Levelized Cost of Consumed Electricity

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IHP seminar
9 novembre, 2018.

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Motivation (1) : Integrating RE is a challenge

- In the future the production of electricity has to be decarbonized.
  - RE,
  - CCS.
- Challenges associated with a higher penetration of RE generation.
  - Variability : night and day, seasons,
  - Intermittency : cloud cover...

Motivation (2) : Variability and intermittency affect LCOEs

- The economic profitability of PV installations is usually appraised in the literature using the concept of levelized cost of electricity (LCOE) which completely ignores the intermittency : RE generation is based on annual electricity generation (Reichelstein and Yorston 2013, Darling *et al.* 2011).

- Wrong computation of the levelized cost of electricity : ignoring variability and intermittency and reasoning on average values gives an undue advantage to renewable sources and leads to taking wrong decisions (Joskow, 2011).

Motivation (3) : Smart grids as a way to integrate renewable energies

- We account for 2 levels of equipment in SG
  - Installation of smart meters
  - Energy storage
- What is the UK consumers' Willingness To Pay (WTP) for :
  - solar panels (1.9kW peak PV system) ?
  - smart meters ?
  - batteries (Tesla Powerwall) ?

  → *Durmaz, T., Pommeret A. and Ridley I, (2018), Willingness to pay for solar panels and smart grids.*
- What is the HK consumers' Willingness To Pay (WTP) for 3kW peak PV system and/or smart meters and/or batteries ?
  → *Durmaz, T., Pommeret A. and Ridley I, (2018), Willingness to pay for solar panels and smart grids in HK.*

Existing literature (1)

- Optimal energy source mix for electricity generation (fossil fuels and renewables) when intermittency is considered (see Ambec and Crampes, 2012, 2015).
- Energy dispatch problem when storage can
  - take care of peak electricity or excess nuclear energy production (see Jackson, 1973 ; Gravelle, 1976 ; Crampes and Moreaux, 2010).
  - minimize the interaction between a household and the utility (Fares and Webber, 2017)
  - follow an exogenous suboptimal rule (Castillo-Cagigal, 2011, MIT energy initiative, 2015)
- More technical studies have been conducted and show, for instance, that with a PV size below 5 kW peak, electricity consumption in UK passive houses needs to be reduced by 70% to reach zero-energy targets (Ridley et al., 2014).

Existing literature (2)

Electricity demand management and smart grids have recently received a lot of attention

- in the academic literature (De Castro and Dutra, 2013, Léautier, 2014, Hall and Foxon, 2014 or Bigerna et al., 2016 and Brown and Sappington, 2017),
- in the media (The Economist, 2009 ; The Telegraph, 2015b,a),

Not much work has been done that investigates the cost of solar PV systems and accounting for intermittency. Exceptions are :

- Hirth *et al.* (2016) propose a system LCOE,
- This paper.

Intuition

Solar generation is variable and intermittent, and therefore, cannot be used in isolation, and requires to be integrated into a system.

$\Rightarrow$ In the case of an HH, the system to be considered is all the means and devices the HH utilizes in addition to the solar panel to obtain the electricity it consumes.

$\Rightarrow$ The value of the LCOCE will then be dependent on the devices (such as a battery and a smart meter) owned by the HH.

What we do

- Propose a new method to compute the average cost of renewables that accounts for intermittency, flexibility options provided by smart grids, such as the provision of electricity generated by solarphotovoltaic (PV)panels to the network, battery storage, and smart meters.
- As our focus is on residential electricity consumers, we also introduce a new term, Levelized Cost Of Consumed Electricity (LCOCE).
- We provide and calculate these measures using an economic model that allows a household to optimize its electricity consumption as well as grid feed-ins given varying electricity tariffs, weather conditions (solar irradiance) and smart grids used.

Specific features

Our approach is very innovative because it also accounts for

- location-specific (regional) household (HH) behavior that optimizes its electricity consumption,
- uncertainty in solar irradiation both within the day and seasons,
- variations in tariff rates, cost of acquisition and installation of smart grids, including smart meters, batteries, etc.

Outline

- Computation of the LCOCE
- Data and model
- Results

Standard LCOE

Applying LCOE, it is, in fact, striking to see that solar power has already had a breakthrough (see IEA, 2011, or EIA, 2017). A simplified LCOE equation can be written as follows :

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t: investment cost at year t

M_t: maintenance and operation costs at year t

F_t: cost of the energy used

E_t: generated quantity of electricity

r: discount rate

n: system lifetime

Accounting for intermittency

Intermittency has two significant consequences when considering the levelized cost of renewable energy at the HH level :

- when no electricity is generated, the HH has to use another electricity source (e.g., the grid or battery) to meet its electricity demand. This is costly and should increase the average cost of electricity generation through renewables.
- when too much electricity is generated compared to the HH's needs, there may be a possibility for the HH to sell the excess power to the grid. This should reduce the average cost of using the renewable source.

Deriving LCOCE

For a HH, the system to be considered is all the means and devices the HH utilizes in addition to the solar panel to obtain the electricity it consumes. A simplified LCOCE equation can be written as :

$$LCOCE = \frac{\Sigma_{t=1}^{n} \frac{I_t + M_t + G_t}{(1+r)^t}}{\Sigma_{t=1}^{n} \frac{C_t}{(1+r)^t}}$$

I_t: investment cost at year t, including storage and other smart equipment
M_t: maintenance and operation costs at year t for all the equipment
G_t: cost to use the grid
C_t: consumed quantity of electricity
r: discount rate
n: system lifetime

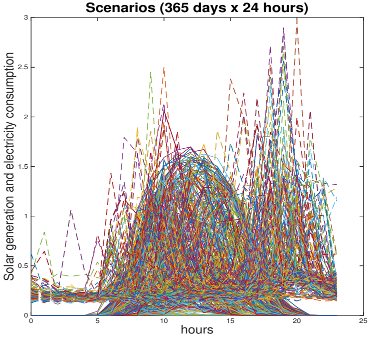
Data on investment cost

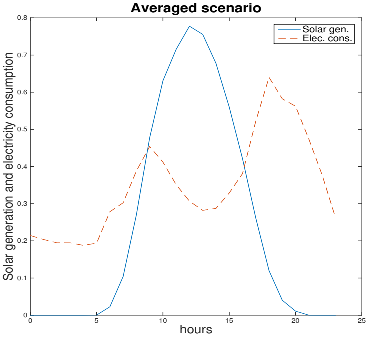
- Cost per HH of installing smart meters in the UK : \$290 (Department of Energy and Climate Change).
- Cost of solar PV was from \$2.55/W to \$4.47/W for a residential PV system in the first half of 2017 (based on Feldman et al., 2017).
  - between \$4845 and \$8493 for a 1.9kW peak PV system, which we consider for the UK case,
  - for HK, the size of the system being larger (3kW peak system), the cost is between \$7650 and \$13410.
- Total cost of Tesla Powerwall 1 : \$11200. Round-trip efficiency : 92.5%.
- Discount rate : $r = 0.05$.
- 20 years of financial lifetime (Arimura et al., 2012 ; Ossenbrink et al., 2013).

Electricity consumption and generation : UK

- Data from a low energy dwelling in South Wales UK, the performance of which was extensively monitored (Ridley et al., 2014)
- Hourly data May 2012-April 2014
- Represents the behaviour and consumption patterns of HHs whose dwellings include
  - PV generation (thus, data on Solar radiation)
  - Net metering
  - No storage capacity

Solar power generation and electricity consumption : UK

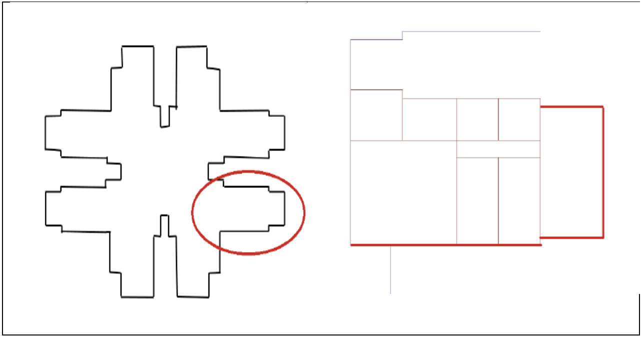




Data for HK : high rise apartment block

- 3 bedroom apartment located on the 10th floor of a 20 floor Harmony public housing block.
- Floor area of 73m2. Window area : 8 m2
- Constructed from medium weight concrete with 100mm thick walls.
- Overshadowed by the other apartments in the block.
- The modelled apartment is located in the south east quadrant of the Harmony double cross shaped floor plan.

Data for HK : high rise apartment block



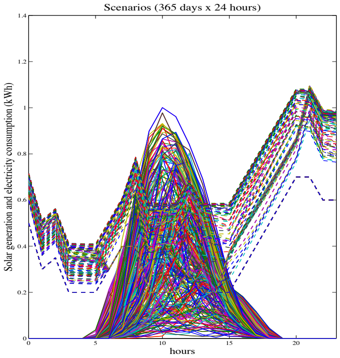
Data for HK : Simulation of electricity consumption (flat)

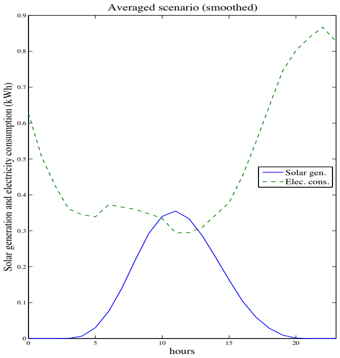
- AC is provided in the main living room, and in the bedrooms, 75% of the floor area is conditioned.
- Week day : AC in the living room operates from 16 :00 to midnight, AC in the bedroom operates from 10pm to 6am.
- Weekends : AC in the living room operates from 9 :00 to midnight.
- AC operates from May to October inclusive, with a thermostat set point of 26 deg C.
- COP of the AC is 4.

Data for HK : Simulation of electricity generation (flat)

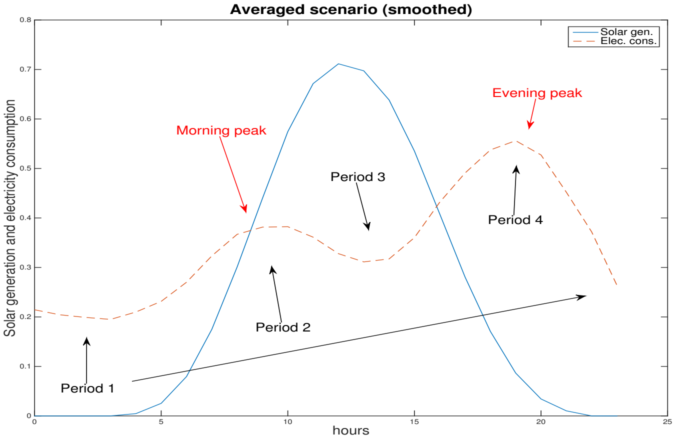
- 3kW peak PV system covers 18 m2 of the south and east façade of the apartments walls.
- PV panels are applied to the south walls of the living room and bedroom 1 and 2 and the south and east facades of the master bedroom.
- The PV panels occupy 27% of these wall facades.
- The total annual electricity consumption is 3919 kWh, with AC consumption of 725 kWh accounting for 18% of the total.
- After inverter loss, the PV system generates 995 kWh, equivalent to 25% of consumption.
- Net metering
- No storage capability

Solar power generation and electricity consumption in the flat



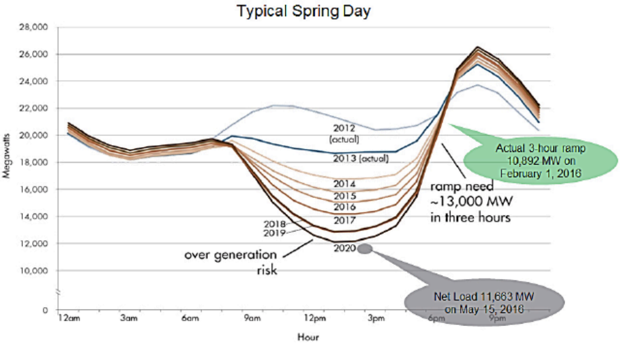


Solar power generation and electricity consumption : summary



The Duck Chart (CAISO)

When sun shining at off-peak time.



Model

$$
\begin{aligned}
&\max_{\{s_i, g_i\}} \quad u_1\left(g_1 - s_1 + s_0\right) - p_1 g_1 \\
&+ \int_0^1 \Big[u_2\left(x\bar{K} + g_2(x) - s_2(x) + \phi s_1\right) - p_2 g_2(x) \\
&+ \int_0^1 \Big[u_3\left(y\bar{K} + g_3(x,y) - s_3(x,y) + \phi s_2(x)\right) \\
&+ u_4(g_4(x,y) + \phi s_3(x,y)) - \sum_{i=3,4} p_i g_i(x,y) \Big] dF^y(y) \Big] dF^x(x)
\end{aligned}
$$

s.t. $s_i \leq \bar{s}, s_i \geq 0,$ and $p_3 > p_4 \geq p_2 > p_1$.

$x\bar{K}$ and $y\bar{K}$: solar power generation ; g_j : grid purchases (or sales) ; s_l : amount of energy storage that is carried to the following period ; ϕ : round-trip efficiency parameter.
The model is solved recursively.

Model

The model is solved recursively.

$$\max_{\{g_4\}} \quad u_4\left(g_4 + \phi s_3\right) - p_4 g_4$$

The optimal level of the grid activity (that is, electricity purchases or feed-ins), g_4^*, solves

$$u_4'\left(g_4^* + \phi s_3\right) = p_4,$$

and, therefore, will be calculated from

$$g_4^* = u_4'^{-1}\left(p_4\right) - \phi s_3.$$

Model

The third period problem :

$$\max_{\{s_3, g_3\}} u_3\left(y\bar{K} + g_3 - s_3 + \phi s_2\right) - p_3 g_3 + u_4\left(g_4^* + \phi s_3\right) - p_4 g_4^*$$
$$\text{s.t.} \quad s_3 \leq \bar{s}, \text{ and } s_3 \geq 0.$$

The FOCs w.r.t the grid activity and energy storage are

$$u_3'\left(y\bar{K} + g_3 - s_3 + \phi s_2\right) = p_3, \quad \text{and}$$
$$-u_3'\left(y\bar{K} + g_3 - s_3 + \phi s_2\right) + \phi u_4'(g_4^* + \phi s_3) + \eta_3 - \nu_3 = 0.$$

ν_3 and η_3 are the multipliers associated with the storage capacity and the corresponding nonnegativity constraint.

Model

$$-p_3 + \phi p_4 + \eta_3 - \nu_3 = 0.$$

The willingness to store energy is determined by the marginal surplus from energy consumption today and in the next period.

Given s_3^*, g_3^* can be calculated as $g_3^* = u'^{-1}(p_3) - y\bar{K} + s_3^* - \phi s_2$.

Model

The problem in the second period is

$$\max_{\{s_2,g_2\}} \quad u_2\left(x\bar{K} + g_2 - s_2 + \phi s_1\right) - p_2 g_2 +$$
$$E_y\left[u_3(y\bar{K} + g_3^* - s_3^* + \phi s_2) - p_3 g_3^* + u_4\left(g_4^* + \phi s_3^*\right) - p_4 g_4^*\right]$$
$$\text{s.t.} \quad s_2 \leq \bar{s}, \text{ and } s_2 \geq 0.$$

The first order conditions are

$$u_2'\left(x\bar{K} + g_2 - s_2 + \phi s_1\right) = p_2,$$
$$-u_2'\left(x\bar{K} + g_2 - s_2 + \phi s_1\right) + \phi E_y[u_3\prime\left(y\bar{K} + g_3^* - s_3^* + \phi s_2\right)] + \eta_2 - \nu_2 = $$

ν_2 and η_2 : multipliers associated with the second-period capacity and nonnegativity constraints.

Model

Given s_2^*, the second-period optimal grid activity, g_2^*, is obtained by solving

$$g_2^* = u'^{-1}(p_2) - x\bar{K} + s_2^* - \phi s_1.$$

Model

The problem in the first period is

$$\max_{\{s_1, g_1\}} \quad u_1\left(g_1 - s_1 + s_0\right) - p_1 g_1 + E_x\Big[u_2\left(x\bar{K} + g_2^* - s_2^* + \phi s_1\right) - p_2 g_2$$
$$+ E_y\left[u_3\left(y\bar{K} + g_3^* - s_3^* + \phi s_2\right) - p_3 g_3^* + u_4\left(g_4^* + \phi s_3^*\right) - p_4 g_4^*\right]\Big]$$
$$\text{s.t.} \quad s_1 \leq \bar{s} \text{ and } s_1 \geq 0.$$

The first order conditions are :

$$u_1'\left(g_1 - s_1 + s_0\right) = p_1,$$
$$-u_1'\left(g_1 - s_1 + s_0\right) + \phi E_x[u_2'(x\bar{K} + g_2^* - s_2^* + \phi s_1)] + \eta_1 - \nu_1 = 0.$$

η_1 and μ_1 be the multipliers associated with the capacity and non-negativity constraints in the first period.

$$g_1^* = u'^{-1}\left(p_1\right) + s_1^* - s_0.$$

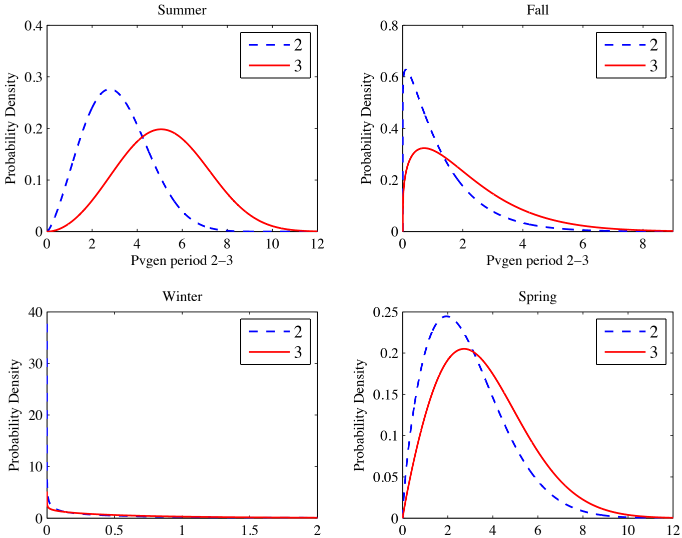
Calibration

- Using electricity consumption data, we calibrate a CRRA utility function (season i and period j) for $\gamma = 5$,

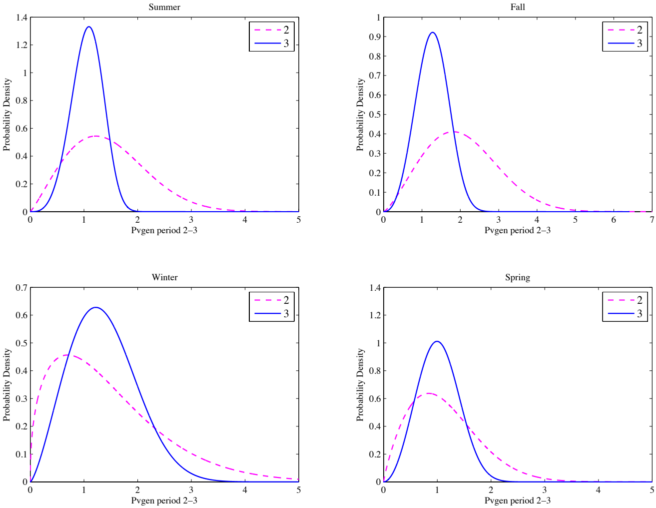
$$u_{ij}(c) = \frac{\alpha(c - \bar{c}_{ij})^{1-\gamma}}{1-\gamma},$$

- We approximate the data with Weibull distributions, whose scale and shape parameters are estimated using maximum likelihood estimation.
- In line with the observation, we assume $p_3 = \frac{4}{3}p_2 = \frac{4}{3}p_4 = 2p_1$ where the average price equals 75 cents/kWh.

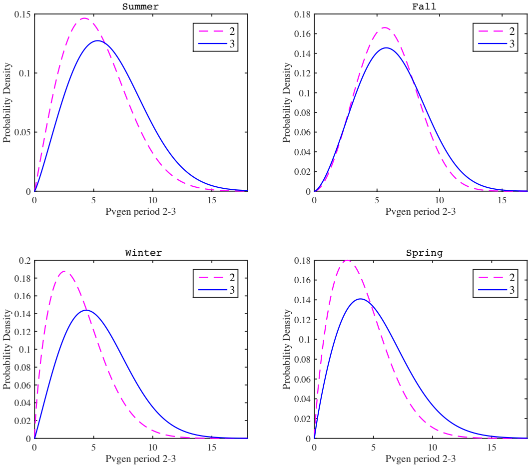
The pdfs for period 2 and 3 at each season in the UK



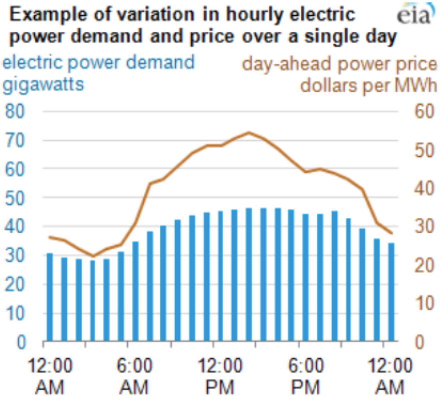
The pdfs for period 2 and 3 at each season in the HK flat



The pdfs for period 2 and 3 at each season in the HK house



Electricity price over the day



We consider 8 scenarios and compute LCOCEs

1. SM, ST, SP - Welfare1 (W_1)
2. ~~SM~~, ST, SP - W_2
3. SM, ST, SP^O - W_3
4. SM, ST, SP^M - W_4
5. SM, ST, ~~SP~~ - W_5
6. SM, ~~ST~~, SP - W_6
7. SM, ~~ST~~, ~~SP~~ - W_7
8. ~~SM~~, ~~ST~~, ~~SP~~ - W_8

Electricity can only be stored using the PV system : LCOCE3 (energy is stored optimally) and LCOCE4 (PV system fills the battery first)

Results

Upper bound : highest costs for PV and storage.
Lower bound : lowest costs for PV and storage.

Equipment Costs		Cases (in US$)							
		UK - grid feed-ins allowed							
		LCOCE1	LCOCE2	LCOCE3	LCOCE4	LCOCE5	LCOCE6	LCOCE7	LCOCE8
	Lower Bound	0.438486	0.203661	0.423975	0.428829	0.4280843	0.22662	0.216218	0.203289
	Upper Bound	0.514049	0.270192	0.499537	0.504391	0.4371926	0.293074	0.216218	0.203289
		UK - grid feed-ins prohibited							
	Lower Bound	0.42321	0.20585	-	-	0.4248363	0.219258	0.216218	0.203289
	Upper Bound	0.496177	0.271078	-	-	0.4339179	0.277952	0.216218	0.203289
		HK - grid feed-ins allowed							
	Lower Bound	0.446231	0.224167	0.43858	0.440355	0.3198921	0.226216	0.099878	0.0975
	Upper Bound	0.569864	0.338044	0.562213	0.563989	0.329767	0.339975	0.099878	0.0975
		HK - grid feed-ins prohibited							
	Lower Bound	0.442417	0.224346	-	-	0.318619	0.223529	0.099878	0.0975
	Upper Bound	0.564415	0.338187	-	-	0.3284562	0.334654	0.099878	0.0975

General results

Some surprising results :

The lowest LCOE is reached for no equipment being installed (LCOCE8) regardless of the feed-ins possibility

- especially for HK (with LCOCE7) where there are low tariffs
- LCOCE with smart meters only (LCOCE7) is higher than the LCOCE without smart meter or solar panels, even when smart meters are quite cheap : even if the HH can adjust its consumption to increase it in the first period (when the price is at its lowest level) and lower it in the third period (when the price is high) the price differential leads to a total higher expenditure with a smart meter.

Results for the UK

- The lowest LCOCE is achieved when the HH has only the PV system installed (LCOCE2),
- followed by the case where the HH only owns a smart meter and benefits from varying tariff rates in this regard (LCOCE7).
- Possessing a battery pack (LCOCE3−5) nearly doubles the net present value of the unit cost of consumed electricity over the lifetime of the energy technologies we are concerned with.
- The differences between LCOCEs among cases 1, 3 and 4 ensue from differences in grid purchases.
- LCOCEs are in general higher for the case with no grid feed-ins (but welfare is always lower).

Results for the UK

LCOE computed for the UK by IRENA is around \$0.365. $\Rightarrow$ unless storage is part of the equipment, LCOCEs are lower than \$0.365 $\Leftrightarrow$ accounting for intermittency in some way lowers the cost of solar generation BUT LCOE and LCOCE do not measure the same thing.

Results for HK

- Not accounting for LCOCE8 and LCOCE7, the solar PV system is going to be the cheapest when only solar panels are installed (LCOCE2),
- LCOCEs are around 28% higher when using the upper bound rather than the lower bound for the PV and battery cost.
- Levelized cost is lower or equal when grid feed-in is prohibited (except for LCOCE2) $\Rightarrow$
  - argument for the HK electricity utilities that oppose to the change in the law that prohibits grid feed-ins.
  - OR allowing grid feed-ins would not have huge consequences as the price of electricity in HK is so low that an HH has no incentive to provide electricity to the network.

Results for HK

In any case, the LCOCEs are significantly higher than the LCOE computed for China (around $0.15) by IRENA. Accordingly, we obtain that accounting for the intermittency significantly increases the system cost of solar PV.

Conclusions

We propose a new computation for the cost for the cost of RE that accounts for :

- intermittency at daily and seasonal levels,
- electricity tariff variations,
- HH electricity consumption behavior ,
- the cost of complementary technologies such as smart meters and batteries.

We apply our method to the UK and Hong Kong data on electricity consumption, solar radiation and electricity tariff, and obtain differing results : accounting for intermittency reduces the cost of solar consumption for the dwelling in the UK while it increases it for the high-rise building apartment in HK.

Implications

- Importance of computing costs that are location dependent, which implies different
  - weather conditions,
  - types of dwelling,
  - consumption habits,
  - and electricity tariffs.
- Our conclusions may be crucial for the design of policies aimed at promoting further investment in home renewable energy systems.