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Optimization of Feed-in Tariff Mechanism for Residential and Industrial Photovoltaic Adoption in Hong Kong

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Abstract

Due to the late introduction of Feed-in Tariff (FiT) Scheme to Hong Kong's context, its effectiveness, efficiency, and optimization have merely been investigated yet. Therefore, this study proposes two FiT mechanisms according to the policy characteristics and structure elucidated from existing literatures (i.e., payoff, tariff, and contract structures): (i) Mechanism 1 (i.e., M1) follows the current policy characteristics with a short-term contract structure, which terminates in 2033; and (ii) Mechanism 2 (i.e., M2) introduced a widely adopted policy characteristic with a long-term contract structure, which allows to sell all electricity generated to the power grid. The proposed FiT rate under M1 and M2 guarantees the profitability of the solar photovoltaic (PV) installers with different scales. For residential PV installers (i.e., small-scale PV systems with installed capacity less than10 kW), 6-10 years of discounted payback period (DPB) is considered as the optimization objective. As for industrial PV installers (i.e., large-scale PV systems with installed capacity of 200-1,000 kW), 8-12% of internal rate of return (IRR) is considered as the optimization objective. Results indicate that the current FiT rate is slightly high for residential PV installers, and it is recommended to be lowered after 2024 to fit the proposed FiT range, and then levered up in 2028 to ensure the profitability of late participation under M1. Meanwhile, the current FiT rate is found significantly low for industrial PV installers, and it is suggested to be levered up to the proposed FiT range. Furthermore, policy reform is highly recommended altering from M1 to M2 when current policy expires (i.e., 2033). In terms of the techno-economic analysis based on the calculation of levelized profit of electricity (LPOE) where self-consumption of PV system-generated electricity is considered as energy bill savings under M1, the long-term profitability for industrial PV installers under M1 is found to be higher than M2, whereas the opposite is observed for residential PV installers. The contribution of this study is attributed to the flexibility and applicability of the optimized results, the context-specific investigation of the market-independent renewable energy development, and the comprehensive parameters considered in the model development. The results of this study are believed to shed light on policy implications, grid parity, and investment recommendations for the government, utility companies, and PV installers in the long run.

Keywords

Feed-in Tariff; Solar PV Adoption; Mechanism Optimization; Discounted Payback Period; Internal Rate of Return

Graphical Abstract

A. Proposed FiT Mechanisms (M1 and M2)

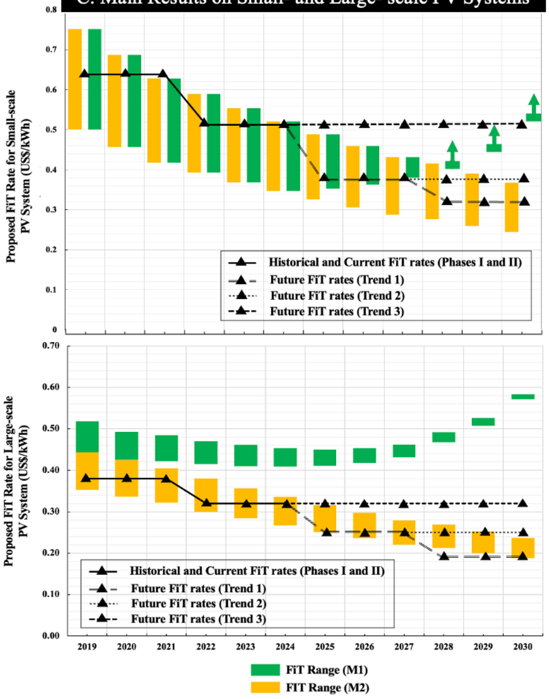
Mechanism	Description	Contract duration	Optimization objectives	
			Small-scale PV	Large-scale PV
Mechanism 1 (M1)	Electricity sold to grid before 2033, and self-consumed after 2033	t to U (2033)*	Annual FiT: ensures $6 \leq DPB \leq 10$ *2025: $6 \leq DPB \leq 9$ *2026: $6 \leq DPB \leq 8$ *2027: $6 \leq DPB \leq 7$ *2028: $DPB \leq 6$ *2029: $DPB \leq 5$ *2030: $DPB \leq 4$	Annual FiT: ensures $8\% \leq IRR \leq 12\%$
Mechanism 2 (M2)	All electricity sold to grid	t to T		

*Note: For small-scale PV installers under M1, although the original physical constraint is set as $6 \leq DPB \leq 10$, this condition cannot be fulfilled for late participants who join the FiT scheme since 2025. Under this circumstance, the maximum DPB will no longer be 10 years as the duration between participation year and 2033 is less than 10 years. Therefore, from the small-scale PV installers' perspective, the duration of receiving FiT becomes shorter, and their expected DPB will also be shortened when 2033 approaches.

B. Assumptions on Future FiT Trends (Trends 1 to 3)

Trend	Description	Duration	FiT rate for small-scale PV system (US$/kWh)	FiT rate for large-scale PV system (US$/kWh)
Trend 1	Future FiT rate follows a decreasing price trend	2025-2027	0.38 (= Phase II, medium-scale)	0.25 (=2 HK$/kWh)
		2028-2030	0.32 (= Phase II, large-scale)	0.19 (=1.5 HK$/kWh)
Trend 2	Future FiT rate first decreases and then maintains	2025-2027	0.38 (= Phase II, medium-scale)	0.25 (=2 HK$/kWh)
		2028-2030	0.38	0.25
Trend 3	Future FiT rate follows a maintained price trend	2025-2030	0.51	0.32

C. Main Results on Small- and Large- scale PV Systems



1. Introduction

Over the past 30 years, attentions over environmental protection and sustainability have been sought by various countries worldwide, which facilitated the development of renewable energy sources for electricity (RES-E). Electricity generated from renewable energy technology (e.g., solar photovoltaic (PV) system, onshore and offshore wind turbines, biothermal and geothermal, etc.) are significantly encouraged by supportive policies, which lead to the nourishing of the renewable energy industry, especially the solar industry. Comparatively, developed countries have experienced energy revolution and energy transition earlier than developing countries. In 1978, the United States added solar energy to the Public Utility Regulatory Policies Act policy it launched, which is regarded as the first country to promote the development of solar energy (Dijkgraaf, van Dorp and Maasland, 2018). In 1994, Japan has launched the Residential PV Dissemination Scheme to subsidize one-third of the capital cost for residential PV installations less than 4 kW (Kurokawa and Ikki, 2001). Gradually, different countries all over the world have successively launched RES-E supportive policies according to their specific geographical, topographic and climatic conditions (Firozjaei et al., 2020). Although these policies are miscellaneous and diverse owing to the uniqueness of each country, Feed-in Tariff (FiT) is universally adopted as a fiscal policy implemented to boost the development of RES-E, and has been proven to be one of the most effective policy instruments by countries with previous experience (Carley, 2009; Jenner, Groba and Indvik, 2013; Dijkgraaf, van Dorp and Maasland, 2018; Zhang et al., 2019; Setiawan et al., 2022). From 1990 to 2011, 23 European Union countries have introduced FiT policy successively, to address the rising concerns over climate change and air pollution (Jenner, Groba and Indvik, 2013). Among them, Germany is regarded the first country to stipulate FiT policy by obligating large utility companies to accommodate small-scale PV system-generated electricity into the power grid, and remunerate the installers at a fixed rate (i.e., 90% of the retail electricity price) (Dijkgraaf, van Dorp and Maasland, 2018). Many countries that have initiated FiT in the early stage have transferred from the pre-FiT era with high rates to the post-FiT era with lower rates. Ultimately, the FiT will be replaced or gradually phased out with market-dependent instruments (e.g., renewable portfolio standards) as the market matured, and such countries include Mainland China, South Korea, the United States and Italy (Lee and Seo, 2019). Nonetheless, there are some countries that still rely on the FiT to promote RES-E since they are late participants in the renewable energy market. Hong Kong is regarded as a representative case where the FiT is currently under implementation as a market-independent instrument starting from 2019, and the FiT mechanism is designed to remunerate investors with a preferential fixed price per unit of electricity (i.e., kWh). Although studies related to FiT have been extensively conducted, it is still of importance to understand the structure and mechanism of FiT policy for its successful implementation considering regional particulars (e.g., whether it is market-dependent or market-independent) in target countries or regions (Firozjaei et al., 2020).

1.1. The Structure of FiT Policy

The FiT policy shows different characteristics in terms of payoff, tariff, and contract structures depending on the country. In general, two payoff structures are employed for the FiT policy in different countries: (i) Fixed rate, which guarantees PV installers to sell the total electricity generated from the PV system to the power grid at a set price during a specified time; and (ii) Premium tariff, which adds a pre-specified premium price on top of the wholesale electricity price for PV installers to sell their generated electricity. Specifically, fixed price FiT is more popular and widely employed by most countries than premium tariff FiT. For example, the United States, China and Japan all adopted fixed price FiT mechanism. In the European Union, Denmark and Cyprus are the only countries that have implemented a premium tariff FiT whereas all other countries employ the fixed price one (Kim and Lee, 2012; Jenner, Groba and Indvik, 2013).

Apart from the payoff structure, the tariff and contract structures also vary among countries. More specifically, within a specific payoff structure, the specific amount of tariff that PV installers can receive may vary in one or more of the following features: (i) Tariff amount, the tariff rate may vary domestically in terms of system location, system size, and the function of the host building (Jenner, Groba and Indvik, 2013; Zhang et al., 2020b; Dato, Durmaz and Pommeret, 2021); (ii) Digression, the tariff may gradually decrease owing to the fact that the capital cost of the PV system decreases over time due to the learning curve effect (Elshurafa et al., 2018; Castrejon-Campos, Aye and Hui, 2022a); and (iii) Contract duration, the tariff payment is subject to a duration stipulated by the contract, which can be a long-term contract covering the lifespan of the PV system (i.e., 20 to 25 years) (Benhmad and Percebois, 2018; Chu and Takeuchi, 2022) or a short-term contract with the expiration year (i.e., 2033) (Mah et al., 2018).

1.2. FiT Mechanism in Hong Kong

To mitigate the climate change and global warming challenges, the Environment Bureau of Hong Kong has implemented *Hong Kong's Climate Change Action Plan 2030+* (Environment Bureau, 2017), which aggressively voices support for the development and deployment of RES-E in Hong Kong. This initiative is bonded by the New Scheme of Control Agreements (SCAs) signed between the Hong Kong government and two local utility companies in 2017, namely, China Light & Power Company Syndicate (i.e., CLP) and Hong Kong Electric Company (i.e., HK Electric). The SCAs involve continuous cooperation between the Hong Kong government and utility companies, which stipulates the responsibilities of each side of the stakeholders. Utility companies are obligated to increase the share of non-fossil fuel (e.g., natural gas) and renewable energy in electricity supply (i.e., RES-E), and the Hong Kong government is responsible for providing a stable economic and financial environment. Accordingly, two utility companies have launched the FiT policy in 2019 to actively promote the development of solar energy (GovHK, n.d.; Dato, Durmaz and Pommeret, 2021). The mechanism of Hong Kong's FiT policy is summarized in Table 1, and it has the following features in terms of the payoff, tariff, and contract structures:

i. Payoff structure: A fixed FiT rate is paid with a digression. From Jan 2019 to Apr 2022 (i.e., Phase I), the tariff remains unchanged. Three years after commencement, the tariff is decreased to Phase II.

ii. Tariff structure: Tariff amount varies between system sizes. For small-scale PV systems (i.e., installed capacity ≤10 kW), the installers receive the highest rate; for medium-scale PV systems (i.e., installed capacity from 10 to 200 kW), the installers receive the intermediate rate; For large-scale PV systems (i.e., installed capacity from 200 to 1,000 kW), the installers receive the lowest rate.

iii. Contract structure: Contract duration is subject to the expiration of FiT policy. The purchase of the electricity generated from the PV system will be restricted to the launching duration of the FiT scheme in Hong Kong, which is the end of 2033. The electricity generated after 2033 will be self-consumed by the installers.

Table 1. Mechanism of FiT Policy in Hong Kong

Facility type	Installed capacity	FiT Phase I: From Jan. 2019 to Apr. 2022 (US$/kWh)	FiT Phase II: From Apr. 2022 on (US$/kWh)
Small-scale PV system	≤10 kW	0.64	0.51
Medium-scale PV system	10 – 200 kW	0.51	0.38
Large-scale PV system	200 – 1,000 kW	0.38	0.32

1.3. Literature Review and Research Objective

Realizing that the FiT mechanism in every country or region is distinctive, it is crucial to evaluate the optimal tariff according to the policy structure practically implemented in that country/region. Extensive studies on FiT optimization have been conducted to analyze the effectiveness and efficiency of the current one, and shed light on the improvement of the mechanism regarding its payoff and tariff structures. The specifics of the literatures in terms of country/region, existing/proposed FiT mechanisms, main methodology, and optimization objectives are summarized in Table 2. It is found that the proposed FiT mechanisms are (i) usually consistent with the current one in their countries/regions (Rigter and Vidican, 2010; Fagiani, Barquín and Hakvoort, 2013; Lin and Wesseh, 2013; Muhammad-Sukki et al., 2013; Firozjaei et al., 2020); or (ii) improved with modifications on the payoff or tariff structures such as (ii-a) proposing a premium tariff and hybrid payment (Kim and Lee, 2012; Barbosa et al., 2018; Yang and Ge, 2018; Zhang et al., 2020b); (ii-b) recommending a tariff range with investment considerations (Zhang et al., 2020b); (ii-c) proposing a price-floor regime (Barbosa et al., 2018); and (ii-d) revising current tariff considering specific geographical, topographic and climatic conditions (Yang and Ge, 2018). The methodologies applied in these studies are mainly economic analysis based on the net present value (NPV), real option, internal rate of return (IRR), payback period (PP), and return on investment (ROI) with certain optimization objectives such as (i) profit maximization (Kim and Lee, 2012; Lin and Wesseh, 2013; Firozjaei et al., 2020); (ii) expectations on investment (Rigter and Vidican, 2010; Barbosa et al., 2018; Yang and Ge, 2018; Zhang et al., 2020b); (iii) risk minimization (Fagiani, Barquín and Hakvoort, 2013); and (iv) scenario comparison (Muhammad-Sukki et al., 2013).

Although there have been various previous studies on FiT optimization, research gap still exists. Firozjaei et al. (2020) presented a stochastic model on four FiT payoff structures from a broad perspective, however, they also pointed out that the actual policy implementation depends on regional particulars (e.g., whether the renewable energy development is market-dependent or market-independent). Besides, the learning curve effect has not been considered in their study, which is regarded as a critical parameter when establishing the PV cost model. Fagiani, Barquín and Hakvoort (2013) adopted NPV to reverse the investment risk for PV installers, and concluded that the effectiveness of FiT significantly depends on the rates. Nonetheless, no financial limit is considered in their study, which means that the subsidy budget of FiT is regarded as infinite. Henceforth, such assumption is believed to cause a considerable financial burden to the government or utility companies, which will affect the effectiveness of their results. Lin and Wesseh (2013) utilized a stochastic dynamic program to estimate the optimal FiT against the value of solar energy technology with and without external costs. However, the limitation of their model is that the average value of FiT rates is used despite that the historical FiT rates constantly changed. Muhammad-Sukki et al. (2013) investigated the economic performance of PV projects by two possible FiT rates, and justified the appropriate rate by comparing the rate of investment and PP with other countries. Although the comparative analysis enables the economic performance of PV projects to be more straightforward, the optimization of FiT alone seems to be inexplicable. Barbosa et al. (2018) developed a FiT optimization model under market-dependent conditions, and the most characterized parameters are regulation uncertainties and managerial flexibility in the renewable energy market. Nonetheless, their proposed model is not applicable under market-independent conditions. Yang and Ge (2018) have adopted financial models to simulate the cashflow of PV projects to find the optimal FiT rates, however, the PV system degradation factor is not considered in their study, and the results only indicate a short-term policy implication in terms of optimal FiT rates. Comparatively, Firozjaei et al. (2020) and Rigter and Vidican (2010) comprehensively considered the missing parameters which other studies failed to address, nevertheless, both studies used closed-form equation in their optimization models, which lead to only a single result of optimal FiT rate. Hence, the flexibility and applicability of such results can be minimized in real situation.

To fulfill these research gaps, this study intends to use Hong Kong as a case study, where the systematic investigation on FiT optimization is scarce due to the late introduction of the FiT scheme, to propose the optimal FiT rate under a market-independent condition. Since concerns about the uncertainty of financial return from PV installation have been raised by residential sectors (Mah et al., 2018), this study intends to investigate the effectiveness and efficiency of the current FiT policy as the first purpose, and more importantly, optimize the FiT rate from the PV system installers' perspectives ultimately. In accordance with the classification of FiT rate (Table 1), this study selects small-scale PV systems (installed capacity less than 10kW) and large-scale PV systems (installed capacity between 200-1,000 kW) as facility types to investigate the optimal FiT rate. This study does not take medium-scale PV systems into consideration owe to the facts that (i) the financial information on medium-scale PV system in Hong Kong is lacking; (ii) the characteristics of medium- and large- scale PV systems are similar (e.g., both are installed for commercial and industrial application); and (iii) the FiT rate of large-scale PV systems is especially worth investigating since it is the lowest among all scales of PV systems. In this study, small-scale PV systems are regarded as residential installation whereas large-scale PV systems are regarded as industrial installation. Under this circumstance, the tax payment will differ according to different facility types. As indicated by (Asian Energy Studies Centre, 2017; Mah et al., 2018), the greatest barrier and concern for the small-scale PV installers (i.e., usually residential PV installers) is the uncertainty of the PV system PP, whereas, for large-scale PV installers, profitability is the determined aspect. Since the Hong Kong government and the utility companies announced that the PP of residential PV systems under the FIT scheme will be 6-10 years (Hong Kong Electric, 2018), this study will apply this value as optimization objectives to optimize the FiT rate of small-scale PV system, however, in the form of discounted payback period (DPB) to better take time value into account. For large-scale PV systems, this study will apply the favourable IRR range mostly accepted by

RES-E investors (i.e., 8-12%) as indicated by (Ling-zhi et al., 2018; Zhang et al., 2020b) to conduct the FiT rate optimization.

Table 2. Summary of literature review on FiT optimization

Ref.	Country /Region	Existing FiT mechanism	Proposed FiT mechanism	Main methodology	Optimization objectives
Firozjaei et al. (2020)	Iran	Fixed price integrated with adjustment factor	Fixed rate differentiated from regions	Expectation value (EV) of NPV	Minimum price paid by government to guarantee the project profitability
Kim and Lee (2012)	USA	Fixed price integrated with inflation adjustment	(i) Fixed rate (ii) Premium payment (iii) Hybrid payment	NPV and consumer behaviour modelling	Budget, remuneration and revenue constraints of customers
Zhang et al. (2020b)	Mainland China	Fixed price with long-term contract	FiT range classified according to IRR range and regions	NPV, IRR and real option methods	Investors' expectations on IRR (i.e., 8% to 15%)
Fagiani, Barquín and Hakvoort (2013)	Austria	Fixed price with long-term contract	Fixed rate with degression	NPV method	Risk aversion
Lin and Wesseh (2013)	Mainland China	Fixed price with long-term contract	Fixed rate	Real option method	Backward induction of project value, benefit optimization
Rigter and Vidican (2010)	Mainland China	Fixed price with long-term contract	Fixed rate with or without digression	Closed-form equation development of PV cost, NPV method	Investors' expectations on IRR
Muhammad-Sukki et al. (2013)	UK	Fixed price with long-term contract	Fixed rate	PP and ROI methods	Comparative study based on scenario analysis
Barbosa et al. (2018)	Portugal	Fixed price with long-term contract	Price-floor regime (i.e., FiT rate with minimum price guarantee)	NPV, and real option methods	Investment threshold
Yang and Ge (2018)	Mainland China	Fixed price with long-term contract	FiT range classified according to PV system effective utilization hours and regions	Simulation of dynamic cashflow of PV system	Investors' expectations on IRR (i.e., 8%)

1.4. Proposed FiT Mechanisms

To investigate the optimal FiT rate for small- and large- scale PV systems, this study refers to the existing literature and proposes the following two potential FiT mechanisms (Table 3.): (i) Mechanism 1 (M1), which complies with the current one in terms of payoff, tariff, and contract structures. In other words, M1 optimizes the FiT rates from small- and large- scale PV installers' perspectives following a FiT mechanism (i) at a fixed rate (ii) with digression, (iii) under a short-term contract (i.e., contract terminates in 2033). Under M1, the examined period covers from t to U, where t denotes the year when PV system is installed, and U denotes the year of contract termination (i.e., 2033); and (ii) Mechanism 2 (M2), which complies with the current one in terms of payoff and tariff structures, but considers modifying the current contract structure to a long-term contract, which covers the lifespan of the PV system. Under M2, the examined period covers from t to T, and T denotes the year when PV system is decommissioned. M2 is proposed in addition to M1 because it is the widely used mechanism by most countries. Under M2, all electricity generated from the PV system will be sold to the utility companies. The investigation of the optimal FiT rates under these two mechanisms proposed in this study is considered as a novel study to examine the effectiveness and efficiency of the current FiT mechanism, and is believed to magnificently provide policy and price implications on the reform and improvement of renewable energy mechanisms in Hong Kong.

Table 3. Proposed FiT mechanisms

<table>
<tr><th rowspan="2">Mechanism</th><th rowspan="2">Description</th><th rowspan="2">Contract duration</th><th colspan="2">Optimization objectives</th></tr>
<tr><th>Small-scale PV</th><th>Large-scale PV</th></tr>
<tr><td>Mechanism 1 (M1)</td><td>Electricity sold to grid before 2033, and self-consumed after 2033</td><td>$t*$ to U (2033)</td><td rowspan="2">Annual FiT: ensures $6 \leq DPB \leq 10$

*2025: $6 \leq DPB \leq 9$
*2026: $6 \leq DPB \leq 8$
*2027: $6 \leq DPB \leq 7$
*2028: $DPB \leq 6$
*2029: $DPB \leq 5$
*2030: $DPB \leq 4$</td><td rowspan="2">Annual FiT: ensures $8\% \leq IRR \leq 12\%$</td></tr>
<tr><td>Mechanism 2 (M2)</td><td>All electricity sold to grid</td><td>t to T</td></tr>
</table>

* Note: For small-scale PV installers under M1, although the original physical constraint is set as $6 \leq DPB \leq 10$, this condition cannot be fulfilled for late participants who join the FiT scheme since 2025. Under this circumstance, the maximum DPB will no longer be 10 years as the duration between participation year and 2033 is less than 10 years. Therefore, from the small-scale PV installers' perspective, the duration of receiving FiT becomes shorter, and their expected DPB will also be shortened when 2033 approaches.

2. Methodology

2.1. Model and Database Development

2.1.1. PV system capital expenditure (CAPEX)

In terms of the financial information on small- and large-scale PV systems, this study refers to the historical capital expenditure (CAPEX) of small-scale PV systems (i.e., residential rooftop PV systems) and large-scale PV projects (i.e., the Electrical and Mechanical Services Department Headquarters PV project and the Disneyland Resort PV project) in Hong Kong (Research Office and Legislative Council Secretariat, 2018; HK RE Net, 2022). Subsequently, the unit CAPEX of small- and large-scale PV systems are calculated as 3,817 US$/kW and 3,033 US$/kW, respectively, which will be regarded as the initial CAPEX of the examined period. Furthermore, this study employs the learning curve (LC) theory to estimate the future CAPEX of PV systems. LC reflects the learning processes during technological the development of energy systems through various approaches (e.g., learning-by-development, learning-by-doing, learning-by-using and learning-by-researching, etc. (Elia et al., 2021)). In the solar industry, the rate of LC represents the deduction rate in CAPEX as the cumulative solar PV installed capacity doubles (Elshurafa et al., 2018; Castrejon-Campos, Aye and Hui, 2022a). Besides, it is especially crucial to obtain an appropriate CAPEX to optimize the future FiT rates because the CAPEX accounts for as high as 82% of the levelized cost of electricity of PV systems (Elshurafa et al., 2018). The learning curve can be calculated using Eqs. (1) and (2), (Kersten et al., 2011; Castrejon-Campos, Aye and Hui, 2022b):

$$C_c = C_i\left(\frac{P_c}{P_i}\right)^{-\beta} \tag{1}$$

$$LR = 1 - 2^{-\beta} \tag{2}$$

Where C_c and C_i are the average global unit CAPEX of the PV system (US$/kW) in the starting and ending years, respectively (The International Renewable Energy Agency (IRENA), 2021a); P_c and P_i are the cumulative solar PV installed capacities (MW) in the starting and ending years, respectively (The International Renewable Energy Agency (IRENA), 2021b); β is the slope of the function; and LR is the learning rate of LC. The starting and ending years examined by this study is 2010 and 2020, respectively, since the solar industry has been developed rapidly to maturity in terms of its technology and diffusion during these years (Jäger-Waldau, 2021). Therefore, the LC from 2010 to 2020 can significantly reflect the trend of CAPEX. As a result, LR is calculated as 33.67%, which means that the unit CAPEX will decrease 33.67% when the cumulative solar PV installed capacity doubles.

2.1.2. PV system cash outflow (CO)

PV system cash outflow considers all expenses throughout the lifetime of the PV system. Besides the CAPEX, operating expense (OPEX), decommissioning expense (DEX) and tax expense are also considered in the calculation of PV system cash outflow. OPEX is a continuous expense annually including operation and maintenance (O&M) cost (1% of the CAPEX (An et al., 2020)), and a one-time replacement cost of the PV system inverter occurs approximately at the 13th year for a 25-year lifespan PV system (9.5% of the CAPEX (Swift, 2013a)). DEX refers to the removal and dismounting cost that occurs at the end of the PV system's service (5% of the CAPEX (Ouyang and Lin, 2014)). In addition, tax expense (i.e., profit tax) occurs when the PV system is connected to grid and receives FiT as revenue. It is worth mentioning that for small-scale PV systems, tax expense is not considered in the cash outflow because of the following reason: small-scale PV systems are mostly adopted by residential sectors (CLP Power Hong Kong Limited, 2021; CLP Power Hong Kong Limited., 2021), so this study considers small-scale PV system as residential rooftop PV system. Specifically, The Land Revenue Department of Hong Kong has announced that tax is exempted for residential individuals who install rooftop PV systems at their premises when participating in the FiT Scheme, and they are not required to pay the profit tax in respect of their revenue from the FiT Scheme (Inland Revenue Department, 2017). As for large-scale PV system, tax is not exempted since the installers are usually business sectors, it will be paid at the rate of 8.25% on assessable profits up to HK$2,000,000 (US$254,781); and 16.5% on any part of assessable profits over HK$2,000,000 (GovHK, 2022). Thus, the cash outflow of small- and large-scale PV systems is expressed by Eqs. (3) and (4), respectively.

$$CO_t^S = (CAPEX_t^S + \sum_t^T OPEX^S + DEX_T^S) * I^S \tag{3}$$

$$CO_t^L = (CAPEX_t^L + \sum_t^T OPEX^L + DEX_T^L) * I^L + \sum_t^T TAX^L \tag{4}$$

Where CO_t refers to cash outflow of PV system throughout its lifetime (US$), $CAPEX_t$ is the unit capital expense at installation year t (US$/kW), $OPEX$ is the unit operating expense (US$/kW), DEX_T is the decommissioning cost at the ending year of PV system's service T (US$/kW), I is the installed capacity of PV system (kW), TAX is the tax expense for large-scale PV installers (US$). Superscript "$S$" and "$L$" denote small- and large-scale PV systems, respectively.

2.1.3. PV system cash inflow (CI)

PV system cash inflow refers to the revenue from participating in the FiT Scheme by connecting the PV system to the power grid and selling the solar PV electricity to utility companies. Cash inflow of small- and large-scale PV systems are expressed by Eqs. (5) and (6), respectively:

$$CI_t^S = \sum_t^U G_e^S * FiT^S \quad (5)$$

$$CI_t^L = \sum_t^U G_e^L * FiT^L \quad (6)$$

Where CI_t refers to the cash inflow of revenue by participating in the FiT Scheme (US$), G_e refers to the PV system electricity generation (kWh) with an annual degradation rate of 0.9% (Swift, 2013b; Xia and Song, 2017; An, Hong and Lee, 2022). FiT is the FiT rate (US$/kWh), and U denotes the year when FiT Scheme expires. Tax expense from the above revenue for large-scale PV systems can be calculated by Eq. (7):

$$TAX^L = \begin{cases} CI_t^L * 8.25\%, & CI_t^L \leq 254{,}781 \\ CI_t^L * 16.5\% - 21019, & CI_t^L > 254{,}781 \end{cases} \quad (7)$$

The specifications of small- and large- scale PV systems are summarized in Table 4.

Table 4. Specifications of PV System

Facility type		Small-scale PV system	Large-scale PV system
Installed capacity		≤ 10 kW	200 – 1,000 kW
CAPEX		3,817 US$/kW	3,033 US$/kW
OPEX	Annual O&M cost	1% of CAPEX	
	Inverter replacement cost	9.5% of CAPEX at 13^{th} year	
Decommissioning cost		5% of CAPEX at the end of system service	
Degradation rate		0.9%	
System service life		25 years	
Learning rate		33.67%	
Tax payment		Tax exempted	Profit tax required

2.1.4. Solar PV electricity generation (G_e)

Annual solar PV electricity generation (G_e) is calculated based on daily PV system electricity generation as expressed by Eq. (8) (Deb and Brahmbhatt, 2018; Roberts, Evija and Davis, 2019; Vakili, Schönborn and Ölçer, 2022):

$$E = H * A * \gamma * PR \quad (8)$$

Where E is the daily PV system electricity generation (kWh/day), H is the monthly average daily global radiation (MJ/m^2/day), A is the total area of solar panels (m^2), γ is the solar panel yield (%), and PR is the performance ratio. γ is the amount of energy harvested from solar panels, which are subjected to external factors such as orientation, wind speed, shade, ambient temperature, and dust deposition. PR measures the efficiency of energy output and thus considers the possible internal losses during the conversion of solar energy into electricity (i.e., inverter losses and cable losses) by the PV system. γ is taken as 16.53% for a 320 W polycrystalline PV module with unit solar panel area of 1.6 m^2 (Dharpure et al., 2019; Focus Technology Co., 2022), which has assumed that the solar PV system is installed with 14-22° tilt angle and south-oriented for the optimized efficiency (EMSD, 2021). PR is taken as the default value of 0.75. (Photovoltaic Software, 2022).

Angstrom–Prescott (A-P) model is applied to estimate the monthly average daily global radiation (H) in Hong Kong's context. It is a single parameter-based model relates the solar irradiation and sunshine duration in a specific location, and has been widely applied in existing studies (Gopinathan, 1992; Bakirci, 2009; Razmjoo, Heibati and Ghadimi, 2016; Nwokolo et al., 2022a). The A-P model shows outstanding accuracy regarding its performance since it is capable of interpreting around 90% of the variability in the database in (Paulescu et al., 2016)'s paper. Furthermore, the A-P model is believed superior to other models (i.e., theoretical methods (Tu et al., 2020; Zhang et al., 2020a)) regarding its ability to perform functionally in climatic, geographical and meteorological parameters (Nwokolo et al., 2022b). The formula of the model is presented from Eqs. (9) to (13), as follows.

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) \quad (9)$$

$$H_0 = \frac{24}{\pi} I_{sc}\left(1 + 0.033cos\frac{360D}{365}\right)\left(cos\varphi cos\delta sin\omega_s + \frac{2\pi\omega_s}{360} sin\varphi sin\delta\right) \quad (10)$$

$$\delta = 23.45° \sin\left[\frac{360(D+284)}{365}\right] \quad (11)$$

$$\omega_s = cos^{-1}[-\tan\delta tan\varphi] \quad (12)$$

$$S_0 = \frac{2\omega_s}{15} \quad (13)$$

Where H_0 is the monthly average daily extraterrestrial radiation (MJ/m^2/day); S is the monthly average daily hours of bright sunshine (hours); S_0 is the monthly average day length (hours);

and a and b are empirical coefficients for locations with φ less than 60° (Paulescu et al., 2016). I_{sc} is the solar constant (W/m^2), φ is the latitude of the site (degree, °), δ is the solar declination (degree, °), ω_s is the mean sunrise hour angle (degree, °) for the given month, and D is the number of days of the year. This study chooses the King's Park Meteorological Station as the specific location to calculate the solar irradiation since it is the major observatory in Hong Kong where the government monitors and forecasts weather. Therefore, the data needed in the A-P model (i.e., S and φ) can be reliably accessed from the Hong Kong Observatory (Hong Kong Observatory, 2021; 2022). The parameters used in Eqs. (8) to (13) are summarized in Table 5. As a result, the relationship between daily solar power generation (i.e., E) and daily bright sunshine (i.e., S) is illustrated in Fig. A.1, and the monthly unit solar PV system-generated electricity is demonstrated in Fig. 1. The output of A-P model are summarized in Table A.1.

Table 5. Parameters in daily solar PV electricity generation and A-P model calculation

Facility type	Small-scale PV system	Large-scale PV system
Total installed area	≤ 50 m^2	937.5 – 5,000 m^2
PV module	Polycrystalline panel with a 320-W capacity	
Solar panel yield	16.53%	
Performance ratio	0.75	
Latitude	22.3106°N	
Longitude	114.1743°E	
Elevation	35m	
Daily bright sunshine data	365-days dynamic data	
Solar constant	1,353 W/m^2	
Coefficient a	0.29	
Coefficient b	0.52	
Number of days	365	
System tilt angle	14-22°	
System orientation	South	

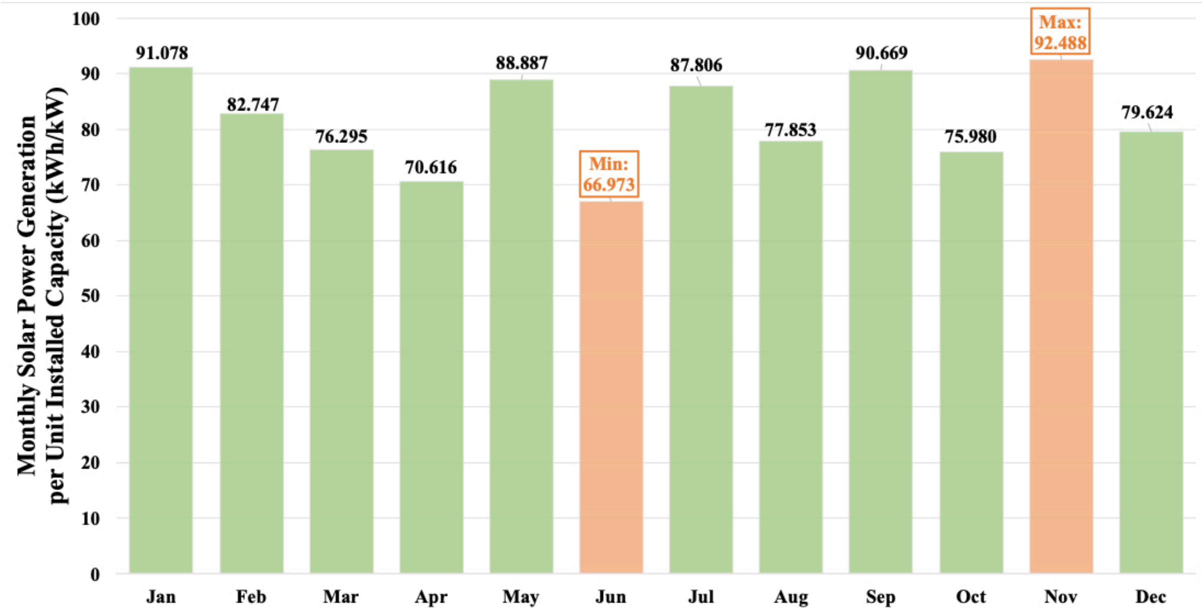


Figure 1. Monthly solar power generation per unit installed capacity

2.1.5. Model validation

After developing the models for PV system CAPEX, cash outflow, cash inflow and electricity generation, statistical metrics are used to test the fitness of aforementioned models. Since all calculations in the expense models (CAPEX, cash outflow and inflow) and electricity generation model are significantly related to LC and A-P models, to simplify the testing procedures, this study validates the aforementioned models by measuring the fitness and accuracy of LC and A-P models using three indicators: (i) mean bias error (MBE); (2) root-mean-square error (RMSE); and (3) mean absolute percentage error (MAPE). The formulas are expressed in Eqs. (14) to (16) (Paulescu et al., 2016; Yang et al., 2018; Kim, Kim and Song, 2021; An, Hong and Lee, 2022; Hiris, Pop and Balan, 2022):

$$MBE = \frac{1}{n*\bar{a}_y}\sum_{y=1}^{n}(a_y - \hat{a}_y) \quad (14)$$

$$RMSE = \frac{1}{\bar{a}_y}\sqrt{\frac{1}{n}\sum_{y=1}^{n}\left(a_y - \hat{a}_y\right)^2} \quad (15)$$

$$MAPE = \frac{100}{n}\sum_{y=1}^{n}\frac{a_y - \hat{a}_y}{a_y} \quad (16)$$

Where a_y is the empirical value provided by (Prado et al., 2019; The International Renewable Energy Agency (IRENA), 2021a; Electrical and Mechanical Service Department, 2022; Himalaya Bir, 2022), $\hat{a}_y$ is the predicted value in this study, $\bar{a}_y$ is the mean of all predicted values, and n is the number of simulations.

Table 6. Results of model validation

Model	MBE	RMSE	MAPE
LC model	3.939%	4.317%	3.717%
A-P model	0.751%	2.358%	0.427%

Regarding the statistical testing result (Table 6), it is concluded that the LC and A-P models applied in this study indicate high prediction accuracy and outstanding fitness of data. After the model validation, the tax-excluded cash outflow (CO) comprising of CAPEX, OPEX and DEX on small- and large-scale PV systems are calculated and demonstrated in Fig. 2.

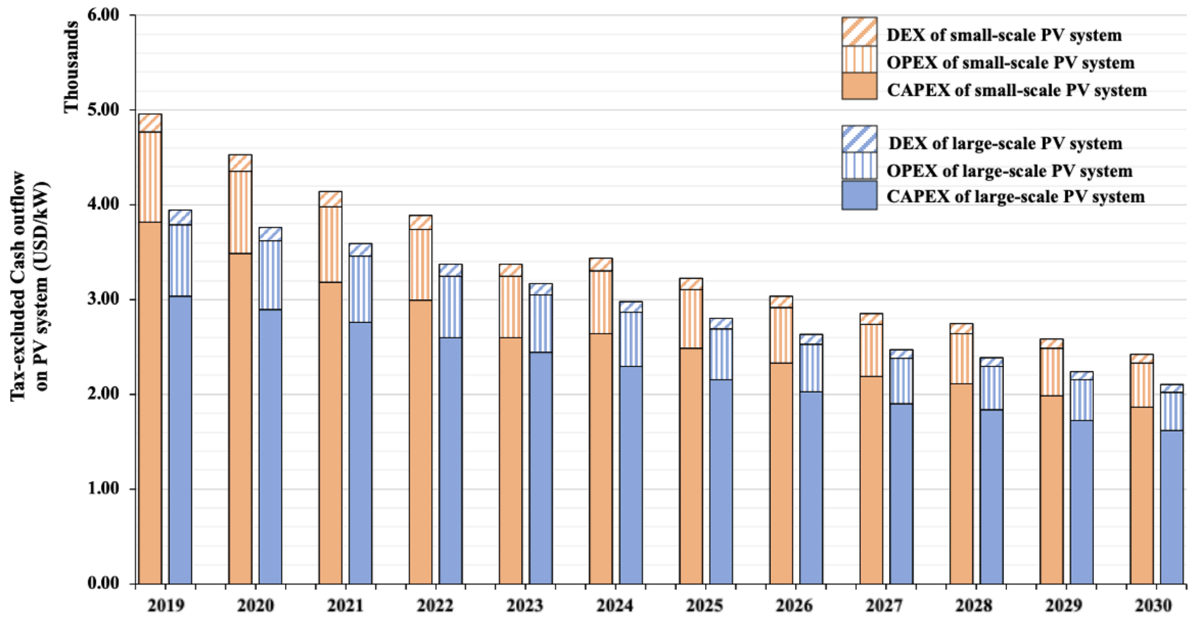


Figure 2. Tax-excluded cash outflow on small- and large- scale PV systems

2.2. Assessment Methods for Optimization Objectives

2.2.1. Discounted payback period (DPB)

DPB measures the number of years needed to break even the initial expenditure of the solar PV project by discounting future cash flows, and can be calculated using Eq. (17) (Maghsoudi and Sadeghi, 2020a; 2020b). This research will set DPB ranging from 6 to 10 years as the optimization objective to calculate the corresponding FiT rates for small-scale PV system.

$$\sum_{t=1}^{Y} \frac{CI_t - OPEX}{(1+i)^t} = CAPEX_t \quad (17)$$

Where the minimum value of Y represents the expected value of DPB and i is the discount rate (%), which is set as 3%, according to the lowest and highest levels (1.3% and 4.3%, respectively) of the real interest rate in Hong Kong from 2015 to 2020 (The World Bank, 2022).

2.2.2. Internal Rate of Return (IRR)

IRR evaluates the expected return on investment, expressed as a percentage (%), to ensure the investors' minimum acceptable rate of return (i.e., hurdle rate) is satisfied (Dhavale and Sarkis, 2018; López Prol and Steininger, 2020). The calculation of IRR is the discount rate needed for NPV to be equal to zero, as indicated in Eq. (18).

$$NPV(IRR) = \sum_{t=1}^{T} \frac{CI_t - CO_t}{(1+IRR)^t} = 0 \quad (18)$$

Where NPV measures the discounted cashflow of the solar PV project considering the time value, expressed as a currency amount (US$). It is widely applied to analyze the financial performance of the renewable energy projects (Adusumilli, Davis and Fromme, 2016; Abdelhady, 2021), and can be calculated by Eq. (19). The investment is considered economically infeasible if $NPV < 0$.

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+i)^t} = \sum_{t=1}^{T} \frac{CI_t - CO_t}{(1+i)^t} \quad (19)$$

As shown in Eq. (18), the calculation of IRR involves a complicated higher-order equation. To solve this problem, linear interpolation method is employed in this study as expressed in Eq.

(20) (Zhao et al., 2016). The optimization objective of IRR is 8% to 12% for large-scale PV systems.

$$IRR = i_1 + \frac{NPV(i_1)}{NPV(i_1)+|NPV(i_2)|}(i_2 - i_1) \tag{20}$$

Where i_1 and i_2 are the two estimated IRRs which satisfy $NPV(i_1) > 0$, $NPV(i_2) < 0$, and $i_2 > i_1$; the smaller the difference between i_2 and i_1, the better. The iteration and optimization of FiT rates are conducted by Matlab with the support of the Financial Toolbox.

2.3. Techno-economic Indicator

Levelized Cost of Electricity (LPOE) is introduced as a techno-economic indicator (US$/kWh), which evaluates the economic merit of the FiT Scheme by considering the potential revenue (i.e., profits from receiving the FiT rate) and savings (i.e., electricity bill savings from self-consuming the PV system-generated electricity after the expiration of FiT Scheme) (Yan et al., 2019). LPOE can be calculated by Eq. (21).

$$LPOE = \frac{\frac{\sum_{t=1}^{U} FiT * G_e^U * (1-r)^{t-1} + \sum_U^T G_e^T * (1-r)^{U-1} * P_e - \sum_{t=1}^{T} CO_t}{\sum_{t=1}^{T} (1+i)^t}}{\sum_{t=1}^{T} \frac{G_e * (1-r)^{t-1}}{(1+i)^t}} \tag{21}$$

G_e^U is the amount of PV-generated electricity sold to utility companies before FiT expires (kWh), and G_e^T is the amount of PV-generated electricity consumed by PV installers after FiT expires (kWh). P_e is the retail electricity price (US$/kWh), it can be residential retail electricity price (RREP) or business retail electricity price (BREP) considering whether the investigating target is a small-scale or large-scale PV system, respectively.

According to the breakdown of charge items data from utility companies (The Treasury Branch of Financial Services and the Treasury Bureau, 2018; CLP Power Hong Kong Limited, 2022a; 2022b; HK Electric Investments Limited, 2022b; 2022a), and the electricity consumption and population data released by the Census and Statistics Department in Hong Kong (Census and Statistics Department, 2021), the RREP and BREP are calculated as summarized in Table 7.

Table 7. Summary of RREP and BREP under two utility companies

Utility companies	RREP (US$/kWh)	BREP (US$/kWh)
CLP	0.17	0.18
HKE	0.14	0.19

2.4. Assumptions on the future trend of FiT rates

Ultimately, this study intends to compare the results of optimized FiT rates with historical (i.e., Phase I), current (i.e., Phase II), and future FiT rates to evaluate the effectiveness and efficiency of the current FiT policy, and provide policy implications regarding the price adjustment and mechanism modification in the future. Towards this end, the future FiT trends have been assumed with justification in this study. Although the future trend of FiT rates after Phase II currently has not been determined and announced by the utility companies yet, it is rather clear that the future FiT rate will mostly be continuously lowered down, or at least maintained at the same rate as the current one. Henceforth, three trends of future FiT rates are summarized in Table 8: (i) Future FiT rate is possible to follow a decreasing trend (i.e., Trend 1), or first decreases and then maintains (i.e., Trend 2), or maintains current rate (i.e., Trend 3); (ii) Digression interval of FiT rate is assumed to remain unchanged as the historical one (i.e., at three-year intervals); (iii) The FiT rate for small-scale PV systems is assumed to decline to that of medium- or large- scale PV systems in Phases II gradually under Trends 1 and 2, which is in accordance with the historical declining trend of FiT rate shown in Table 1 (e.g., the FiT rate of small-scale PV system in Phase II equals that of medium-scale PV system in Phase I, and the FiT rate of medium-scale PV system in Phase II equals that of large-scale PV system in Phase I); and (iv) The FiT rate for large-scale PV systems is assumed to be declined 0.5 HK$/kWh in every digression interval in accordance with its historical declining trend (i.e., 3 HK$/kWh in Phase I and 2.5 HK$/kWh in Phase II).

Table 8. Assumptions on future FiT trends and rates

Trend	Description	Duration	FiT rate for small-scale PV system (US$/kWh)	FiT rate for large-scale PV system (US$/kWh)
Trend 1	Future FiT rate follows a decreasing price trend	2025-2027	0.38 (= Phase II, medium-scale)	0.25 (= 2 HK$/kWh)
		2028-2030	0.32 (= Phase II, large-scale)	0.19 (= 1.5 HK$/kWh)
Trend 2	Future FiT rate first decreases and then maintains	2025-2027	0.38 (= Phase II, medium-scale)	0.25 (= 2 HK$/kWh)
		2028-2030	0.38	0.25
Trend 3	Future FiT rate follows a maintained price trend	2025-2030	0.51	0.32

3. Results and Discussion

3.1. Proposed FiT rate and Policy Implication

Expected FiT rates under proposed mechanisms are summarized in Figs. 3 and 4 respectively, comparing with current FiT rates. As can be seen from Fig. 3, for small-scale PV systems (residential rooftop PV systems), the proposed FiT range which allows the DPB to fall in between 6-10 years under M1 and M2 is the same before 2024. However, the proposed FiT range under M1 begins to narrow down from 2025, and starts to represent the lower bound of the FiT rate that satisfies the target DPB from 2028. In addition to the proposed FiT rates under optimization objectives, the DPB of small-scale PV systems and IRR of large-scale PV systems under historical (Phase I) and current (Phase II) FiT rates are summarized in Table 9.

By comparing the proposed FiT rates under M1 and M2 with historical and current ones, it can be found that although the level of historical FiT rates in 2019 and 2020 is almost aligned with the proposed ones, it is still slightly close to the upper boundary. As can be seen from Table 9, under the historical FiT rate of 0.64 US$/kWh during Phase I, the DPB of small-scale PV systems is 6-7 years in 2019 and 2020, which is regarded as sufficient to reimburse the expenses of installing the small-scale PV systems. Furthermore, the results also imply that the historical

FiT rate in 2021 is a little higher than the proposed range with a DPB of 5-6 years, indicating that the corresponding FiT rate is overpriced, which may cause an unexpected financial burden to the utility companies. Accordingly, the utility companies have lowered the FiT rate to the current one in 2022, which is also considered sufficient to satisfy the installers' expectations on the DPB. If we consider the duration of the current FiT rate (0.51 US$/kWh) implemented in Phase II is the same as that in Phase I (three years), then the DPBs from 2022 to 2024 are 7-8 years, 6-7 years and 6-7 years, respectively.

Table 9. DPB of small-scale PV system and IRR of large-scale PV system under historical (Phase I) and current (Phase II) FiT rates

Classification		FiT Phase I			FiT Phase II		
		2019	2020	2021	2022	2023	2024
Small-scale PV system	DPB (years)	6-7	6-7	5-6	7-8	6-7	6-7
Large-scale PV system	IRR	5%	5%	5%	-1.35%	-2%	-2.5%

The results of proposed FiT rates shown in Fig. 3 expose the deficiency of the current FiT mechanism when comparing the proposed FiT rates under M1 with historical and current FiT rates on one hand, and provide explicit policy implications when analyzing the future trend of FiT rates on the other hand. If we assume that the future FiT rate decreases every three years (i.e., Trend 1), it is revealed that the subsidy rate is insufficient to reimburse the installers' expenses before the scheme expires (2033) from 2027. Furthermore, due to the reason of a shortened DPB required when 2033 approaches mentioned earlier, the expected FiT rate is proposed to be levered up constantly from 2028 to 2030, which results in even higher rates compared to the current ones. Under this circumstance, the future FiT rate is unlikely to guarantee the installers of a profitable investment before the scheme expires. If we assume that the future FiT rate first decreases in 2025 and then maintains the same value (i.e., Trend 2), then the situation is basically the same as the previous assumption. Nevertheless, if we assume that the future FiT rate maintains the current value (i.e., Trend 3), it is then regarded as slightly high to be paid as a subsidy, considering the upper bound of proposed FiT rates is still lower than the current ones. Though a higher FiT rate can encourage more participation, a significantly higher FiT rate will lead to a heavy financial burden on utility companies instead. Besides, the current FiT rate is unlikely to support a profitable investment after 2030. Moreover, when comparing the proposed FiT rates under M2 with historical, current, and future FiT rates, the same conclusion is drawn considering the period 2019 to 2024 since the proposed FiT rates under M1 and M2 are the same during this period. However, from 2025 to 2030, the proposed FiT rates under M2 indicate different characteristics from that of M1. Specifically, the digression nature of FiT rates under M2 is consistent with that of Trend 1, which is applicable in practice if policy reform is considered in Hong Kong. Besides, if Trend 2 is assumed to be the future trend, then the FiT rates are regarded appropriate from 2025 to 2027, but slightly high from 2028 to 2030. However, if Trend 3 is assumed to be the future trend, then the FiT rates are considered significantly overpriced from 2025 to 2030. Particularly, it should be noted that the FiT rate implication is directly formulated under M1, while the contract structure change should be considered under M2.

Therefore, this study has concerned about the profitability of installing small-scale PV systems from the residential sector's perspective if the future FiT rate decreases, and the feasibility of implementing the current FiT mechanism until 2033 from the utility companies' perspective. To address these concerns, this study first recommends the utility companies lower the FiT rate after 2024 and adjust it to fit the proposed range under M1, and lever it up in 2028 to ensure the profitability of late participation. Meanwhile, the utility companies are suggested to consider adopting the most widely used FiT mechanism (M2) as the future subsidizing mechanism for small-scale PV systems. As indicated by the results, the proposed FiT rates under M2 follow a decreasing trend, which is able to facilitate the profitability of investment for installers, and continuously release the financial burden for utility companies simultaneously.

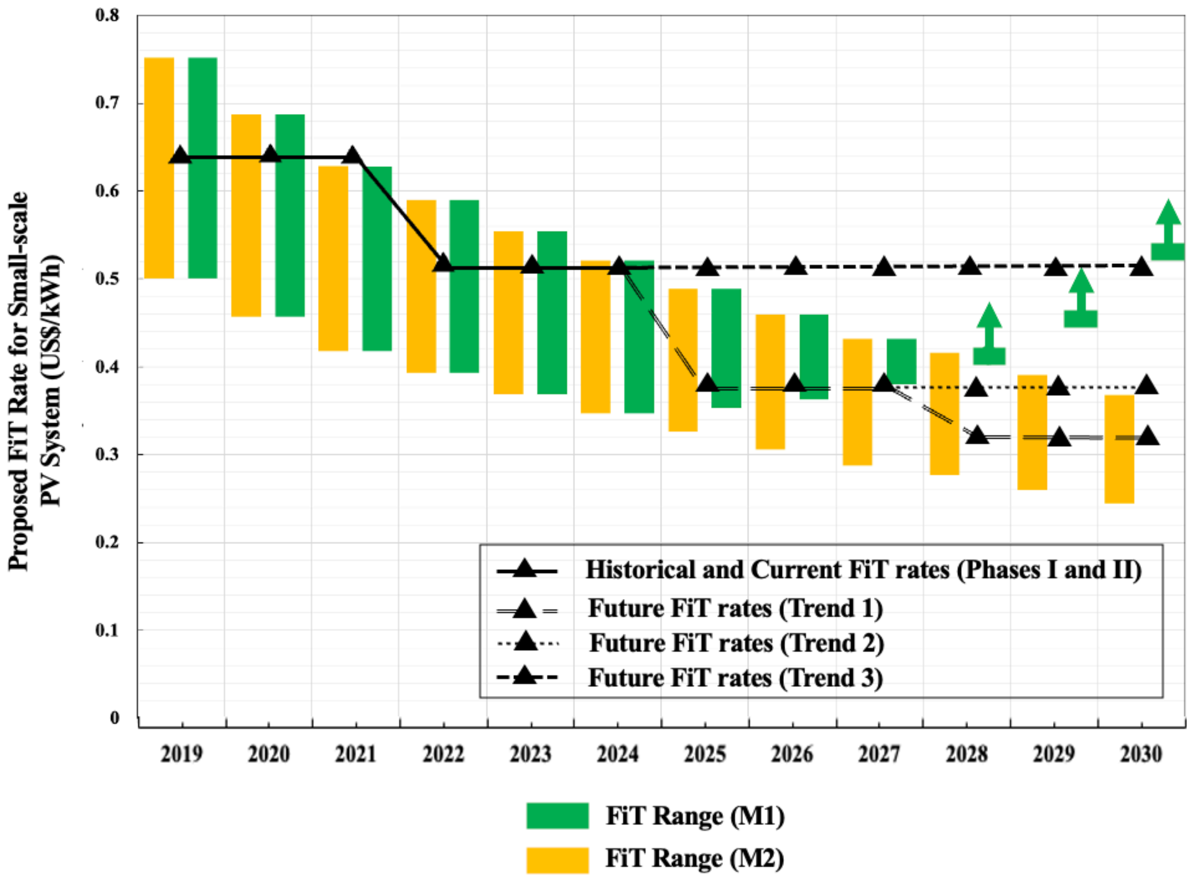


Figure 3. Proposed FiT rate under M1 and M2 for small-scale PV systems

In terms of the large-scale PV systems (Fig. 4), the historical and current FiT rates are found insufficient to guarantee the IRR of the project falls between 8-12% compared with the expected FiT rates proposed under M1, despite assuming which future trend of FiT rate will be following. When comparing historical, current, and future FiT rates with the proposed FiT rates under M2, it is found that the FiT rates under Trends 1 and 2 basically follow the proposed FiT rates under M2, in spite of some deviations in 2028 and 2029 for under Trend 1, as well as in 2030 under Trend 2. If Trend 3 is assumed to be the future trend, then the FiT rates are considered overpriced from 2025 to 2030.

According to Table 9, the IRR of investing in large-scale PV systems is 5% from 2019 to 2021 in Phase I with a FiT rate of 0.38 US$/kWh, and the IRR will drastically drop to negative values in Phase II with a FiT rate of 0.32 US$/kWh from 2022 to 2024 (i.e., -1.35%, -2% and -2.5% respectively). If the utility companies would like to ensure a favorable IRR (i.e., 8-12%) for large-scale PV system investors under the current mechanism, the FiT rate is suggested to be levered up within the range under M1. Nonetheless, significant raise in the FiT rate from 2026 on is essential for late participation's profitability due to the scheme expiration in 2033. Besides, the results have exposed that the historical and current FiT rates, as well as possible future FiT rates are aligned with the proposed FiT rates under M2, which indicates that the utility companies could also consider subsidizing with the relatively lower price, but under a long-term contract.

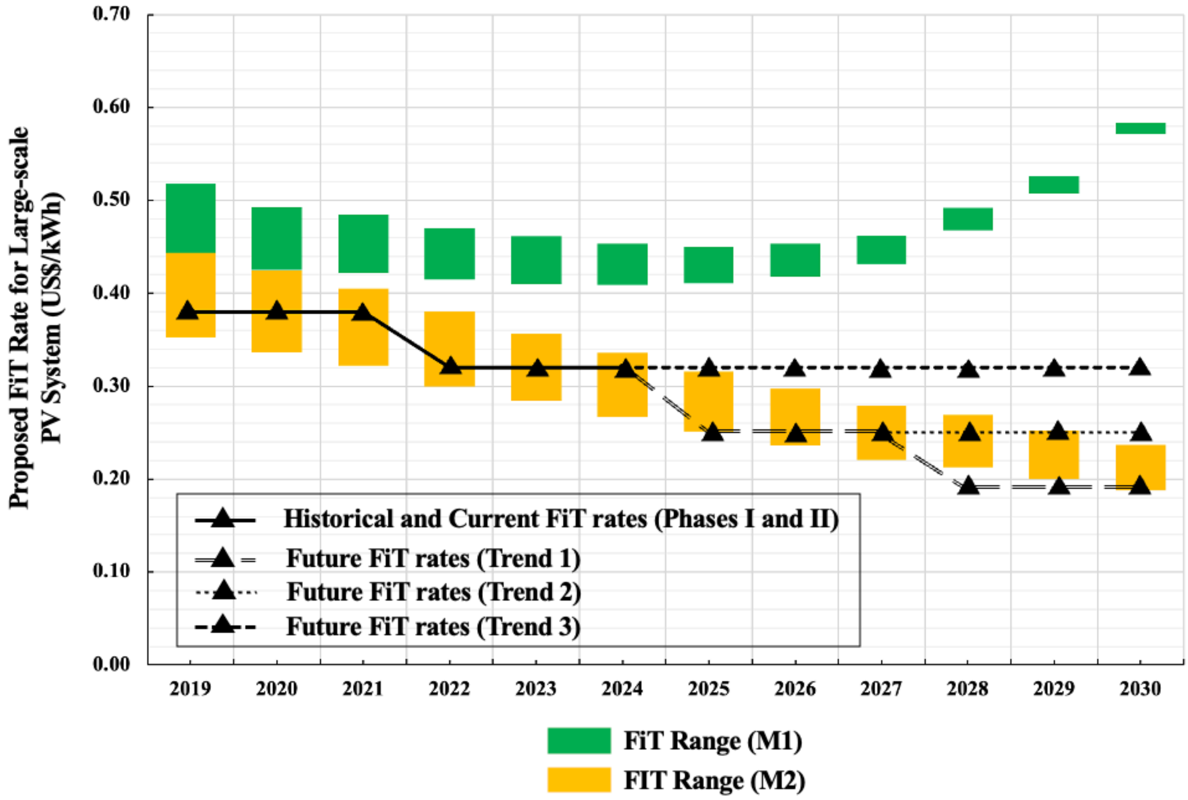


Figure 4. Proposed FiT rate under M1 and M2 for small-scale PV systems

3.2. Techno-economic Analysis

3.2.1. Small-scale PV System

The results and comparisons of LPOE of small-scale PV systems are demonstrated in Fig. 5, considering not only the revenue from participating in the FiT Scheme (i.e., profit from FiT subsidy) but also the electricity bill savings potentially from self-consuming the PV system-generated electricity. It is worth mentioning that since all PV system-generated electricity is going to be sold to the utility companies, so there is no self-consumption of electricity considered in the LPOE model under M2. As for M1 and the current mechanism, LPOE is measured considering the RREP of two utility companies, respectively. Comparatively, LPOE of selling all PV system-generated electricity to the utility companies (i.e., M2) is higher than that of subsidizing-combining self-consuming (i.e., M1) under the same FiT rate. Besides, the LPOE for CLP residential end-users is generally higher than that of HK Electric end-users, owing to the fact that the RREP of CLP is higher than that of HK Electric. Furthermore, all positive results of LPOE reveal that installing small-scale PV systems are profitable under all investigated scenarios, which effectively addresses the financial concern of the PV installers on late participation. Therefore, it is concluded that installing small-scale PV systems is techno-economically profitable in the long-term perspective.

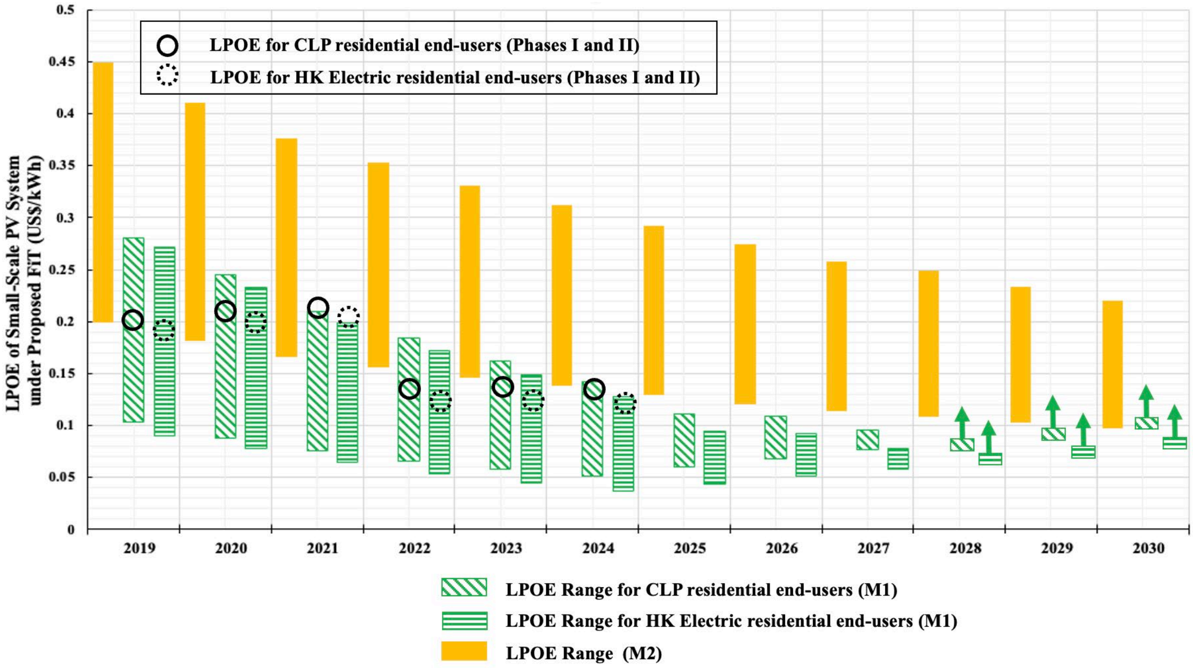


Figure 5. LPOE of small-scale PV systems

3.2.2. Large-scale PV system

The results of LPOE calculations are illustrated in Fig. 6. It is not surprising to find that the historical and current LPOE are significantly lower than the proposed ones owe to the insufficient FiT subsidy considered in this study. Unlike the LPOE of small-scale PV systems (Fig. 5), the LPOE of large-scale PV systems under M1 is found to be within the LPOE range under M2 from 2019 to 2024, and then the LPOE under M1 begin to surpass that of M2 since 2025. Besides, it can be found that the LPOE under M2 is decreasing over time, whereas the LPOE under M1 decreases annually from 2019 to 2025, and begins to increase annually since 2026. This implies that the long-term profitability of subsidizing-combining self-consuming (i.e., M1) is higher than selling all PV system-generated electricity to the utility companies (i.e., M2) under the same FiT rate, although all the LPOE values are positive. In addition, comparatively, the LPOE for CLP business end-users is generally lower than that of HK Electric end-users, owing to the fact that the BREP of CLP is lower than that of HK Electric. It can be concluded in general that, investing in large-scale PV systems is techno-economically profitable as well considering the long-term potential in electricity bill savings.

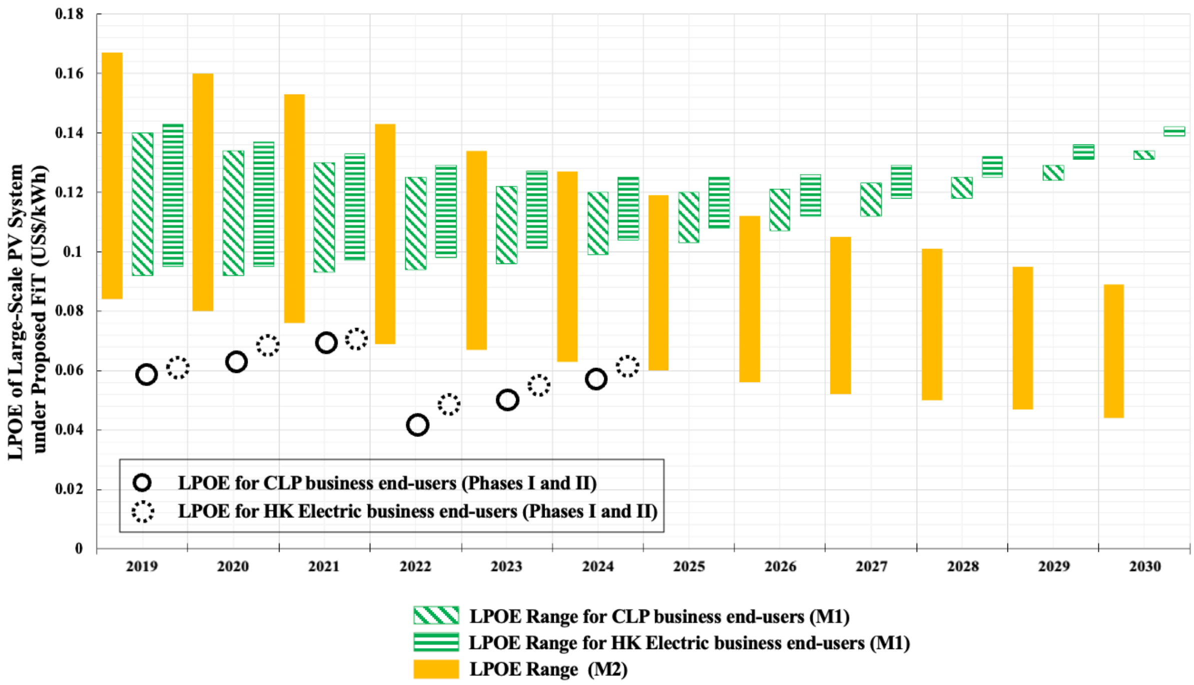


Figure 6. LPOE of large-scale PV systems

3.3. Sensitivity Analysis

Sensitivity analysis has been conducted to evaluate the influences of various factors on the FiT rates. Factors including the price factors (i.e., CAPEX, OPEX and decommission cost), technological factors (i.e., PV system degradation rate and annual solar power generation) as well as economic factors (i.e., discount rate and tax rate) with 10% increase and decrease (i.e., ± 10%) are considered in the sensitivity analysis. Results indicate that, for the small-scale PV system (Fig. 7 (a)), CAPEX and annual solar power generation are the two most influential factors to affect the proposed result of FiT rate under M1 and M2. It is found that a 10% decrease in CAPEX and a 10% increase in annual solar power generation will lead to around 0.035 US$/kWh and 0.032 US$/kWh decrease in FiT rate, respectively, to satisfy the residential PV installers' expectation in terms of DPB while releases the financial burden of utility companies. Besides, less impact of other factors was found on FiT rate, e.g., a 10% decrease in discount rate, OPEX and PV system degradation rate will lead to 0.005, 0.004 and 0.002 US$/kWh decrease in FiT rate, respectively.

In terms of the large-scale PV system (Fig. 7 (b)), it can be seen that the influences of CAPEX and annual solar power generation are as well significant under the condition of guaranteeing investors' favorable IRR, of which a 10% decrease in CAPEX will lead to 0.027 US$/kWh decrease in FiT while a 10% increase in annual solar power generation will lead to 0.024 US$/kWh decrease in FiT. In addition, less impact of other factors was found on FiT rate, e.g., 10% decrease in discount rate, tax rate, OPEX and degradation rate will lead to 0.008, 0.002, 0.002 and 0.001 US$/kWh decrease in FiT, respectively. Nonetheless, decommissioning cost is found to have a negligible impact on FiT rate for both small- and large- scale PV systems. As a conclusion to sensitivity analysis, it is revealed that specific price factor (i.e., CAPEX) and technological factor (i.e., annual solar power generation) are the most influential factors affecting the FiT rates, which sheds light on the policy implications for policymakers, indicating policies such as subsidy policies in CAPEX or incentive policies in facilitating the efficiency of solar PV-generated electricity may enhance the development of FiT Scheme in long run.

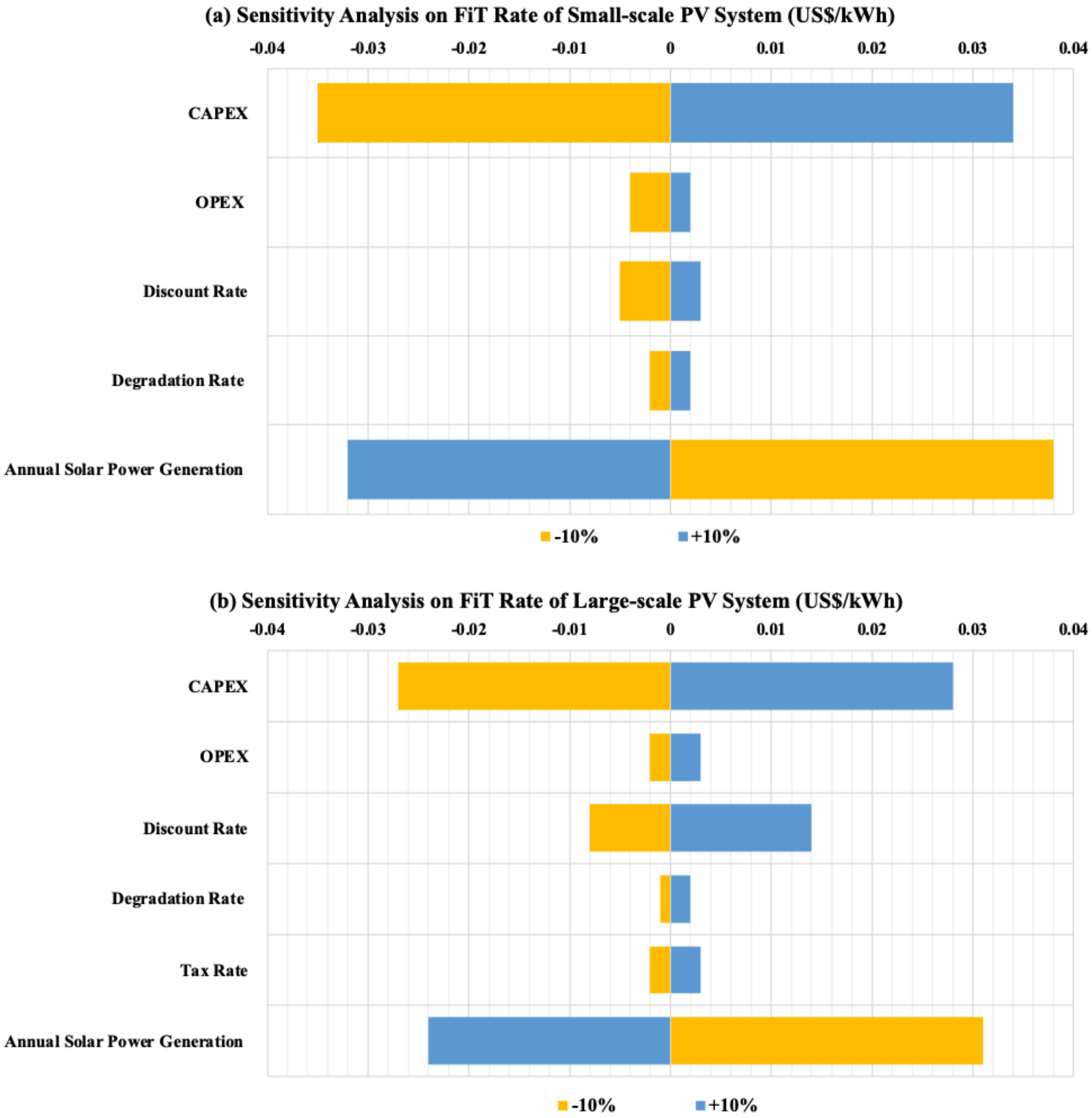


Figure 7. Result of sensitivity analysis

To conclude the result and discussion section, Table 10 summarizes and compares the FiT rate, grid parity year, and LPOE under proposed FiT mechanisms (i.e., M1 and M2) and current mechanism.

Table 10. Summary of conclusions on the FiT rate, grid parity year, and LPOE

Classification	Small-scale PV systems (Residential installers)			Large-scale PV system (Industrial installers)		
	M1	M2	Current	M1	M2	Current
FiT Rate						
2019 – 2025	↓	↓	$$	↓	↓	-$$
2026 – 2030	↑	↓	$$	↑	↓	-$$
Grid parity year						
CLP end-users	2027	2027	2027	2026	2027	Undetermined
HK Electric end-users	2030	2030	2030	2025	2026	
LPOE						
2019 – 2024	M1 < M2		~ M1	M1 ∈ M2		~ M1
2025 – 2030	M1 < M2			M1 > M2		

Note: ↓ denotes "decreasing"; ↑ denotes "increasing"; $$ denotes "higher"; -$$ denotes "lower"; ~ denotes "trend compliance"; ∈ denotes "range coverage".

4. Conclusion

The active promotion of solar PV adoption in Hong Kong indicates the dertermination of the government and utility companies to address the climate change challenge. As such, CLP and HK Electric have commenced FiT Scheme to facilitate residential and industrial PV installations. Although FiT Scheme is considered the most widely adopted policy instrument worldwide, its characteristics vary across countries regarding its payoff, tariff, and contract structures. Due to the late introduction of the FiT Scheme in Hong Kong, the optimization of the FiT mechanism considering PV installers' expectations on investment has not been investigated yet. Therefore, this study has proposed two FiT mechanisms (i.e., M1 and M2) to examine the optimal small- and large-scale FiT rate which fulfills the interest of residential (i.e., DPB) and industrial (i.e., IRR) installers, respectively. Main conclusions of this research are summarized as follows:

- Regarding the effectiveness and efficiency of the current FiT mechanism, the result of this study reveals that the current FiT rate is slightly high for small-scale PV systems, but significantly low for large-scale PV systems.

- If the government and utility companies intend to maintain the current policy mechanism (i.e., M1), it is recommended that for small-scale PV systems, the current FiT rate should be lowered after 2024 and adjusted to fit the proposed range, and then levered up in 2028 to ensure the profitability of late participation. For large-scale PV systems, current FiT rate is suggested to be levered up within the range.
- Regarding policy reform, this study has proposed a modified FiT mechanism (i.e., M2) with a long-term contract structure and conducted comprehending techno-economic analysis to justify its suitability in a long run. This study recommends the government and utility companies consider policy reform and adopt M2 when current policy expires.
- If self-consumption of PV system-generated electricity is considered as energy bill savings in the profitability calculation (i.e., LPOE), the long-term profitability of selling all PV system-generated electricity to the utility companies (i.e., M2) is higher than subsidizing-combined self-consuming (i.e., M1) for residential PV installers. On the other hand, the opposite conclusion is driven for large-scale PV installers.
- Sensitivity analysis indicates that CAPEX, annual solar power generation, and discount rate are influential factors to affect the FiT rate.

This study is believed to fulfill the knowledge gaps in terms of the following aspects. First, regarding the optimization objectives, this study has set explicit physical constraints on the lower and upper bound limits considering economic performance. Different from previous studies that used closed-form equations to calculate only one single fixed FiT rate, the optimization objective inequalities applied in this study allow the optimal FiT rates to be presented in the form of price range, which indicates more flexibility and applicability to policymakers and PV system installers. Second, regarding the research context, instead of conducting a broad investigation on FiT optimization, this study chose Hong Kong as a study model due to its representative characteristics of renewable energy mechanism (i.e., highly market-independent). As a late participant in solar PV development compared to other countries, FiT optimization for Hong Kong alone is still critical despite extensive work have been done in other countries. Although this study is context-specific, it is believed that the proposed models and optimization algorithms can be widely applied to other countries or regions where the development of renewable energy is lagging. Third, regarding the model development, this study has comprehensively considered the parameters and variables that may affect the results of optimization. Compared to previous studies, this study does not make any assumptions about data collection, instead, the database developed by this study is collected from reliable sources and materials. Besides, the consideration of the learning curve effect in the PV investment model and the model validation justifies the reliability and applicability of the results obtained in this study. Last, the adoption of DPB to optimize the FiT rates for small-scale PV systems is believed to be more reliable than the way that the government announced (i.e., PP), which has taken the time value of the cashflow into consideration, and is regarded as a more superior approach. Nonetheless, the limitation of using DPB is also identified since it ignores the cashflow after reaching the PP. Fortunately, this study has addressed this issue by analyzing a lifetime techno-economic performance using LPOE. Future studies are recommended to consider this limitation when utilizing DPB.

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Appendix

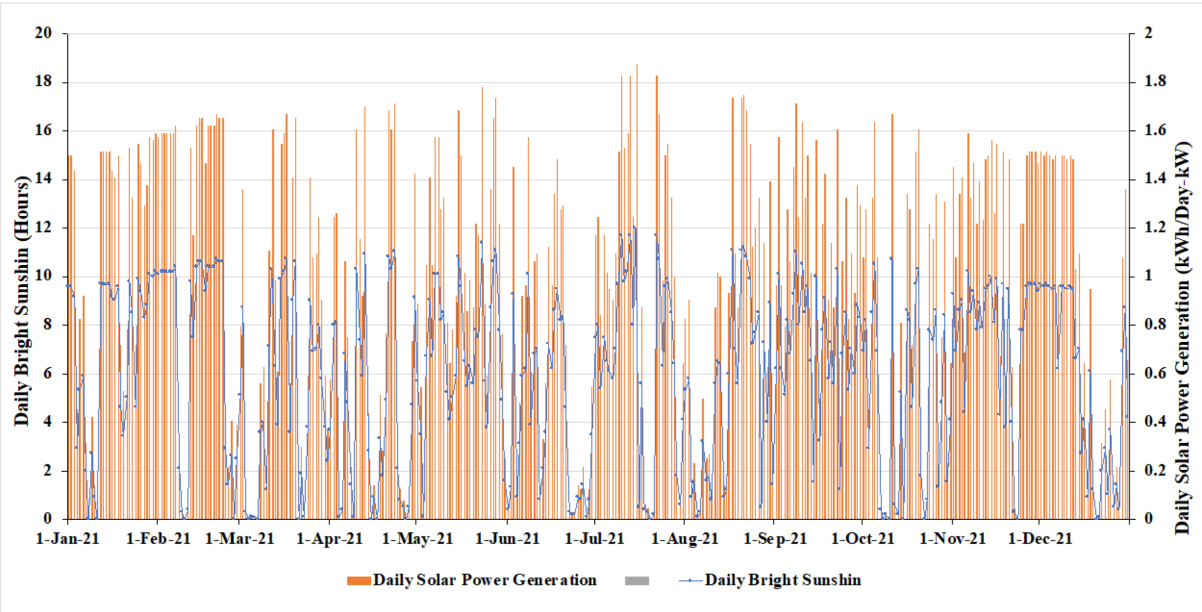

Figure A.1. relationship of daily solar power generation (i.e., E) and daily bright sunshine (i.e., S)

Table A.1. Parameters in the A-P model

Month	H (MJ/m^2/Day)	H_0 (MJ/m^2/Day)	H/H_0	S (Hours)	S_0 (Hours)	S/S_0
Jan	17.063	33.568	0.508	7.0	12.0	0.583
Feb	17.163	32.783	0.524	7.3	11.9	0.615
Mar	14.293	33.651	0.425	4.9	12.0	0.411
Apr	13.670	33.841	0.404	4.4	12.1	0.363
May	16.652	33.313	0.500	6.9	12.0	0.576
Jun	12.965	32.998	0.393	4.1	11.9	0.342
Jul	16.450	33.401	0.492	6.6	12.0	0.547
Aug	14.585	33.627	0.434	5.2	12.0	0.429
Sep	17.552	33.881	0.518	7.3	12.1	0.604
Oct	14.234	33.333	0.427	4.8	12.0	0.401
Nov	17.905	32.993	0.543	7.8	11.9	0.652
Dec	14.917	33.375	0.447	5.6	12.0	0.463

Nomenclature

A. Acronyms

FiT	Feed-in Tariff
DPB	Discounted payback period
IRR	Internal rate of return
LPOE	Levelized profit of electricity
RES-E	Renewable energy sources for electricity
PV	Photovoltaic
SCAs	Scheme of Control Agreements
CLP	China Light & Power Company Syndicate
HK Electric	Hong Kong Electric Company
M1	Mechanism 1
M2	Mechanism 2
NPV	Net present value
ROI	Return of investment
PP	Payback period
DPB	Discounted payback period
CAPEX	Capital expenditure
LC	Learning curve
OPEX	Operating expense
DEX	Decommissioning expense
O&M	Operation and maintenance
A-P	Angstrom–Prescott
MBE	Mean bias error

RMSE
Root-mean-square error

MAPE
Mean absolute percentage error

CI
Cash inflow

CO
Cash outflow

RREP
Residential retail electricity price

BREP
Business retail electricity price

B. List of Symbols

C_c
Average global unit CAPEX of the PV system in 2010 (US$/kW)

C_i
Average global unit CAPEX of the PV system in 2020 (US$/kW)

P_c
Cumulative solar PV installed capacities in 2010 (MW)

P_i
Cumulative solar PV installed capacities in 2020 (MW)

β
Slope of the function

LR
Learning rate of LC (%)

CO_t
Cash outflow of PV system throughout its lifetime (US$)

$CAPEX_t$
Unit capital expense at installation year t (US$/kW)

DEX_T
Decommissioning cost at the ending year of PV system's service T (US$/kW)

I
Installed capacity of PV system (kW)

TAX
Tax expense for large-scale PV installers (US$)

CI_t
Cash inflow of revenue by participating the FiT Scheme (US$)

G_e
PV system electricity generation (kWh)

FiT
FiT rate (US$/kWh)

U
The year when FiT Scheme expires

E
Daily PV system electricity generation (kWh/day)

H
Monthly average daily global radiation (MJ/m^2/day)

A | Total area of solar panels (m^2)
γ | Solar panel yield (%)
PR | Performance ratio
H_0 | Monthly average daily extraterrestrial radiation ($MJ/m^2/day$)
S | Monthly average daily hours of bright sunshine (hours)
S_0 | Monthly average day length (hours)
a and b | Empirical coefficients for locations with φ less than 60°
I_{sc} | Solar constant (W/m^2)
φ | Latitude of the site (degree, °)
δ | Solar declination (degree, °)
ω_s | Mean sunrise hour angle (degree, °)
D | Number of days of the year
i | Discount rate (%)
G_e^U | Amount of PV-generated electricity sold to utility companies before FiT expires (kWh)
G_e^T | Amount of PV-generated electricity consumed by PV installers after FiT expires (kWh)
P_e | Retail electricity price (US$/kWh)

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