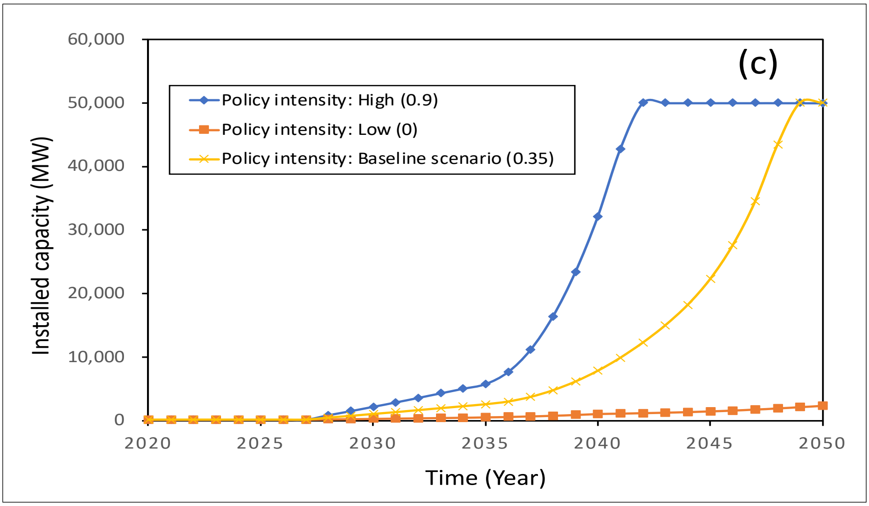

Figure 7c. Total Installed Capacity of Offshore Wind Power Under Different Policy Strengths

5. Limitations

This study has some limitations need to be acknowledged. Firstly, the government must have a concrete commitment to realize the target. As the assumptions we pointed out in the study, the scoring of policy strength is considered only based on the policy clarity not the implementation outcomes. Thus, the study is limited by the assumption that policy implementation occurs within a stable political and economic environment. Secondly, the model does not account for future breakthrough in energy technologies, which would result in the return on investment of alternative energy resources. Thirdly, the model proposed here is constrained by its internal dynamics, with many variables being exogenous and determined by historical domestic data or even the international data such as the T-REC price setting.

IV. Conclusions

This study uses system dynamics to simulate and analyze whether the national renewable energy policy can achieve the renewable energy installed capacity target for 2050 net zero emissions goal in Taiwan. In response to both international and domestic demands, the promotion of Taiwan renewable energy has been implemented by various policies including FIT, RPS, and RECs. Various scenarios are conducted to evaluate the impact of the FIT decline rate, the initial price of T-REC, and the policy strength. Based on the results, the main conclusions are as follows:

- In the baseline scenario, it is expected that onshore wind in 2025, solar in 2028 and offshore wind in 2049 will meet Taiwan's 2050 net-zero emissions target.
- For the current development of renewable energy in Taiwan, FIT plays a significant role in promoting the renewable energy installed capacity. An accelerated FIT phase-out leads to deteriorate the development of PV solar power and offshore wind power while it causes nearly no impact on onshore wind power because the onshore wind power has already been achieved the grid parity in Taiwan.
- It is found that the renewable energy installed capacity is independent of the initial T-REC price. However, excessively high prices may become unaffordable for corporates by causing extra financial burden.
- The impact of policy strength on the onshore wind power is nearly neglectable while solar and offshore wind power require strong policy support to achieve renewable energy targets. As with FIT, the impact of

policy strength is particularly significant on the types of renewable energy in the early stages of development. The improvement of policy strength is conducive to the development of pre-construction, and also has a positive effect on the balance of supply and demand and the reduction of overall prices of T-REC in the later stage.

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Supplementary materials

Analysis of Energy Policy Effects on the 2050 Renewable Energy Target of Taiwan Using Systemic Dynamics Modeling

1. The policy strength evaluation

Table S1. The policy strength evaluation of Taiwan 2050 net zero transition: Wind power/photovoltaic key strategic action plan based on the method proposed by Doan et al.

	Criteria	Agree with criteria	Notes
1	Socialization of renewable energy investment	No	
2	Foreign investment in renewable energy	No	
3	Integration of renewable energy into households	No	
4	Installation of renewable energy in public non-profit administrative units	No	
5	Local employment	Yes	A comprehensive industrial chain and infrastructure are established, along with professional talent training.
6	Commercialization potential of renewable energy	No	
7	Contribution of renewable energy to GDP	No	
8	Increase in renewable energy installed capacity's national structural share	No	
9	Improvement of land use efficiency	No	
10	Development of potential sites	Yes	Wind Power: Negotiate the use of Taiwan's offshore developable spaces. Solar Power: Utilize and develop idle rooftops and maximize multi-use of high-value land. New buildings meeting specific criteria must install rooftop solar panels.

11	Technological advancement in development	Yes	Wind Power: Develop digital operation and maintenance technologies to reduce labor costs, as well as floating turbine technology. Solar Power: Improve solar panel recyclability, lower energy storage costs, reduce expenses, and expand grid connectivity.
12	Effective coordination and communication with local institutions near development sites	Yes	Sensitive development areas are avoided. Compensation and negotiation mechanisms are planned.
13	Amendment/Revision of relevant regulations	No	
14	Capital subsidies	Yes	Policies are planned for floating offshore wind turbine subsidies.
15	Incentives for pilot demonstrations in early development stages	No	
16	Grid expansion	Yes	Strengthen infrastructure to improve grid integration and technology.
17	Renewable energy saturation		System Calculation
	Total Score		6/17 = 0.352 (additional scores may be added from renewable energy saturation)

2. Stock and flow diagrams (SFD) for each subsystem

2.1 Supply and Demand for REC Price System

This subsystem refers to the study of Zhao et al., and the changes in supply, demand and REC prices are presented as online flow graphs (EIA, 2023). The REC price will change due to the gap between supply and demand, and the adjustment time is set at two months. The demand for REC rises with the increase in renewable energy demand and electricity consumption across the country, in line with Eq. 6. If the REC held by the buyer is insufficient for the target demand, the buyer will continue to buy and will be affected by the penalty. The degree of penalty is determined by multiplying the demand by the substitution divided by the maximum REC price. The deposit rate is 4 NTD/kWh, and the maximum REC price is 2.2 NTD /kWh (Zhang et al., 2012), which follows Eq. 6. The single energy demand is affected by the REC capacity allocation, which is calculated in Eq. 8. The supply increases with the increase in the price of the voucher according to the law of supply and demand, referring to Eq. 10.

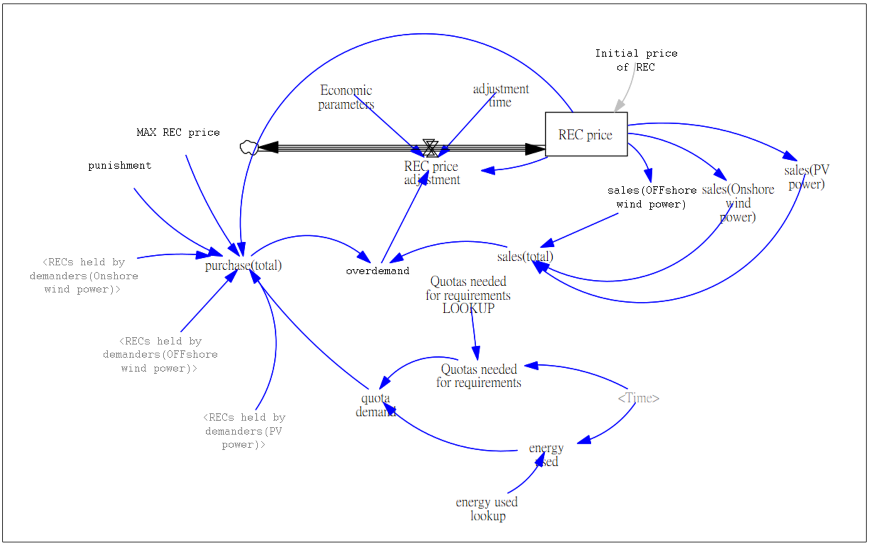

Figure S1. The SFD model of supply and demand for REC subsystem

Table S2. The parameter of supply and demand for REC subsystem

Parameter	unit
REC price	NTD/MWh
Initial price of REC	NTD/ MWh
Economic parameters 1	Year × NTD / MWh
REC price adjustment	NTD / MWh
Adjustment time	Month
Punishment	NTD /kwh
MAX REC price	NTD / MWh
Purchase (total)	MWh
Sales (total)	MWh
RECs held by demanders (Onshore wind power)	MWh
RECs held by demanders (Offshore wind power)	MWh
RECs held by demanders (PV power)	MWh
Sales (Onshore wind power)	MWh
Sales (Offshore wind power)	MWh
Sales (PV power)	MWh
Overdemand	MWh
Quotas needed for requirements.	–
Quota demand	MWh
Energy used	kwh

REC price = INTEGE (REC price adjustment)
Initial Value: Initial price of REC (2)

REC price adjustment =
Overdemand × Economic parameters 1/adjustment time (3)

adjustment time =2/12 (4)

Economic parameter 1= 2.046×10^{-7} (5)

purchase(total)=
Initial price of REC/REC price × (punishment/(max REC price)) × (quota demand-RECs held by demanders(Offshore wind power) - RECs held by demanders(Onshore wind power) - RECs held by demanders (PV power) (6)

quota demand=
(energy used × Quotas needed for requirements)/1000 (7)

Purchase (PV power) =
(Green Power Plant Production (REC) (PV power))/ ([Green Power Plant Production (REC)(PV power)+Green Power Plant Production(REC)(Onshore wind power)+ Green Power Plant Production(REC) (Offshore wind power)]) (8)

Sales(total) =
Sales (Onshore wind power) + sales (Offshore wind power) + sales (PV power) (9)

Sales (PV power) =
(REC price)/Initial price of REC) × REC held by Green Power Plant (PV power) (10)

2.2 Policy Strength Subsystem

The policy strength subsystem consists of the sum of the policy strength score and the renewable energy saturation in the previous chapters, which are “Policy strength 1” and “Policy strength 2”, respectively. Referring to the formula for subsidy in the system of Zhang et al. (2017)., the Policy subsidy parameters" of policy subsidy were sorted out. The policy subsidy parameters will participate in the subsequent investment intensity, and the participating parameters are shown in Table S3.

Table S3. Subsystem parameter of policy strength

parameter	unit
Policy strength 1	-
Policy strength 2	-
Policy strength total	-
development restrictions	kw
land restrictions	kw
Policy subsidy	NTD/kw
Policy subsidy parameters	-
Economic parameters 3	-

Policy subsidy (PV power) =
Policy strength (PV power)) total × Economic parameters 3 (11)

Policy subsidy parameters (PV power) =
(FIT price (PV power) +Policy subsidy (PV power))/LCOE (PV power) (12)

2.3 Investment Subsystem

According to Zhang and Zhao et al., when renewable energy prices are higher than the benchmark price, investors' profits rise, and they add more renewable energy power plants to increase their profits. However, as electricity production rises, profits fall. In order to maintain profits, investors reduce their investment in new and renewable energy power plants (Zhang et al., 2012; Zhao et al., 2020). The calculation of the investment factor is shown in Table S4. The investment intensity formula for FIT is based on the benchmark price in 2020, taking into account the policy subsidy parameters included in the formula.

Table S4. Investment Subsystem parameters

Parameter	unit
the impact of REC price on investment(T-REC)	Kw
the impact of price on investment (FIT)	kw
Green Power Plant Investment(T-REC)	kw
Green Power Plant Investment (FIT)	kw
Economic parameters 2	_
Net profit per unit of green power plant	NTD/kwh
Net profit per unit of FIT	NTD/kwh
Cumulative green power installation capacity(T-REC)	kw
Cumulative green power installation capacity (FIT)	kw

The impact of REC price on investment (T-REC,PV power) =(REC price/Initial price of REC)×Cumulative green power installation capacity(T-REC,PV power) (13)

The impact of price on investment (FIT, PV power) = {[FIT price (PV power) /Initial price of FIT (2020, PV power)] +Policy subsidy parameters (PV power)}×Cumulative green power installation capacity(FIT,PV power) (14)

Net profit per unit of green power plant(TREC ,PV power) =
[(Green Power Plant revenue/Green Power Plant Production (T-REC, PV power))] – LCOE (PV power) (15)

Net profit per unit of green power plant (FIT, PV power) = FIT price (PV power)- LCOE (PV power) (16)

Green Power Plant Investment (FIT, PV power) =
Economic parameter(investment)×the impact of REC price on investment (FIT, PV power). (17)

Green Power Plant Investment (T-REC, PV power) =
Economic parameters (investment) ×the impact of REC price on investment (T-REC, PV power) (18)

Economic parameters (investment) = 0.01 (19)

2.4 FIT Subsystem

According to the literature, FIT rates will decrease year by year, with solar energy falling by 8% per year, onshore wind and offshore wind falling by 1%

per year, and the lower bound is the levelized cost of energy. The additional plant capacity will flow into the cumulative unit capacity, and the renewable energy plant will be used to generate electricity for bulk purchase. When the contract expires or the unit is replaced, the capacity of the unit will flow out. If the profit margin of FIT is higher than that of REC, renewable energy generators will choose to renew the contract or install a new renewable energy unit. The cumulative plant capacity will increase depending on the impact of the investment. There will be a delay of at least 9 years among the termination factors. The life cycle of solar panels is about 30 years, and that of onshore and offshore wind turbines is about 25 years. Based on these considerations, there will be a corresponding delay in the replacement of equipment capacity.

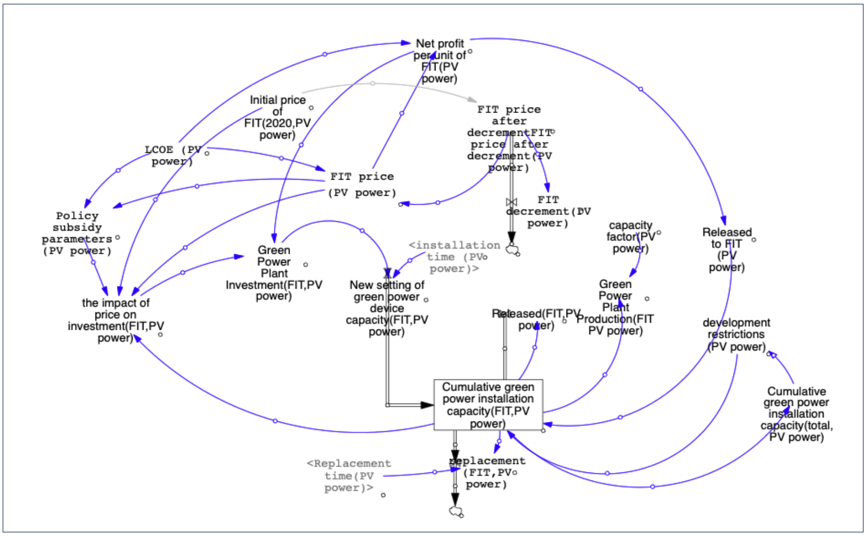

Figure S2. The SFD model for FIT subsystem

Table S5. FIT Subsystem parameters

parameter	unit
FIT price	NTD/kwh
FIT price after decrement FIT price after decrement	NTD /kwh
FIT decrement (PV power)	NTD /kwh*Year
Initial price of FIT (2020)	NTD /kwh
New setting of green power device capacity (FIT)	kw
installation time	Year
Cumulative green power installation capacity (FIT)	kw
Cumulative green power installation capacity(total)	kw
Released (FIT)	kw
contract time (20 year)	Year
Replacement (FIT)	kw
Replacement time	Year
Green Power Plant Production (REC)	kwh
capacity factor (PV power)	%

FIT price after decrement (PV power) =
INTEG [-FIT decrement (PV power)]
Initial Value: Initial price of FIT (2020, PV power) (20)

FIT price (PV power) =
MAX [FIT price after decrement (PV power), LCOE (PV power)] (21)

New setting of green power device capacity (FIT, PV power) =
Green Power Plant Investment (FIT, PV power) (22)

installation time (PV power) = 2 (23)

installation time (Onshore wind power) = 4 (24)

installation time (Offshore wind power) = 7 (25)

Cumulative green power installation capacity
(FIT, PV power) =
INTEG{New setting of green power device capacity (FIT, PV power)-Released (FIT, PV power)-replacement (FIT, PV power) + Released to FIT (PV power)} (26)

Released (FIT, PV power) =
Cumulative green power installation capacity (FIT, PV power) /contract time (20 year)
Delay time: 9 (27)

replacement (FIT, PV power) =
Cumulative green power installation capacity (FIT, PV power) / Replacement time (PV power)
Delay time: 19 (28)

Replacement time = 30 (29)

Replacement time (Onshore wind power) = 25 (30)

Replacement time (Offshore wind power) = 25 (31)

2.5 REC Subsystem

In the renewable energy market, increasing the price of RECs will increase the willingness to invest and add new equipment capacity. The cumulative capacity of units will increase due to the capacity of new installations, and will also decrease due to the expiration of power purchase contracts and the replacement of units. Depending on the change in profits, there is an option to renew or renew the renewable energy unit. When the remaining development capacity is greater than zero, the cumulative plant capacity is equal to the new plant capacity plus the renewal part minus the contract expiration and the unit replacement part. If the remaining development capacity is less than the capacity of the new installation, the smaller one will be selected as the new part. If there is no remaining development capacity, the cumulative plant capacity will be the renewal portion minus the contract expiration and unit replacement portion. The amount of REC generated by a renewable energy plant multiplied by the amount of REC per 1,000 kWh of electricity is the amount of REC held by the renewable energy generator. The trading volume of REC depends on supply and demand, and when supply is greater than demand, the trading volume is equal to the demanded volume and vice versa. The purchaser uses the voucher to meet the quota of the obligation.

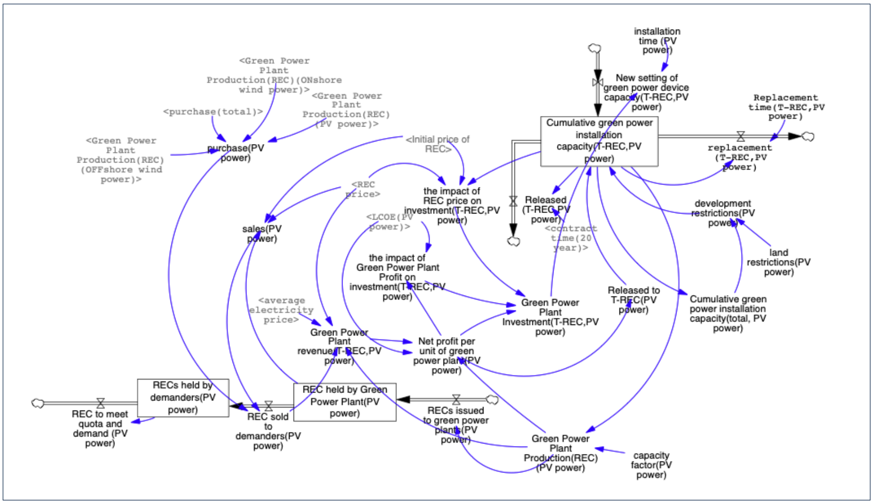

Figure S3. The SFD model for REC subsystem

Table S6. REC Subsystem parameters

parameter	unit
Cumulative green power installation capacity(T-REC)	kw
New setting of green power device capacity(T-REC)	kw
Replacement (T-REC)	kw
contract time (20 year)	Year
Released (T-REC)	kw
Cumulative green power installation capacity(total)	kw
RECs issued to green power plants	MWh
REC held by Green Power Plant	MWh
REC sold to demanders	MWh
RECs held by demanders	MWh
REC to meet quota and demand	MWh

Cumulative green power installation capacity (T-REC, PV power) =
New setting of green power device capacity (T-REC, PV power) +Released to T-REC (PV power)-Released (T-REC, PV power)-replacement (T-REC, PV power) (32)

New setting of green power device capacity (T-REC, PV power) =
Green Power Plant Investment (T-REC, PV power)

Delay time: installation time (PV power) (33)

Released (T-REC, PV power) =Cumulative green power installation capacity (T-REC, PV power))/ contract time (20 year)
Delay time:17 (34)

replacement (T-REC, PV power) =
Cumulative green power installation capacity (T-REC, PV power) /Replacement time (T-REC, PV power)
Delay time: 27 (35)

Green Power Plant Production (REC) (PV power) =
capacity factor (PV power) × Cumulative green power installation capacity (T-REC, PV power)× 8760 (36)

RECs issued to green power plants (PV power) =
Green Power Plant Production (REC) (PV power) /1000
(37)

REC held by Green Power Plant (PV power) =
INTEG (RECs issued to green power plants (PV power)" -"REC sold to demanders (PV power)) (38)

REC sold to demanders (PV power) =
MIN (purchase(PV power) , sales(PV power)) (39)

RECs held by demanders (PV power) =
INTEG [REC sold to demanders (PV power) - REC to meet quota and demand (PV power)] (40)

REC to meet quota and demand (PV power) =
RECs held by demanders (PV power) (41)

2.6 Contract Renewal and Unit Replacement Subsystem

When the contract expires, the renewable energy generator can choose to terminate the contract or renew it. After the termination of the contract, the renewable energy unit can be re-signed and directly included in the cumulative unit capacity for power generation without going through the construction time and construction cost. When the unit is replaced, the cumulative unit capacity will be reduced due to the loss of some units, and the remaining developable capacity will be increased. If there is no longer interest in renewing or developing the energy source, the energy developer may choose to stop investing or move to other highly profitable energy sources. If the profit of this energy source is higher than that of other energy sources, it can choose to rebuild and build units for development.

Table S7. Subsystems for contract renewal and unit replacement

The name of the factor	unit
Released to FIT	kw
Released to T-REC	kw
Released capacity(TOTAL)	kw

Released capacity (TOTAL PV power) =
Released (T-REC, PV power) + Released (FIT, PV power) (42)

IF Net profit per unit of FIT (PV power)>Net profit per unit of green power plant (PV power):
Released to T-REC (PV power) =
Released capacity (TOTAL PV power) (43)

IF Net profit per unit of green power plant (PV power) >Net profit per unit of FIT (PV power):
Released to FIT (PV power) =
Released capacity (TOTAL PV power) (44)

development restrictions (PV power)
= land restrictions (PV power) -Cumulative green power installation capacity (total, PV power) (45)