City and Environment Interactions 10 (2021) 100056

Contents lists available at ScienceDirect

City and Environment Interactions

journal homepage: www.elsevier.com/locate/carcint

Feed-in tariff policy in Hong Kong: Is it efficient?

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ARTICLE INFO

Keywords:
Energy policy
Solar PV
Intermittency
Prosumers
Optimization

ABSTRACT

In this paper, we investigate whether the current feed-in tariff (FIT) policy in Hong Kong SAR can ensure the development of solar photovoltaic (PV) systems. To do so, we rely on the calibration of a dynamic model of household optimization. We account for the optimal residential consumer behavior under stochastic solar radiation to derive a break-even FIT, which we compare to the one in Hong Kong. Results show that the current FIT policy does not provide sufficient incentives to guarantee the development of solar PV installations. We calculate the break-even FIT for various solar PV and battery installation costs, payback periods, equipment lifetime, as well as the discount rate. We conclude by making recommendations for an efficient FIT policy in Hong Kong.

1. Introduction

In the discussion of climate change policy and economics, the four pillars to reach carbon neutrality are often referred to illustrate priorities for policy design and climate action roadmap [4].[1] Among the four, zero-emission electricity generation presents an important milestone in transitioning to decarbonized energy and fuel mix. As 27% of global electricity consumption comes from the residential sector (see [6]), renewable electricity investments at the household level can significantly contribute to this objective. Effective storage capacity and demand management offer new opportunities for flexibility (see [7,2,12]) to tackle the challenges of intermittent renewable electricity generation [18]. However, investments in solar PV panels and battery systems are costly. To help households cover the investments costs, feed-in tariff (FIT) is a widely discussed policy initiative to encourage expansion of renewable energy systems at different scales. It is defined as a policy (mechanism) that decides the purchase price (tariff) and period of electricity generated by each kind of distributed energy resources [10].

Since April 2017, such a mechanism has been in place in Hong Kong. Under the scheme, “people who install solar PV or wind systems at their premises can sell the renewable energy (RE) they generate to the power companies at a rate as high as about five times more than the normal electricity tariff rate” (Hong Kong government website[2]). In this paper, we investigate whether the FIT policy is efficient. We measure to which extent the policy can generate windfall effects or, on the contrary, can provide insufficient incentives to guarantee the development of PV and wind systems once the intermittency of such systems is accounted for. To do so, we rely on the calibration of a dynamic model of household optimization (*i.e.*, we account for the optimal household behavior) to derive the break-even FIT and compare it to the current FIT in Hong Kong. Results show that the current FIT scheme in Hong Kong is not sufficient to cover for the investment cost in solar panels. To develop solar PV capacity in Hong Kong, our results suggest that the FIT needs to be significantly higher.

Previous studies have analyzed the economic implications of a FIT policy in Hong Kong before such a policy has been implemented. Li et al. [8] evaluate a FIT scheme that consists in selling the electricity to the grid at the buying price. This study estimates the payback period for a PV system on an institutional building (12 PV panels, 80 Watt peak (Wp) each) in Hong Kong by computing the ratio between the cost of PV installation and the annual electricity generated valued at the average commercial electric tariff. The results indicate that this simple monetary payback is 72.5 years, which is reduced to 61.4 years when the benefits from carbon trading are included. Song et al. [17] use the levelized cost of electricity (LCOE) approach. They compute the gap between the LCOE of PV electricity generation and grid electricity tariff. The study then estimates the feed-in premium (FIP) above

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[1] The four pillars of decarbonization are (i) Decarbonized electricity production; (ii) Electrification with an increased reliance on clean electricity and a switch to cleaner fuels; (iii) Improved efficiency and reduced waste; and (iv) Preservation/increase of carbon sink, e.g., forests and other vegetation and soils.

[2] https://www.gov.hk/en/residents/environment/renewable/feedintariff.htm.

https://doi.org/10.1016/j.cacint.2021.100056

the average grid tariff that covers this gap within 20 years and makes it acceptable for private agents to invest in PV panels. Based on gains in competitiveness that significantly reduce PV panels installation costs over time, the results reveal a decreasing FIP from 0.51 HKD per kWh in 2016 to 0.23 HKD per kWh in 2020.

Moreover, Rigter and Vidican [15] compute an optimal FIT, adjusted for different regions in China, by setting the Net Present Value of solar PV investment equal to zero. This FIT for residential solar PV is, on average, calculated to yield USD0.80 per kWh. However, the FIT can be much lower for sun-rich regions (*e.g.,* USD0.44 per kWh in region of Qinghai).

None of these studies focus on the current FIT policy in Hong Kong. They rely on different methods (payback period, LCOE, net present value), which do not include household dynamic optimization. In addition, even though only a few studies have discussed the current FIT policy, they did not analyze the policy's economic implications. (see [1,9,19]). We attempt to fill the gap by calibrating a household's dynamic optimization model using current Hong Kong data to derive the break-even FIT.

In Hong Kong, the FIT scheme seeks to promote the development of RE under the current Scheme of Control Agreements, which were signed between the Government and the respective two power companies in April 2017. Generating capacities of up to 1 megawatts (MW) connected to the company's grid are eligible for prescribed FIT rates. Any units of electricity used at the premises will be purchased from the company's grid at the prevailing tariff rates while FIT will be paid for all units of electricity generated by the RE systems throughout the RE systems' project life until the end of 2033. The FIT rates of the FIT Scheme are:

1. 5 HKD per kWh for a generating capacity less than 10 kW,
2. 4 HKD per kWh for a capacity between 10 kW and 200 kW,
3. 3 HKD per kWh for larger capacities (up to 1 MW).

From 2033 on, generated electricity will belong to the RE system owner. This implies that self-consumption will be possible and sales to the company's grid will be made at the prevailing tariff rates as the electricity purchase. In addition, Hong Kong has been planning a mass roll-out of smart meters from 2020 to 2025. This means that real-time dynamic pricing will be adopted in Hong Kong that will affect the tariff rates of the electricity used at the premise. Converted to USD, FIT in Hong Kong are between 0.39 USD/kWh and 0.64 USD/kWh.[3] This is a lot higher than the FIT prevailing in the neighboring countries. According to the East Forum [5], FITs in the region range from 0.06 to 0.014 USD/kWh in Indonesia to 0.2 USD/kWh in Thailand. They are 0.15 USD/kWh in Vietnam, 0.11–0.17 USD/kWh in Malaysia and 0.167 USD/kWh in the Philippines.[4] Finally, according to the bureau of China's National Development and Reform Commission [13], residential solar PV systems are entitled to a FIT of 0.18 RMB/kWh hence 0.028 USD/kWh in China.[5] This suggests that the Hong Kong authorities strongly support residential solar PV development compared to the neighboring countries.

We appraise the welfare gains from installing solar PV systems for an optimizing household living in a flat in a high-rise building as it is the common type of dwelling in Hong Kong. The household optimizes with respect to electricity consumption, storage and grid purchases/sales under stochastic intermittency and diurnal and seasonal variations in solar energy. As the life-time of such systems is typically 20 years, we consider 2 different phases over which the household will own the PV system and optimize its use. Phase 1 corresponds to the current policy, with all the electricity generated from the solar PV system sold to the grid and no time-of-use (TOU) pricing initially. At some point in time during this phase, there is a smart meter roll-out and the household can take advantage of TOU pricing. Phase 2 starts at the end of the current FIT policy when the household has the ability to use part of the electricity from the solar panels for its own consumption and/or store it if equipped with a storage device. To account for household behavior, we construct a 4-period model for each phase under solar generation uncertainty (*i.e.*, intermittency) that is fully microfounded and provides optimal electricity consumption, grid sales/purchases, and storage in time.

We investigate whether the current Hong Kong FIT scheme is efficient in the sense that it provides sufficient incentives for PV development without generating windfall effects. To do so we derive the efficient FIT and compare it with the existing one for a specific PV panel capacity (namely, 3kWp installed power), that would be standard on the facades of high-rise buildings. If the efficient FIT is (significantly) higher than the current scheme, it means that PV is not likely to develop in Hong Kong. If it is significantly lower, this implies that the current scheme generates free-riding and windfall effects. We define the efficient FIT scheme as the level of FIT that is exactly sufficient to avoid welfare losses of installing a PV system. We use a calibrated version of the model to compute these welfare losses. Electricity consumption simulated data are used to calibrate the parameters of the household utility function for different periods within a day and different seasons. Real-time solar electricity generation is used to determine the parameters of Weibull distribution accounting for intermittency.

In the next section, we explain how to model the profitability of solar panels for a household and derive the expression for the efficient FIT. We calibrate this model on Hong Kong data in Section 3. The results are presented in Section 4. Section 5 presents a sensitivity analysis. The results are discussed and the study is concluded in Section 6.

2. Modeling PV profitability

Let us assume that the household benefits from the current FIT policy for N_1 years, *i.e.*, until 2033. Under the current policy, all electricity generated from the solar panels is sold to the grid. Before the end of this FIT policy in 2033, Hong Kong has planed a mass roll-out of smart meters from 2020 to 2025. Let N_d, with $N_d < N_1$, denotes the number of years between the PV installation and the time when the household's meter is replaced with a smart meter. Hence, we assume that for N_d years, the electricity tariff is fixed, and thus, there is no TOU pricing. Following this time period, the household will be charged a TOU price. However, from the point of view of PV profitability, TOU pricing plays no role in the periods between N_d and N_1 as it only affects the electricity purchases. Therefore, we only need to solve for two phases: (i) the current FIT policy from 0 to N_d and (ii) after the end of the FIT policy from N_1 to N_2.

At the end of the current FIT policy (*i.e.*, after N_1 years), electricity generated from the solar panels will belong to the household. The household can feed the excess generation into the public grid but is not obliged to do so. Then, the household will have the ability to consume part of the electricity from the solar panels and/or store it if equipped with a storage device. Hence, TOU pricing will no longer be innocuous for PV profitability. Let N_2 (with $N_1 < N_2$) stand for the lifetime of the solar panels.

Finally, we assume a unit solar PV system cost of f and a discount rate of r, and with it, a discount factor of $\rho = 1/(1 + r)$.

This framework consists of a combination of two different models: (i) the one corresponding to the current policy up to N_1, and (ii) the one that is valid for the remaining lifetime following the end of the

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[3] Exchange rate 7.75 HKD/USD (January 01, 2021).

[4] Note, however, that the quota for solar PV for FIT in Malaysia is already finished, and the new deployment of solar PV will be in the form of large-scale solar, above 1 MWp at capacity.

[5] Exchange rate 6.5 RMB/USD (December 29, 2020).

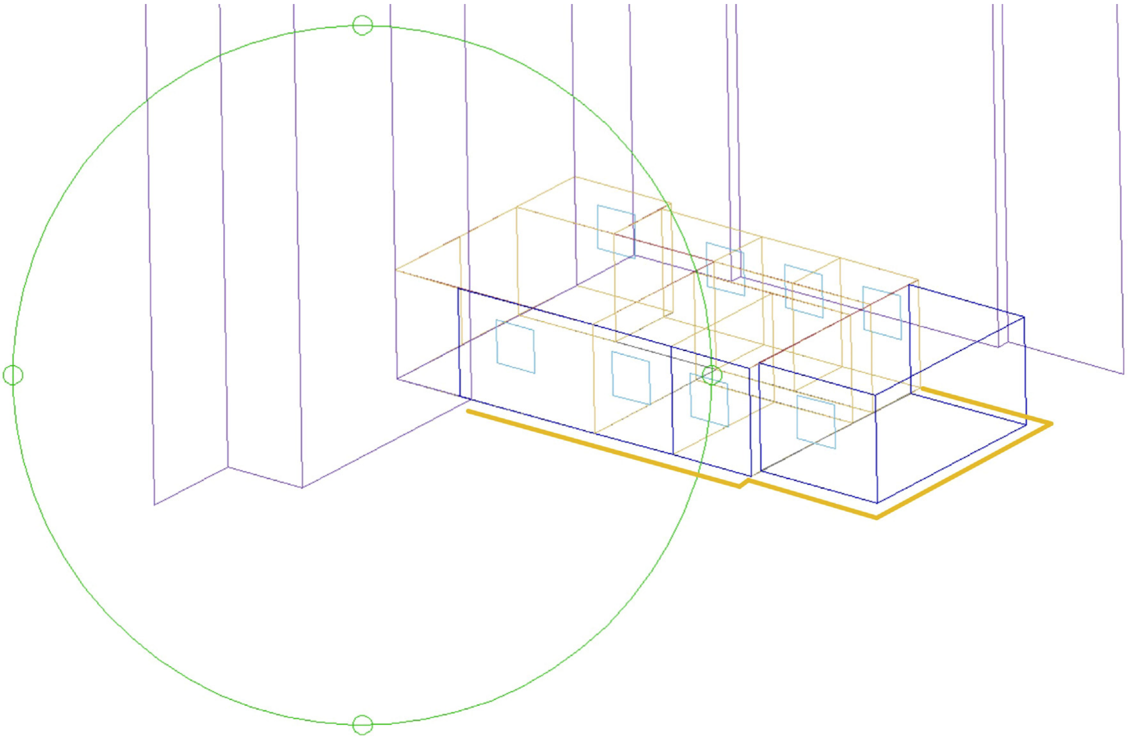

Fig. 1. 3D Schematic of Harmony apartment (position of PV on building Facade shown in yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

current FIT policy, that is, from N_1 to N_2. The change in welfare, ΔW, due to PV system installation is:

$$\Delta W = \sum_{j=1}^{N_1} \Delta W^I \rho^j + \sum_{j=N_1+1}^{N_2} \Delta W^{II} \rho^j$$

where ΔW^I and ΔW^{II} stand for the changes in welfare during phase 1 and phase 2, respectively.

2.1. Phase 1: the model for the current policy

We consider a four-period (night, morning, afternoon and evening) model in which a representative household maximizes its welfare. At each period "i", the household has a gross utility u_i from electricity consumption. We assume standard characteristics for the utility function: $u_i' > 0$ and $u_i'' < 0$, where u_i' and u_i'' are first- and second-order derivatives of the utility function. We first compute the welfare of a household equipped with a PV system and then compare it with the welfare of an unequipped household to measure the required size of the public support.

We assume that the household has $\bar{K}$ capacity of installed solar panels that generates $x\bar{K}$ and $y\bar{K}$, where x and y represent the weather conditions in periods 2 and 3 within a day, respectively. There is no sun and no solar electricity generation during periods 1 and 4, therefore the weather conditions are neglected in these periods. We denote the associated cumulative distribution functions by F^x and F^y. We focus on a specific scheme of FIT in which the FIT, τ, is paid for each units of electricity generated and sold; *i.e.*, $\tau x\bar{K}$ and $\tau y\bar{K}$ are received by the household. In addition, during the FIT policy period, any units of electricity consumed by the household at each period i is purchased from the grid, g_i, and charged at the grid tariff p_i. Therefore, in phase 1, electricity purchases from the grid are completely independent from solar panel installations as self-consumption is not allowed.

A household that is equipped with a PV system solves the following program:

$$W_{pv}^I = \max_{\{g_i\}} u_1(g_1) - p_1 g_1 + \int_0^1 \Big[u_2(g_2) - p_2 g_2 + \tau x\bar{K} + \int_0^1 [u_3(g_3) - p_3 g_3 + \tau y\bar{K} + u_4(g_4) - p_4 g_4] dF^y \Big] dF^x, \tag{1}$$

with $i = 1, 2, 3, 4$. Electricity consumption does not depend on whether the household is equipped with a PV system. Hence, the change in welfare for phase 1 coming from to the installation of the PV equipment is simply the following:

$$\Delta W_{pv}^I = \tau\bar{K}\left(\int_0^1 x dF^x(x) + \int_0^1 y dF^y(y)\right). \tag{2}$$

Do note that neither TOU pricing nor the possibility of storage has any effect on this welfare change.[6]

2.2. Phase 2: After the end of FIT policy

A household equipped with a PV system, smart meter and a storage device maximizes the following welfare:

$$\begin{aligned} W_e^{II} = \max_{\{s_l, g_i\}} u_1(g_1 - s_1) - p_1 g_1 + \int_0^1 [u_2(x\bar{K} + g_2(x) - s_2(x) + \phi s_1) - p_2 g_2(x) \\ + \int_0^1 [u_3(y\bar{K} + g_3(x,y) - s_3(x,y) + \phi s_2(x,y)) - p_3 g_3(x,y) \\ + u_4(g_4(x,y) + \phi s_3(x,y)) - p_4 g_4(x,y)] dF^y] dF^x, \text{s.t.} s_l \leqslant \bar{s}, \ \ s_l \geqslant 0. \end{aligned}$$

with $l = 1, 2, 3$ and ϕ is the round-trip efficiency of the battery.

Contrary to the optimization problem for phase 1, the change in welfare is largely dependent on electricity consumption and storage.

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[6] The welfare of a household equipped with a storage device would be: $W_e^I = \max_{g_i, s_i} u_1(g_1 - s_1) - p_1(g_1) + \int_0^1 \left[u_2(g_2 - s2 + \phi s_1) - p_2(g_2) + \tau x\bar{K} + \int_0^1 [u_3(g_3 - s_3 + \phi s_2) - p_3(g_3) + \tau y\bar{K} + u_4(g_4 + \phi s_3) - p_4(g_4)] dF^y \right] dF^x$,
where ϕ is the round-trip efficiency of the storage device. The change in welfare would still reduce to equation (2)).

We solve the problem recursively (see p. 8–9 Durmaz et al. [3] for the full resolution). Over phase 2, the welfare of the household is then

$$W_e^{II*} = u_1(g_1^{II*} - s_1^*) - p_1 g_1^{II*} + \int_0^1 [u_2(x\bar{K} + g_2^{II*} - s_2^* + \phi s_1^*) - p_2 g_2^{II*} + \int_0^1 [u_3(y\bar{K} + g_3^{II*} - s_3^* + \phi s_2^*) - p_3 g_3^{II*} + u_4(g_4^{II*} + \phi s_3^*) - p_4 g_4^{II*}]dF^y]dF^x$$

where the superscript * sign denotes the levels at the optimum.

The welfare change during phase 2 then depends on whether the household installed a battery together with solar PV. On the basis of the strong will of the Hong Kong authorities to put dynamic pricing in place before the FIT policy is over, we assume that smart meters are installed regardless of the installation of the battery. Two cases can be studied depending on the equipment the household owns.

Case a: the household only installs a solar PV system (subscript “pv”) *vs* the household does not install any equipment (subscript “0”)

We compute the welfare change for phase 2 by comparing the welfare in case of solar PV equipment but no battery with the welfare in case of neither the solar PV system nor battery:

$$\Delta W_{pv,0}^{II} = W_{pv}^{II^*} - W_0^{II^*}$$

where $W_{pv}^{II^*}$ is a special case of W_e^{II*} for $s_l = 0, l = 1, 2, 3$ and $W_0^{II^*}$ is a special case of W_e^{II*} for $\bar{K} = 0$ and $s_l = 0$.

Case b: the household installs a solar PV system alongside with a battery (subscript “e”) *vs* the household does not have any equipment (subscript “0”)

Welfare change for phase 2 is obtained by comparing the welfare with full equipment in phase 2 with the welfare with neither the PV nor batter storage systems in phase 2:

$$\Delta W_{e,0}^{II} = W_e^{II^*} - W_0^{II^*}$$

2.3. Efficient FIT

Case a: In this case, the corresponding welfare change requires to account for the welfare changes during the two phases. Welfare change during phase 1 (*i.e.*, for N_1) periods is:

$$\sum_{j=1}^{N_1} \rho^j \Delta W_{pv}^I = \frac{1 - (1+r)^{-N_1}}{r} \Delta W_{pv}^I$$

Welfare change during phase 2 (*i.e.*, for $N_2 - N_1$ periods) is:

$$\sum_{j=N_1}^{N_2} \rho^j \Delta W_{pv,0}^{II} = \frac{1 + r - (1+r)^{N_1 - N_2}}{r} (1+r)^{-N_1} W_{pv,0}^{II^*}$$

The total welfare change is then:

$$\Delta W_{pv,0} = \frac{1 - (1+r)^{-N_1}}{r} \Delta W_{pv}^I + \frac{1 + r - (1+r)^{N_1 - N_2}}{r} (1+r)^{-N_1} \Delta W_{pv,0}^{II^*}$$

that needs to be compared with the cost of PV system, hence the efficient FIT level:

$$\tau_{pv,0}^* = \frac{-\frac{1+r-(1+r)^{N_1-N_2}}{r}(1+r)^{-N_1}\left[W_{pv}^{II^*} - W_0^{II^*}\right] + f\bar{K}}{\frac{1-(1+r)^{-N_1}}{r}\bar{K}\left(\int_0^1 x dF^x(x) + \int_0^1 y dF^y(y)\right)}$$

Case b: In a similar way, the total welfare change due to solar panels and storage equipment is:

$$\Delta W_{e,0} = \frac{1 - (1+r)^{-N_1}}{r} \Delta W_{pv}^I + \frac{1 + r - (1+r)^{N_1 - N_2}}{r} (1+r)^{-N_1} \left[W_e^{II^*} - W_0^{II^*}\right]$$

that needs to be compared with the cost of PV system and battery, hence the efficient FIT level:

Table 1
Tariff per kWh.

Quarter	Tariff (per kWh)
Dec-Feb	0.90
Mar-May	0.92
Jun-Aug	0.96
Sep-Nov	0.94

$$\tau_{e,0}^* = \frac{-\frac{1+r-(1+r)^{N_1-N_2}}{r}(1+r)^{-N_1}\left[W_e^{II^*} - W_0^{II^*}\right] + f\bar{K} + s}{\frac{1-(1+r)^{-N_1}}{r}\bar{K}\left(\int_0^1 x dF^x(x) + \int_0^1 y dF^y(y)\right)}$$

where *s* is the cost of the storage device.

3. Data and calibration

3.1. Data

In our analysis, we consider a high-rise apartment block in Hong Kong. This dwelling is a three-bedroom apartment located on the 10th floor of a 20-floor Harmony public housing block with 73 m^2 of floor area. The modeled apartment is located in the southeast quadrant of the harmony double cross-shaped floor plan. The apartment’s window area of 8 m^2 provides a window-to-floor (area) ratio of 0.11. The dwelling is constructed from medium-weight concrete with 100 mm thick walls.

The main living room and bedrooms are equipped with air conditioners (AC), leading to 75% of the air-conditioned floor area. On a weekday (weekends) AC in the living room operates from 4 pm (9 am) to midnight, AC in the bedroom runs from 10 pm to 6 am. AC works from May to October inclusive, with a thermostat set point of 26 °C. The coefficient of performance (COP) of the AC is 4.

The 3 Kw peak PV system covers 18 m^2 of the south and east facade of the apartment walls (see Fig. 1). The PV panels are applied to the south walls of the living room, bedroom 1 and 2, and the south and east facades of the master bedroom. The PV panels occupy 27% of these wall facades.

The total annual electricity consumption is 3919 kWh, with AC consumption of 725 kWh accounting for 18% of the total. After the inverter losses, the PV system generates 995 kWh, equivalent to 25% of consumption. The apartment’s PV system would produce less than a rooftop version because of the (non-optimum) placement of the PV panels on the vertical walls and the shading of the south facade in the afternoon by the other apartments in the block. The net import of electricity during the period in concern is 3221 kWh. 698 kWh of PV generated electricity (18% of the total consumption) are consumed on-site. Finally, 297 kWh are exported to the grid.

The simulation is run using the standard City University of Hong Kong Energy Plus weather file.

3.1.1. Cost of equipment

For preliminary assessment, both utilities in Hong Kong provide some ballpark parameters of a typical 1 kW solar PV system.[7] According to this reference scenario, a typical 1 kW solar PV system’s construction cost is estimated to lie between 30,000 HKD and 50,000 HKD. The reference points to the fact that these parameters are subject to site conditions and the renewable energy power system’s design. Because we consider facade solar panels, we expect the construction costs to be higher. Therefore, while we keep these reference values in the analysis, we provide a broader range of costs when conducting sensitivity analysis (see Section 5).

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[7] See, for example, https://www.hkelectric.com/en/customer-services/smart-power-services/feed-in-tariff-scheme.

Table 2
TOU tariff rates.

Dec-Feb	Residential tariff	0.9		**Jun-Aug**	Residential tariff	0.96	
	% increase from off peak price	82			% increase from off peak price	82	
	off peak	price	0.64		off peak	price	0.68
	on peak	price	1.16		on peak	price	1.24
	morning peak	price	0.90		morning peak	price	0.96
	evening peak	price	0.90		evening peak	price	0.96
		avg	0.90			avg	0.96
Mar-May	Residential tariff	0.92		**Sep-Nov**	Residential tariff	0.94	
	% increase from off peak price	82			% increase from off peak price	82	
	off peak	price	0.65		off peak	price	0.67
	on peak	price	1.19		on peak	price	1.21
	morning peak	price	0.92		morning peak	price	0.94
	evening peak	price	0.92		evening peak	price	0.94
		avg	0.92			avg	0.94

Table 3
Minimum consumption levels in kWh ($\bar{c}_{ij}$).

	Period 1	Period 2	Period 3	Period 4
Winter	1.35	1.30	1.20	3.30
Spring	1.86	1.66	1.69	4.03
Summer	2.67	2.01	2.38	5.28
Fall	1.96	1.57	1.77	4.34

Table 4
Parameters of the Weibull distributions.

	Parameters			
	Period 2		Period 3	
Season	Scale	Shape	Scale	Shape
Winter	1.62	1.43	1.54	2.37
Spring	1.28	1.84	1.15	2.95
Summer	1.65	2.13	1.67	4.10
Fall	2.32	2.32	1.42	3.38

Table 5
Break-even feed-in tariffs under various cost and equipment scenarios - 10-year payback period.

	Break-even feed-in tariffs (HKD) per kWh	
Cost of solar PV per kW ($\times$100 HKD)	τ_a	τ_b
300 (min)	10.44	20.52
500 (max)	17.41	27.48

Note: Whereas τ_a is the break-even FIT in case (a) where the household installs solar PV panels only, τ_b is the break-even FIT in case (b) where the household installs both PV and storage equipment.

Table 6
Optimal feed-in tariffs under various cost and equipment scenarios

	Break-even feed-in tariffs (HKD) per kWh	
Cost of solar PV per kW ($\times$100 HKD)	τ_a	τ_b
300 (min)	8.17	16.07
500 (max)	13.75	21.65

Regarding the cost of the storage system, we consider the most standard storage device that can be used by the household, namely the Tesla Powerwall 1, with a capacity of 6.4 kW. The battery can be ordered at 3000 USD, but significant installation costs have to be added. One can buy a Tesla Powerwall 1 online and have the DC- (or AC-coupled) storage system fully installed for 6000 USD (or 6500 USD). In any case, one needs to buy a SolarEdge Upgrade inverter and optimizers (fully installed) as well. This adds 4700 USD to the bill. In case solar panels directly feed the battery, a DC-coupled storage system is enough, and the total cost of the battery is 10700 USD. In case one considers grid feed-ins, an AC-coupled system is utilized. In this case, the total cost becomes 11200 USD ($\approx$ 86805 HKD). Also, note that the Tesla Powerwall 1 has a 92.5% round-trip efficiency when charged or discharged.

An alternative to an energy storage system would be an electric vehicle. Under such a scenario, one can assume away the storage cost as the vehicle would have already been purchased. We also address this issue and check the outcome of various cost values for the battery in the sensitivity analysis section.

Lastly, as in Meng et al. [11], we consider 20 years of financial lifetime. The 20-year period also corresponds to module manufacturers' current minimum performance duration warranty [14].

3.2. Calibration

To calibrate the model on Hong Kong data, we first calculate the peak and off-peak tariff based on the information provided by SCMP [16]. To do this, we start by calculating the percentage difference between the two tariffs. According to SCMP [16], the tariff was 1.13 HKD per unit while the CLP charged 60 (Hong Kong) Cents more for the peak tariff (*i.e.*, 1.73 HKD) and 18 Cents lower for the off-peak tariff (*i.e.*, 0.95 HKD). We deduce that peak tariff is 82.11% higher than the off-peak tariff. Assuming that P is the peak tariff and p is the off-peak tariff, we have the following equation: $P = (1 + a)p$, where $a = 82.11\%$. Furthermore, there are also two intermediary peak tariffs, namely the morning (P_m) and evening peak (P_e) tariffs. As suggested by a standard profile for the variation in hourly electric power demand and price over a single day provided by the Energy Information Administration,[8] we assume that these two tariffs are equivalent and given by the average of the off-peak and peak tariffs. Thus,

$$P_m = P_e = \frac{P + p}{2} = \frac{(1 + a)p + p}{2} = p(1 + a/2).$$

TOU prices are set such that the current tariff ($\bar{p}$) corresponds to the average of the four tariffs:

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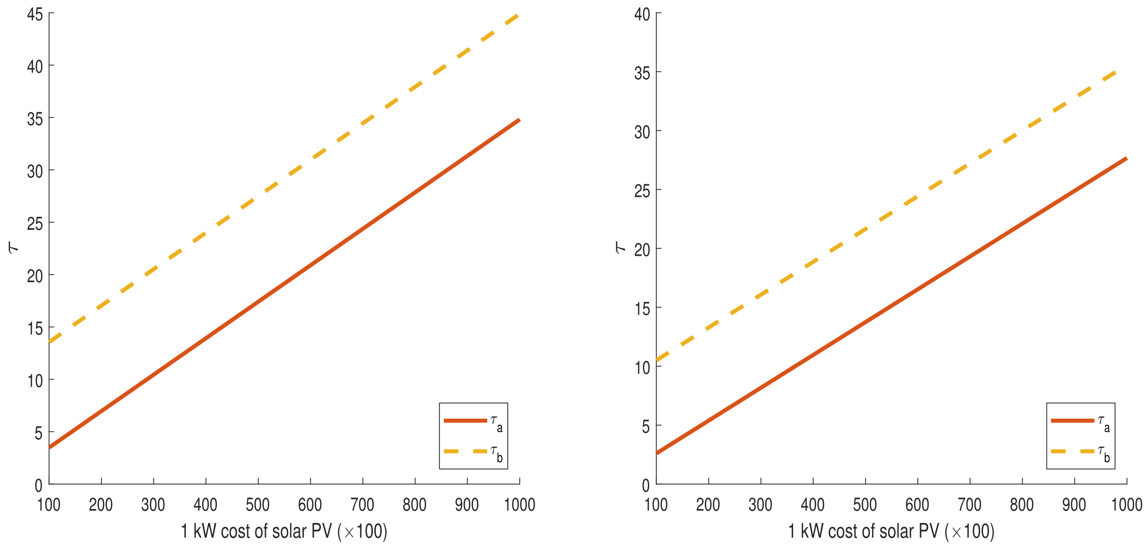
[8] Source: EIA, http://www.eia.gov/todayinenergy/detail.cfm?id=6350.



(a) *10-year payback period* (b) *20-year payback period*

Fig. 2. Break-even FITs per kWh under various cost scenarios for solar PV system.

$$\bar{p} = \frac{P_m + P_e + p + P}{4} = \frac{p(2+a) + (2+a)p}{4} = p(1 + a/2).$$

As a result, we can calculate the tariffs as follows:

$$p = \frac{\bar{p}}{1 + a/2},$$

$$P = (1+a)p = (1+a)\frac{\bar{p}}{1 + a/2},$$

$$P_m = P_e = p(1 + a/2) = \bar{p}.$$

The above equations are applied to the current tariff in each of the four seasons to derive the corresponding tariffs. The tariff calculations for the four seasons are based on 2020 prices. Because we differentiate the analysis for the seasons, we calculate the total amount of tariff paid in each season and divide them by the total electricity consumption to obtain the tariff per kWh, which we later use in the numerical analysis. The tariff for each season is presented below in Table 1. (See the appendix for further details on the calculations for each month).

In light of our earlier analysis at the beginning of this section, the TOU prices are calculated to yield the following results (see Table 2):

We use a Stone-Geary utility function, $u_{ij} = \alpha(c_{ij} - \bar{c}_{ij})^{1-\gamma}/(1-\gamma)$. Here, c_{ij} is the level of electricity consumption in season i and period j, α is a scale parameter, $\bar{c}_{ij}$ is the minimum level of electricity consumption needed in the corresponding season and period, and $\gamma$is a risk aversion parameter. Calculations yield that $\alpha = 0.009$ and the minimum consumption levels given in Table 3:

Finally, we take $\gamma = 5$. For further details about these computations, we refer the reader to Durmaz et al. [3, p. 10].

To obtain the probability density functions of the 2nd and 3rd period PV generation for each season, we approximate the data with Weibull distribution. Specifically, to estimate the scale and shape parameters of the two-parameter Weibull density functions for each season and period of the day, we use maximum likelihood estimation. The parameters of the Weibull distributions for the second and third periods in a day at each season are presented in Table 4.

4. Results

Given the data and the calibration described above, we derive the optimal feed-in tariffs under different cost and equipment scenarios. According to the information provided by CLP[9] and Hong Kong Electric[10] on the FIT, the construction cost of solar panels is in the range of [30,000 HKD −50,000 HKD] per kW and the payback period is approximately 10 years. Thus, we first calculate the optimal FIT over 10 years for the minimum and maximum levels of solar PV installation cost. This is done for equipment scenarios (a) and (b) (see p. 10) using only Phase 1 model, which is the relevant one as the current FIT policy will be in place for the next 10 years. The results show that the FIT values required for a 10-year payback period are all higher than the current FIT of 5 HKD per kWh (see Table 5). We can then deduce that under the current FIT policy in Hong Kong, it would take more than 10 years for households to recover their solar panel investments.

Do note that under the current FIT contract, the electricity generated by the solar panels has to be fed to the grid and cannot be stored. Hence PV cannot be more profitable when the household installs a storage device as well, since this device is costly and does not bring any additional benefits. Hence the break-even FIT is a lot higher in case (b) compared to case (a). Even in case (a) however, it remains twice as high as the prevailing one for the lower end of the PV cost range. The break-even FIT is about 5 times as high as the current one in case (b) for the upper end of the PV cost range.

Given that the 10-year period is not sufficient to recover all the investment costs under the current FIT policy, we now analyze the optimal FIT over the lifetime of the solar panels. This requires the use of both Phase 1 and Phase 2 models. Although results presented in Table 6 show a lower FIT than that of the 10-year payback period, the required FIT is still higher than that of the current policy in Hong Kong. We can then conclude that the current FIT policy is inefficient as it does not provide the household with the incentive to install PV.

Once the FIT policy is over, electricity generated by PV panels can be stored. However, case (b) in Table 6 shows that it is not enough to get break-even FITs smaller than in case (a), meaning that additional benefits brought by storage are not very large.

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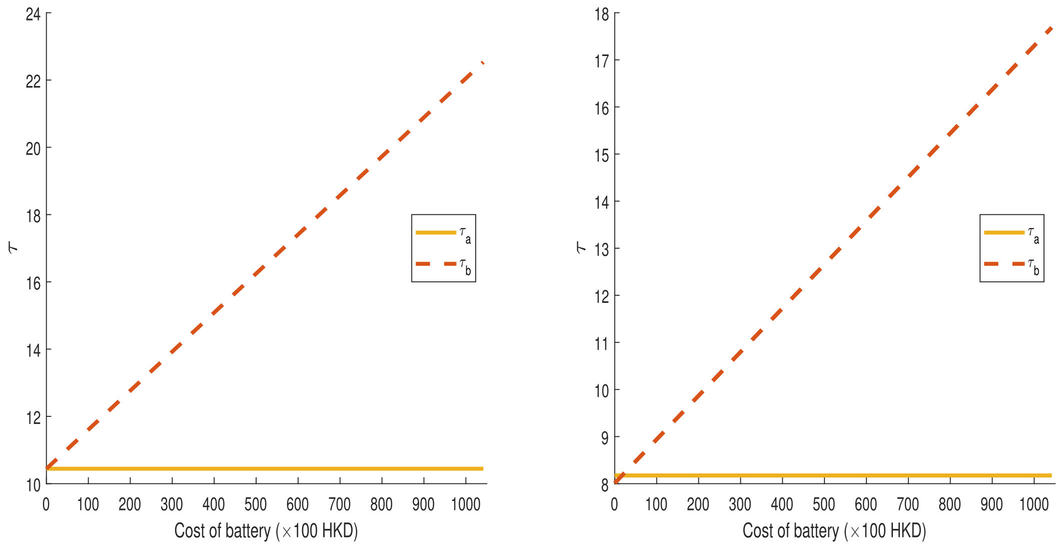
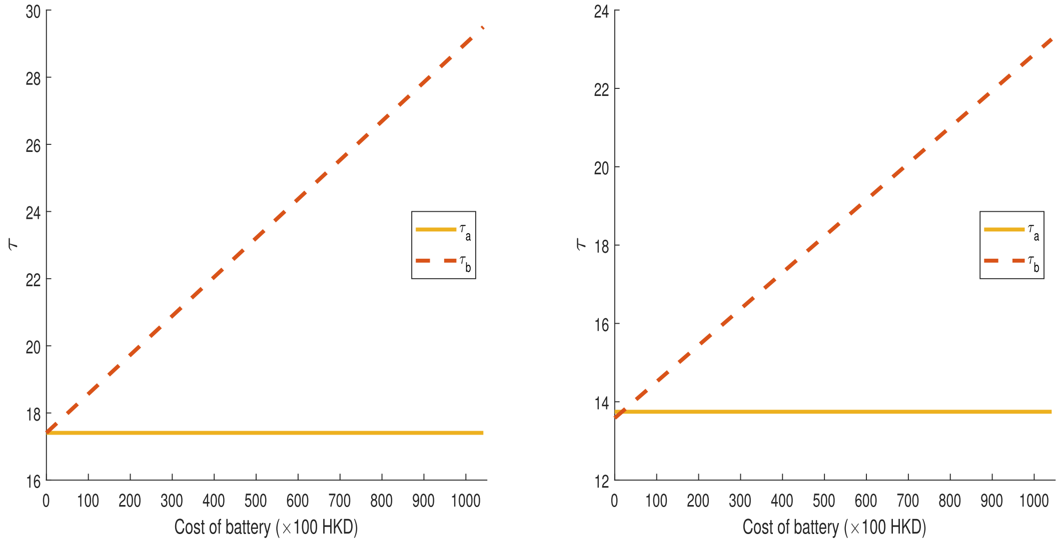
[9] https://www.clp.com.hk/en/community-and-environment/renewable-schemes/feed-in-tariff/feed-in-tariff-residential-customers

[10] https://www.hkelectric.com/en/customer-services/smart-power-services/feed-in-tariff-scheme.



(a) *10-year payback period& solar PV cost: 30,000 HKD* **(b)** *20-year payback period& solar PV cost: 30,000 HKD*



(c) *10-year payback period & solar PV cost: 50,000 HKD* **(d)** *20-year payback period & solar PV cost: 50,000 HKD*

Fig. 3. Optimal feed-in tariffs per kWh under various cost scenarios for battery system.

In the following section, we present the sensitivity analysis to investigate the consequences of different costs of the solar PV system and battery, the lifetime of these equipment, and the discount rate on the break-even FITs.

5. Sensitivity analysis

5.1. Cost of a solar PV system

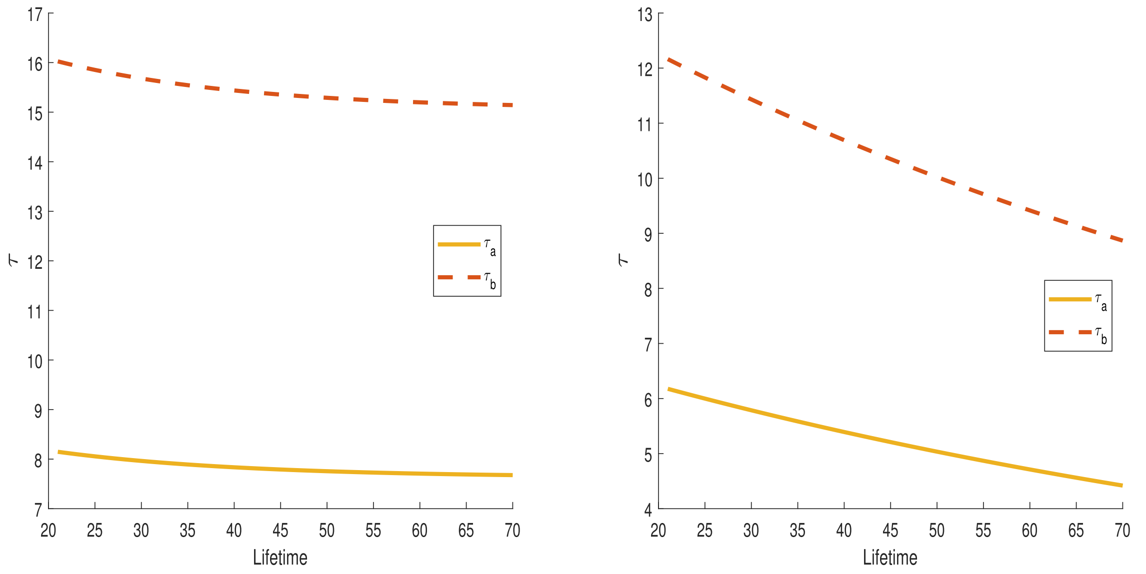
Fig. 2 presents the break-even FITs under various cost scenarios for a solar PV system. According to the results, it is only for a cost of 1kWp PV system less than 15,000 HKD that a FIT rate at 5 HKD per kWh is enough to recover the cost within 10 years. Costs as high as 19,000 HKD per kWp PV system can be recovered within 20 years with such a FIT. However, it would still be significantly out of the likely range for the current cost of such a PV system.

5.2. Cost of the battery

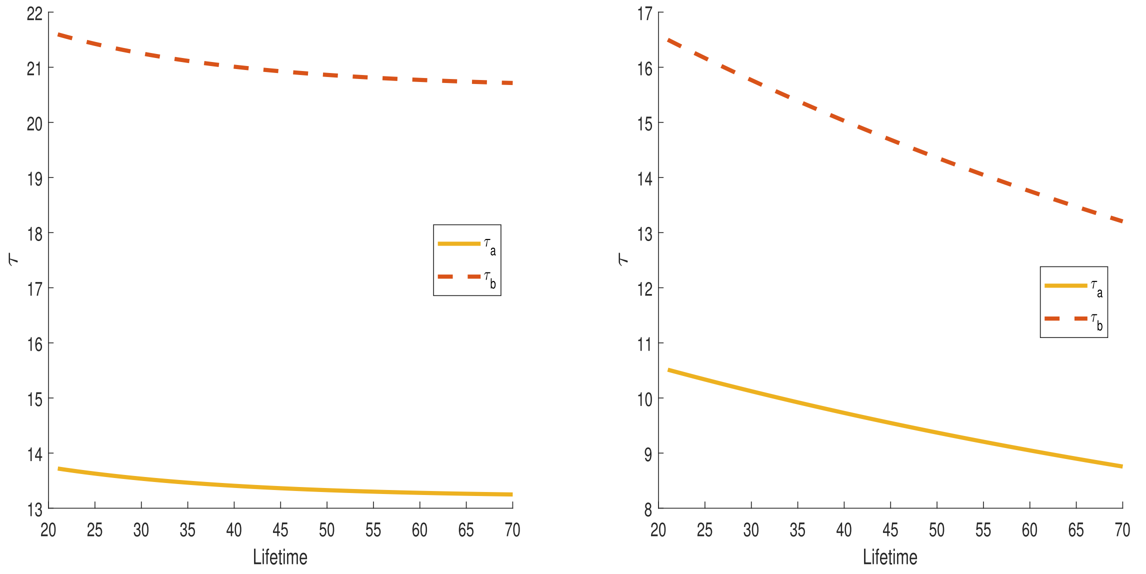
Fig. 3 shows the break-even FITs per kWh under various cost scenarios for the battery system. Of course, the battery cost only affects case (b), where the battery and solar PV system are installed together. Consistent with the intuition, as the storage device is rather expensive but does not affect the benefits coming from the installation of the solar PV system that much, even a free battery (*e.g.,* having an electric car) would not make it beneficial to invest in PV in Hong Kong for the prevailing FIT, regardless of the cost of the PV equipment (within the likely range).

5.3. Lifetime of the equipment

Fig. 4 shows that a 70-year lifetime would not be enough for the household to cover its investment cost with the current Hong Kong FIT, except for a solar PV cost close to the lower end of the range



(a) *Solar PV cost: 30,000 HKD & r=0.05* **(b)** *Solar PV cost: 30,000 HKD & r=0.01*



(c) *Solar PV cost: 50,000 HKD & r=0.05* **(d)** *Solar PV cost: 50,000 HKD & r=0.01*

Fig. 4. Optimal feed-in tariffs per kWh under various PV lifetimes.

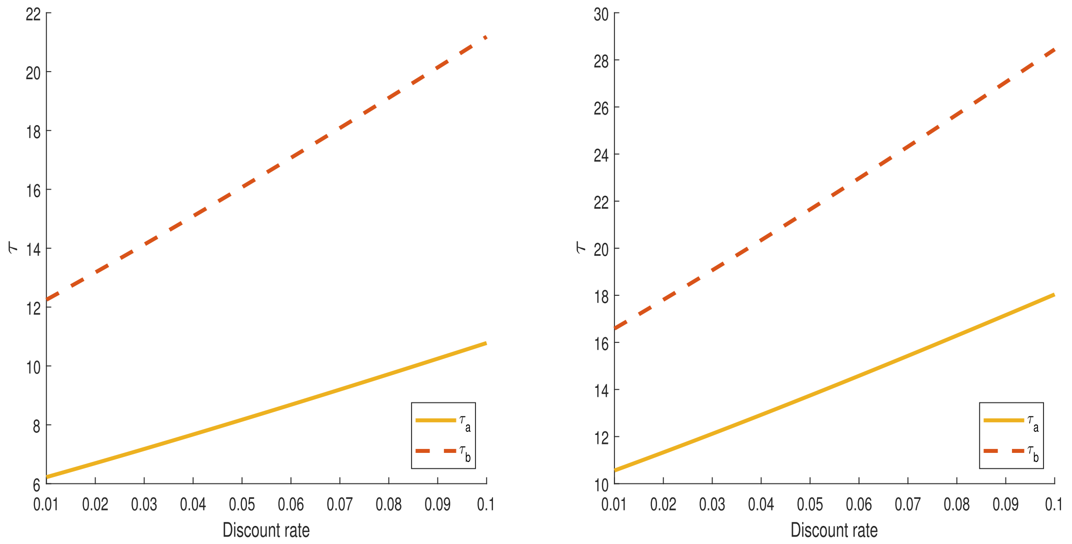
and a discount rate equal to 1%. However, even in the latter case, a 50-year lifetime is required, which is a lot longer than the current solar PV lifetime. In addition, one can note that the break-even FIT is less sensitive to the lifetime of solar PV when the discount rate is equal to 5% (rather than 1%). This is not surprising as a high discount rate erodes the PV benefits accruing in the distant future.

5.4. Discount rate

As can be seen in Fig. 5, a higher discount rate reduces the benefits of installing a solar PV system that are spread out in time, without affecting the cost that occurs once for all at the beginning. As the discount rate increases, a higher and higher FIT will then be required for the household to recover the initial cost. Considering case (a), where the household only installs a solar PV system, the break-even FIT should be as high as 10 HKD per kWh for the lower bound PV cost (and 17 HKD per kWh for the upper bound PV cost) for a 10% discount rate. Results for the 10-year payback period are similar.

6. Discussion and conclusions

A FIT policy has been in place in Hong Kong since April 2017. In this paper, we measure to which extent this policy can provide sufficient incentives to guarantee the development of the residential solar PV systems in Hong Kong. Our results indicate that the current FIT policy cannot ensure the development of PV in Hong Kong. Specifically, a policy that consists of a FIT rate at 5 HKD per kWh for the next 13 years does not lead to a 10-year payback period as announced by the Hong Kong government. Rather, the current FIT policy leads to a minimum 50-year payback period, which is a lot longer than the lifetime of solar



(a) *20-year payback period & solar PV cost: 30,000 HKD* (b) *20-year payback period & solar PV cost: 50,000 HKD*

Fig. 5. Optimal feed-in tariffs per kWh under various discount rates.

panels. The break-even FIT is instead 8 HKD per kWh (for the lower bound of the PV cost, whereas it is 13.75 HKD per kWh for the upper bound). This is the FIT rate that would provide sufficient incentives over the 20-year lifetime of the solar PV panels for the household without generating windfall effects. Do note that a 10-year payback period–as announced by the Hong Kong government–would require a FIT larger than 10 HKD per kWh (for the lower bound of the PV cost). However, a 10-year payback would, in some way, generate windfall effects.

This is in sharp contrast with the results of Song et al. [17] who find that a 4 HKD per kWh FIT should be enough for the LCOE of PV electricity generation in Hong Kong to be below the retail price in 2020. However, note that based on a steep learning curve, the PV panels installation cost is assumed to be 19,260 HKD per kWp capacity in 2020,[11] which is outside the official range currently announced by the Hong Kong government. In fact, this cost is twice lower than the Hong Kong government's mean value which explains why Song et al. [17] is much more optimistic than we are, regarding the current Hong Kong FIT policy's efficiency. For a cost of 19,260 HKD per kWp capacity, which stands significantly below the lower-bound reference cost scenario in Hong Kong, the break-even FIT is calculated to yield 5.3 HKD per kWh. This break-even FIT value nearly overlaps with the FIT rate set out by the latest Scheme of Control Agreement for generating capacities less than 10 kW.

On the contrary, our results are in line with Li et al. [8] who also find a payback period much longer than the lifetime of the PV panels. Using a simple monetary payback approach, the authors obtain a 72.5 year payback time. Consistent with our conclusion, this result suggests that further monetary incentives are required to achieve a reasonable payback period that, in particular, needs to be less than the lifetime of the solar panels. Moreover, we show that ownership of a storage device would not improve the results. On the contrary, the FIT ensuring that it is profitable to install both the solar panels and the battery is higher, reaching 16 HKD per kWh for the lower end of the PV costs.

We conducted a partial equilibrium analysis in the sense that we considered that the household took electricity prices as given for the whole lifetime of the solar panels. In fact, in case of a significant deployment of solar PV panels in Hong Kong, electricity prices will go down at times when majority of households want to sell electricity and go up at times when they want to purchase electricity. This is likely to reduce the profitability of PV panels further. As a result, our optimal FIT levels can even constitute a lower bound for the ones that would ensure households with a profitable solar PV system. This strengthens our conclusion that the current FIT is much too small to foster PV development in Hong Kong.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Calibration

The Residential Tariff in Hong Kong is based on monthly meter readings. The tariff is the sum of a basic charge and a fuel clause charge (FCC).[12] In particular, consumption in a month is charged according to the following block rate tariff table (see Table 7):

FCC is adjusted on a monthly basis to reflect changes in the cost of fuels to produce electricity in a timely manner (see Table 8). In our

Table 7
Hong Kong Electric block rate tariff for 2020 (Source: https://www.hkelectric.com/en/customer-services/billing-payment-electricity-tariffs/residential-tariff. Accessed on Aug 1, 2020.

Consumption (In Blocks)	Basic charge (Cents/unit)
For each of the first 150 units	60.4
For each of the next	
150 units (151–300)	74.3
200 units (301–500)	88.2
200 units (501–700)	111.8
300 units (701–1,000)	125.7
500 units (1,001–1,500)	139.6
From 1,501 units and above	153.5

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[11] See Song et al. [17], Table 3.

[12] We ignore the very small 0.4 Hong Kong Cents per unit of special rent & rate rebate.

computations, we introduce the fuel clause charge as the average of the charges from Jan to Aug 2020 which is 23.4 Cents, as data for Sept-Dec are note available.

In light of the monthly electricity consumption data provided by Table 9, the basic charge and the FCC, the bill for each month is presented below in Table 10.

Table 8
FCC per month.

Year 2020	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
FCC (Cents/unit)	24.8	24.8	23.1	23.1	24.6	25.2	22.9	18.5

Table 9
Monthly electricity consumption.

Month	Electricity Consumption (kWh)
December	271.25
January	271.25
February	245.00
March	271.25
April	262.50
May	374.50
June	379.63
July	412.47
August	401.47
September	389.22
October	378.00
November	262.50

Table 10
Monthly bills.

Months	Monthly bills
Dec	244.09
Jan	244.09
Feb	218.45
Mar	244.09
Apr	235.55
May	355.30
Jun	361.02
Jul	397.66
Aug	385.39
Sep	371.72
Oct	359.21
Nov	235.55

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