Climate Change Mitigation in Hong Kong's Electricity Sector

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Abstract

In its Climate Action Plan 2030+, the government of Hong Kong has set clear targets for the reduction of greenhouse gas emissions (GHG). It defined a shift in its energy mix, which is still dominated by fossil fuels, as the main approach.
This paper looks into an important aspect of emission reduction: the role of power plant operation in supply-side changes, namely the shift in the energy mix, demand reduction, and solar PV installation.
So far, no detailed power plant scheduling simulation has been developed for Hong Kong. This paper presents a simulation for 15-minute power plant scheduling and related emission calculation in Hong Kong for the target year 2030. In this simulation, the fuel mix change decided by the government represents the reference case, based on which the impact of demand reduction and solar PV installation are compared.
The results of different scenarios are impressive, clearly showing the potential for substantial emissions cuts. Massive efforts in energy conservation and efficiency could almost half the emissions, by far outperforming the reductions of 29% due to large-scale solar PV.
This paper further discusses major barriers to Hong Kong's energy politics that hinder significant reduction of energy demand. These are identified based on an extensive literature review and 19 semi-structured interviews with local experts and stakeholders. The barriers range from unambitious yet unachieved targets and weak roadmaps over a lack of institutional resources and government leadership all the way down to deficits in transparency.

Recommendation

Based on these findings the author encourages the Hong Kong government and other various stakeholders to urgently invest into a low-carbon future and make an energy transition feasible. The remaining global carbon emission budget of 800 Gt for a global temperature increase of less than 2°C is equivalent to 21 years under constant emissions of 2015. As the Hong Kong government correctly recognised, annual per capita emissions of 2.0 t represent the ultimate target. To achieve this goal on time, the government has to boost its pace of action and joint efforts with business, academia and civil society.

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Abbreviations

CCGT	Combined-cycle gas turbines
CLP	China Light and Power
DBNPS	Daya Bay Nuclear Power Station
EMSD	Electrical and Mechanical Services Department
ESP	Energy Saving Plan
GHG	Greenhouse gas
GSR	Global solar radiation
HKE	Hong Kong Electric
HKGBC	Hong Kong Green Building Council
Kg CO_2e	Kg CO_2 equivalent, as defined by the Intergovernmental Panel on Climate Change (IPCC)
mn	Million
RE	Renewable energy

Terms

Full-year scheduling	Scheduling performed for all days in the target year 2030
One-day scheduling	Scheduling performed for one single selected day in the target year 2030
Solar PV / reservoir PV	Both terms are used interchangeably within this paper
Utilisation ratio	Measure for the scale of solar PV implementation (percentage of reservoir surface within the CLP-supplied territory covered with solar panels)

Acknowledgements

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Finally, the data on global solar radiation of Hong Kong was provided by the Hong Kong Observatory.

1 Introduction

Along with Hong Kong's economic rise and growing prosperity, the city´s electricity demand has constantly risen over the last decades. In 2014 it reached 43.9 TWh, which is 12% higher than in 2004 [1, p. 22]. Electric power in 2015 was supplied by 48% from coal-fired units, 27% from combined cycle gas turbines (CCGT), and 25% from the Mainland-based Daya Bay Nuclear Power Station (DBNPS) [2, p. 20]. It is therefore not surprising that 70% of Hong Kong's carbon footprint in 2016 came from the power sector [2, p. 21].

In 2017, the government published "Hong Kong's Climate Action Plan 2030+". According to the Paris Agreement at COP21, the annual per capita emissions of CO_2 should not exceed 2.0 t to keep average global warming below 2.0 degree Celsius. In contrast, Hong Kong emitted 6.2 t per capita in 2014. [2, p. 6].
The Hong Kong Climate Action Plan 2030+ defined an absolute emission reduction target of 26–36% until 2030 (the base year is 2005) [2, p. 6], to be achieved mainly by changing the fuel mix from coal to gas. In parallel and in addition, the "Energy Saving Plan For Hong Kong's Built Environment 2015–2025+" targets at energy intensity reductions of 40% by 2025 (base year 2005) [3, p. 5], which would equal to an absolute electricity consumption reduction of 12 percent [4, 1, p. 22].

NGOs, advisory councils, and scholars have urged the government to set more ambitious targets [5, 6]. For example, the Hong Kong Green Building Council (HKGBC) published its "HK3030 Vision" and drafted a roadmap towards a 30% absolute electricity consumption reduction by 2030 [7, 8].
The Water Services Department is currently conducting tests on floating solar PV on reservoirs [2, p. 29], while scholars and engineers discuss the general potentials of solar PV in Hong Kong. But their estimations of potentials and emission reduction are mostly based on *annual* data [9, 10, 6]. They do not consider the effects of electricity infeed from solar PV on the operation of conventional power plants, neglecting technical limitations (minimum stable operation limits, start-up times, etc.) So far, power plant scheduling of Hong Kong has not been simulated in more detail and closer to reality.

Against that background, this paper contains two sections:

In section I, a simulation for Hong Kong's power plant scheduling with 15-minute granularity is developed and utilised. The implementation of the fuel mix change represents the reference case. Based upon this, the impacts of demand reduction and solar PV installation on the scheduling of Hong Kong's conventional power plants are analysed. The results clearly show the importance of demand reduction to phase out coal units and achieve necessary GHG emission reduction.

In section II, major barriers in Hong Kong's energy politics are identified, which hinder substantial electricity demand reduction. This critical review is based on a literature review and 19 semi-structured interviews with local experts. This information is clustered and analysed along a specially developed "Essential Building Blocks Framework".

2 Methodology of power plant scheduling simulation

2.1 Overview

The purpose of the analysis is to simulate in a first step the effects of a change in the fuel mix on the operation of conventional power plants in Hong Kong. Based on that the impact of demand reduction and solar PV installation is calculated.
A simulation model was developed in Excel VBA to simulate the power plant scheduling with a 15-minutes granularity for the target year 2030. As input data electricity load and global solar radiation are taken. Further, technical characteristics of the power plants and the electricity system (capacity ranges of each unit, availability rates, required reserve capacity, the efficiency of solar panels, etc.) are implemented in the algorithm. As the grids of both utility companies are separated, the scheduling simulation is performed only for the power plants of China Light and Power (CLP), which account for 75% of Hong Kong's electricity supply [11, p. 6]. This might serve as a proxy for the whole electric supply system in Hong Kong. No storage technologies are considered, and no grid restrictions are taken into account. It is further assumed that demand is inflexible and must be exactly met at all times.

The following subchapters provide a brief overview of input data, assumptions, and procedures of the simulation. Further details can be provided by the author on request.

2.2 Assumptions

Currently, electricity for Hong Kong is mainly produced by coal- and gas-fired plants on the territory of Hong Kong. Around 25 per cent is delivered by the Daya Bay Nuclear Power Station at the coast of Guangdong Province north of Hong Kong.
For 2030, the following power plants are considered for the simulation [12]:

- Nuclear power plant (Daya Bay Nuclear Power Station (DBNPS))
  - Two units with each 948 MW
- Coal-fired power plant (Castle Peak Power Station)
  - Four large units with each 677 MW
  - Four small units with each 350 MW
- Gas-fired power plant (Black Point Power Station)
  - Eight combined cycle units (CCGT) with each 312.5 MW
  - One proposed CCGT unit with 600 MW (expected to be in operation by 2030) [13]

The coal units will "reach their normal retirement life in the next decade" [2, p. 21] and will be permanently shut down if the then available CCGT capacity is sufficient. Currently, no concrete plans to retire the coal units and no information on new CCGT units beyond the 600 MW unit mentioned above are publicly available. Therefore, we assumed that the above-mentioned coal units are available in 2030, too.

The oil-fired power plant of CLP in Penny's Bay is neglected, as the fuel mix share of oil in total Hong Kong is only 0.6% [14].

The simulation models are further based on the following assumptions and basic parameters:

A1. The availability factor of CCGT units, that means the fraction of hours in a year in which the unit is available, is 90% [15, 16].

$$a_{CCGT} = 0.9 \tag{1}$$

A2. A capacity reserve of 5% of the annual maximum load needs to be available at short notice at all times, similar to the German standard [17]. It ensures supply reliability during sudden load peaks. CCGT units are the preferred choice of power supply to provide this reserve because of their comparably short start-up time.

A3. Coal-fired units need to be operated at least at 40% of their nameplate capacity to ensure stable operation ("minimum stable operation limit") [18]:

$$u_{coal,min} = 0.4 \tag{2}$$

A4. The installed solar panels have an efficiency of 17% and a performance ratio of 0.85 [19]. A performance improvement of commercially available panels until 2030 is not considered.

2.3 Fuel mix change and power plant priority

The government of Hong Kong announced the fuel mix change and defined clear fuel mix targets.

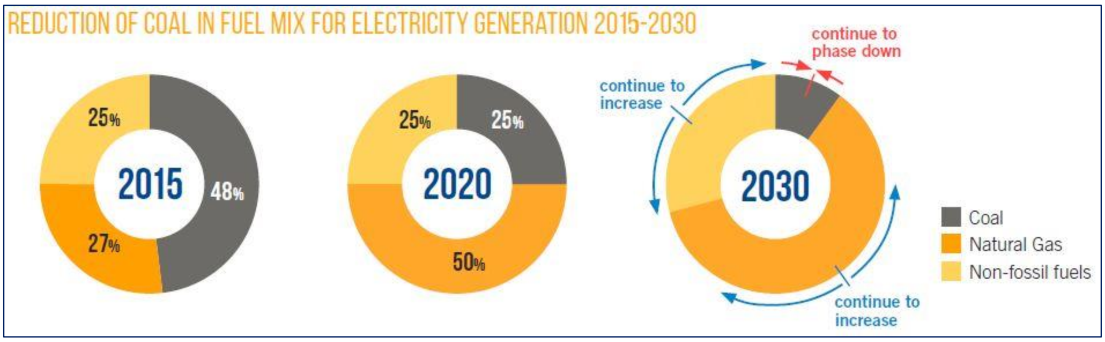

Figure 01: Fuel mix change defined by the government of Hong Kong [2, p. 20]
Target by 2030 is a significant reduction of coal and increase of gas generation with a slight rise of non-fossil fuels (primarily nuclear).

To meet these targets, CLP has undertaken two main measures:

T1. CLP will continue to import 80% of the output from Daya Bay Nuclear Power Station (DBNPS) into Hong Kong, at least until 2034 [2, p. 20, 20, p. 4].

T2. Gas-fired units will continue to bear the base load [20, p. 4].

Thus, the scheduling priority of conventional power plants for this simulation is as follows:

1. Nuclear power
2. CCGT
3. Coal (only if required)

2.4 Input data

2.4.1 Global solar radiation

The most recent data of global solar radiation available for Hong Kong on an hourly basis is from 2014[1]. For the simulation it is assumed that the hourly global solar radiation in 2030 is similar to 2014; no climate change effects are considered. The data shows a significant advantage of solar PV installation in Hong Kong when compared for example to Germany. Firstly, the daily peak in global solar radiation coincides with the demand peak around midday. Secondly, both demand and global solar radiation during summer months are higher than in winter months. Demand and solar radiation run cyclically in the day and throughout the year, which potentially reduces the need for electricity storage.

2.4.2 Electricity demand load

One of the major challenges of this work was the development of demand load profiles as such profiles hardly – surprisingly – exist. A set of load profiles from the year 1999, published by the EMSD [21, pp. 4-2 to 4-5], represent the most recent available data with the desired granularity!
In a *first step,* these profiles were translated into profiles for 2014 by utilising the monthly electricity consumption in 2014 from the Hong Kong Energy Statistics [22]. The resulting profiles, therefore, represent a good approximation for current load characteristics in the city. This derived set of load profiles is named “primary set”.

As a *second step,* demand reduction was considered by defining three demand scenarios for the year 2030. They are developed upon the primary set.

- Scenario 1: “2014 unchanged”

  Electricity consumption in 2030 is at the level of 2014 (43.9 TWh), i.e. the current demand growth rate of 1% is reduced to 0%. The demand profiles for this demand scenario are represented by the primary set.

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[1] Climatological data was provided by courtesy of the Hong Kong Observatory of HKSAR and is measured at a station located in King’s Park in Kowloon.

- Scenario 2: “2030 Energy Saving Plan 2015–2025+” (also “2030 ESP” or “2030 Energy Saving Plan”)

  The successful implementation of the Energy Saving Plan leads to an energy intensity reduction by 40% until 2025/ 2030 [3]. The total annual electricity consumption is reduced by 4.8 TWh from the 2012 level [4] to 38.2 TWh in 2030. To generate the corresponding load profiles, the primary set was re-calibrated to meet the annual consumption of this demand scenario when integrated over the full year.

- Scenario 3: “2030 HK3030 Vision”

  This demand scenario corresponds to the “HK3030 Vision” [7] and the “Market Drivers”-report, [8] published by the HKGBC. The electricity consumption of the building sector (commercial and residential) is reduced to 24.2 TWh in 2030. The industrial consumption is taken from the “2014 unchanged” demand scenario. The profiles for the three sectors were independently re-calibrated to meet these annual target values and were afterwards combined.

2.5 Input parameters

The output scenarios discussed in this paper are based on the following input parameters: the selected day in 2030; the demand scenario; and the installed solar PV capacity. Regarding the latter, the geography and settlement structure of Hong Kong set several limitations, not least due to the reserved stance of the Hong Kong government toward rooftop and building integrated solar PV installations [2, p. 24–34]. With respect to the tests on floating PV panels on reservoirs by the Water Services Department, these represent another opportunity for large-scale solar PV installation in Hong Kong and are in focus here. For our purposes the PV capacity is expressed as a fraction of the reservoir surface area in the CLP-supplied area:

$$A_{PV} = A_{CLP} \times u_{PV} \qquad (3)$$

The reservoirs within the area of CLP[2] have a total surface area of $A_{CLP} = 24.4 \text{ x } 10^6 \text{ m}^2$. The fraction ($u_{PV}$) can be chosen by the user.

2.6 Scheduling algorithm

For better understanding, Figure 12 visualises the algorithm which performs the power plant scheduling for one given day.

The algorithm has to perform three main tasks:

1) The demand load data and the global solar radiation data are prepared, based on the input parameters entered (*steps (1) and (2)*).

[2] The total reservoir surface area of Hong Kong is 25 x 10^6 m^2 [59]. Using the solar map by HKBU [60], the surface area of reservoirs outside of the CLP supply area has been measured and subtracted from the total area.

2) The available power plant capacities and the resulting minimum generation from coal units on the given day are calculated (*steps (3) to (7)*).

3) For both cases – without and with solar PV – the power plants are scheduled for each 15 minutes time step based on the power plant priority defined by the fuel mix targets. In each time step, the total generation must exactly meet the electricity demand.

Appendix A3 explains further limitations of the simulation in more detail.

2.7 Calculation of GHG emissions

To calculate the GHG emissions, the future emission intensities in 2030 for coal and CCGT units were estimated using the power plant efficiencies and specific fuel emissions. The coal units and today´s CCGT units are assumed to be the same in 2030 as today. In addition, a newly proposed 600 MW unit is considered for the CCGT fleet.
Only CO_2 is considered, as the shares of CH_4 and N_2O are very small [23].
The CO_2 emission intensities in 2030 are:

$$z_{coal} \approx 1.03 \frac{kg}{kWh\_el} \quad (4)$$

$$z_{CCGT} \approx 0.45 \frac{kg}{kWh\_el} \quad (5)$$

These values have been validated by calculating the emission intensity for CLP in 2012 (with the exclusion of the proposed 600 MW CCGT unit) based on CLP's fuel mix in 2012 [24, p. 10]. The calculation result ($z_{CLP} = 0.59 \frac{kg}{kWh\_el}$) is very close to the official figure ($0.58 \frac{kg}{kWh\_el}$) [25].

The emissions of CLP result as:

$$Z_{CLP} = E_{coal,CLP} \times z_{coal} + E_{CCGT,CLP} \times z_{CCGT} \quad (6)$$

$E_{coal,CLP}$/ $E_{CCGT,CLP}$ is the annual generation of CLP from coal/ CCGT.

Nuclear power plants and solar PV plants are considered as having zero operational GHG emissions.

To translate the fuel mix results of CLP into GHG emissions of whole Hong Kong, this paper assumes – for reasons of fairness – that the emission intensity of HKE is similar to that of CLP in 2030. Analysis showed that, due to the nuclear share in CLP's portfolio, this would require HKE to generate 100% of its electricity from CCGT. This is therefore assumed in this paper. The generation of HKE in 2014 (11 TWh, [11, 1, p. 22]) is calibrated to 9.6 TWh in the "2030 Energy Saving Plan" scenario and 6.8 TWh in the "2030 HK3030 Vision" scenario. The emissions of HKE are calculated in the same way as for CLP using equation (6). Efficiency improvements of potential new CCGT units at HKE are neglected.

This paper further assumes that until 2030 Hong Kong only reduces its power sector emissions, based on the Climate Action Plan and supported by the emission data from 2005 to 2012 [26, p. 21]. In 2012, Hong Kong's total emissions were 43.1 x 10^9 kg CO_2e including 29.3 x 10^9 kg CO_2e from the power sector. The remaining 13.8 x 10^9 kg CO_2e from other sources are considered as stagnant and will be added in all later introduced scenarios. The absolute emission reduction target of 26% is based on the year 2005, when emissions were 41.2 x 10^9 kg CO_2e [27, p. 2].

3 Results of the simulation

3.1 *Reference case*: Only fuel mix change, no demand reduction, no solar PV

The reference case assumes that the fuel mix changes as planned, but neither the demand is further reduced, nor any solar PV capacities are installed (“2014 unchanged” demand scenario).

3.1.1 Fuel mix change in the one-day scheduling

Figure 02 displays a typical output of the one-day scheduling (01.07.) after implementation of the fuel mix change. The diagram plots the load in Megawatts over the time of the day. The black curve displays the demand load in CLP’s area that must be met. The purple/ black/ blue stacked areas represent electricity generation by nuclear/ coal/ CCGT units respectively.

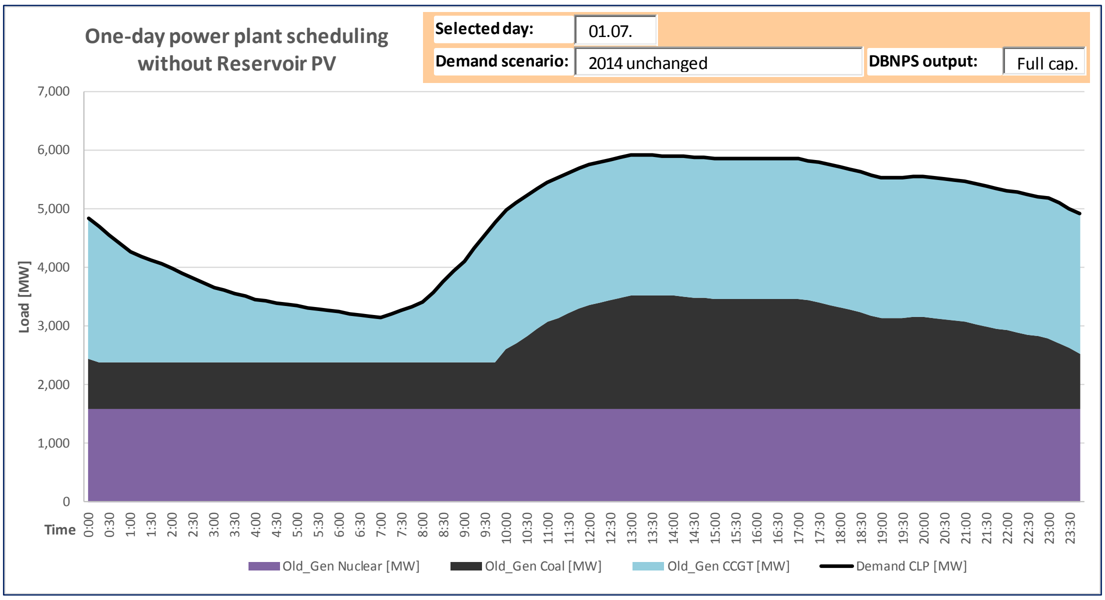

Figure 02: One-day power plant scheduling for a summer day (01.07.) in "2014 unchanged" scenario without solar PV (own compilation)
DBNPS continuously supplies a base load; coal units are ramped up to support CCGT during on-peak times; CCGT supplies as much electricity as possible, but is restricted during off-peak hours by the minimum generation from coal units.

Nuclear power from DBNPS supplies a constant base load of 1,574 MW. During peak load at 13:00, the CCGT units are ramped up to a maximum of 2,396 MW. The remaining load of 1,946 MW has to be covered by coal units, which requires three 677 MW units with total capacity of 2,031 MW. Following assumption A3 (40% minimum stable operation limit), their minimum generation is 812 MW. This minimum generation applies for the whole day since switching off coal units from 02:00 to 08:00 am is infeasible because of their hot start-up time of 3 hours [28, 29, p. 11, 30].
During the minimum load hour (07:00 am), the remaining load after taking nuclear generation into account is 1,562 MW. Theoretically, the capacity of CCGT units is sufficient

to supply this load fully. However, the coal units need to be operated at their minimum generation of 812 MW; this limits generation from CCGT units to 749 MW.
This restriction can be observed throughout the whole year. Even after the implementation of the fuel mix change, the limited CCGT capacity requires coal units during on-peak hours. As a direct result and because cycling coal units being mostly infeasible, coal units must operate at their minimum generation around the clock. As a consequence CCGT units cannot be fully utilised during off-peak hours.

3.1.2 Fuel mix change in the full-year fuel mix

One of the crucial question for future investment in the energy sector is whether the assumed CCGT units are sufficient to achieve the 2030 emission reduction target? Or are additional CCGT units or other measures necessary?

Figure 03 presents the full-year fuel mix of CLP after the fuel mix change with currently eight CCGT units installed plus the proposed 600 MW CCGT unit. This translates into 12.5 x 10^9 kg CO_2e emissions. Hong Kong's emissions will then amount to 31.3 x 10^9 kg CO_2e[3] (see also chapter 2.7), which means an absolute reduction of 24% (compared to 2005).
The lower bound of the emission reduction target (26%) can be almost achieved. But further emission reduction to meet the upper bound of the target (36%) is not possible under this scenario.

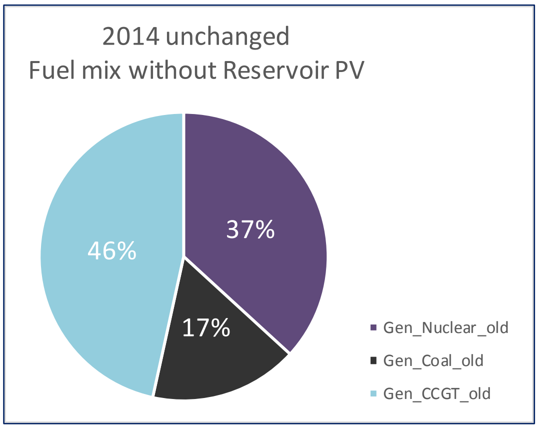

Figure 03: Full-year fuel mix at CLP in "2014 unchanged" scenario without solar PV (own compilation)

3.2 Impact of demand reduction

3.2.1 Demand reduction in the one-day scheduling

In the one-day scheduling, the demand reduction scenarios lead to lower demand values in each time step. While DBNPS supplies the same baseload as in the reference case, the CCGT units can then provide a more significant fraction of the remaining demand, while fewer coal units are required.
Under the "2030 HK3030 Vision" scenario, the one-day scheduling for the months March, April, May, October, and November revealed, that during off-peak hours in the morning even DBNPS alone supplies more electricity to Hong Kong than required.
In this situation potential solutions could be: Reducing the generation from DBNPS or its supply to Hong Kong; interconnecting the grids of CLP and HKE and passing electricity from DBNPS to HKE to substitute HKE's generation from CCGT units; or storing the surplus output of DBNPS in a storage, e.g. pumped hydro storage.
In general, one-day scheduling characteristics do not change with demand reduction.

[3] 5.0 x 10^9 kg CO_2e from HKE.

3.2.2 Demand reduction in the full-year fuel mix

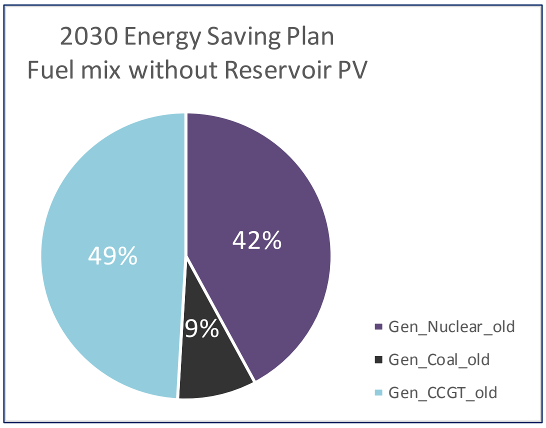

Figure 04: Full-year fuel mix at CLP in "2030 ESP" scenario *without solar PV* (own compilation)

"2030 Energy Saving Plan" scenario

In the *"2030 Energy Saving Plan"* scenario, generation from coal units is substantially reduced, but still cannot be entirely phased out with the assumed CCGT capacity (Figure 04). CLP still emits 9 x 10^9 kg CO_2e annually. Hong Kong's emissions[4] of 27.1 x 10^9 kg CO_2e represent an emission reduction of 34% (compared to 2005).

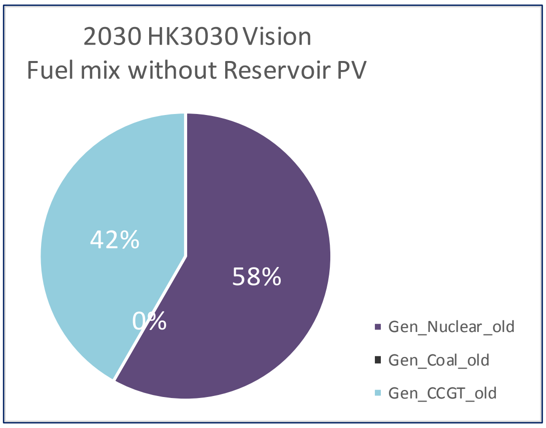

Figure 05: Full-year fuel mix at CLP in "2030 HK3030 Vision" scenario *without solar PV* (own compilation)

"2030 HK3030 Vision" scenario"

In the *"2030 HK3030 Vision"* scenario, coal power plants are not required anymore, and generation from coal units can be entirely phased out (Figure 05). The electricity supply is guaranteed by DBNPS and CCGT units, with DBNPS becoming the major source of electricity. This fuel mix results in 3.9 x 10^9 kg CO_2e emissions, leading to 20.8 x 10^9 kg CO_2e total emissions of Hong Kong[5] and an absolute emission reduction of 49%.

3.3 Impact of solar PV installation

Given the discussion on solar PV installation on Hong Kong's territory, the impact of solar PV will be discussed both in the one-day scheduling and in the full-year fuel mix perspective. The assumption is that 80% of the reservoir surface area in the CLP area is used for panel installations. This equals a solar PV capacity of 2.8 GW_{el} (see assumption A4) and would be less than in Germany in 2017 on a per capita basis (390 vs 500 W/per capita). This paper does not claim that a utilisation ratio of 80% is the technical or economic optimum, it deliberately chooses a high value to scale up and to visualize the potential effects.

[4] 4.3 x 10^9 kg CO_2e from HKE.
[5] 3.1 x 10^9 kg CO_2e from HKE.

3.3.1 Solar PV in the one-day scheduling

Figure 06 shows the impact on the one-day scheduling taking the 28.07. as example. The green stacked area represents infeed from solar PV panels.

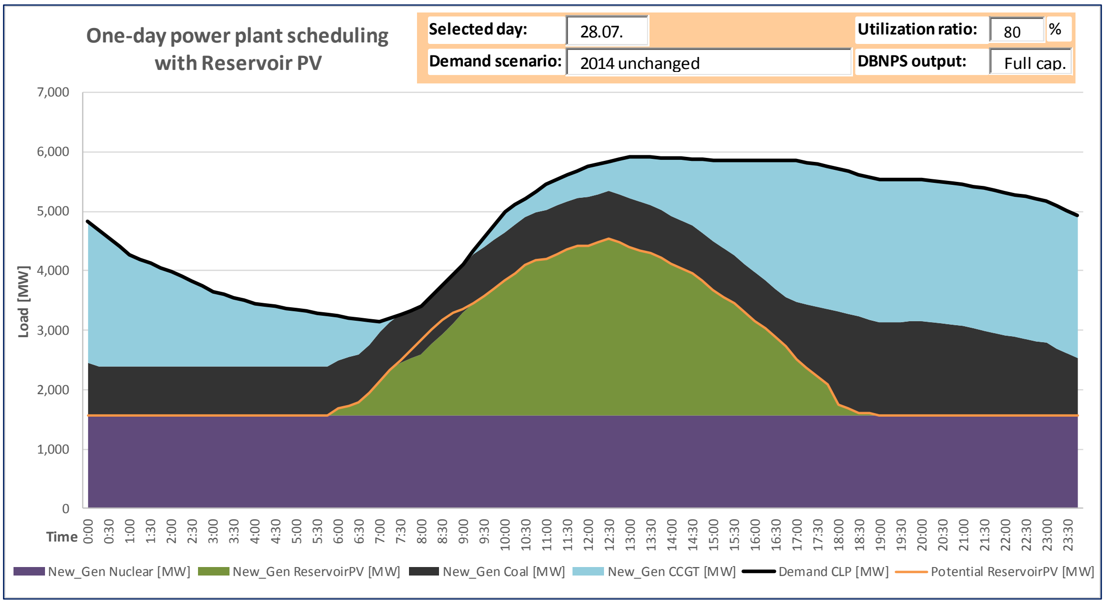

Figure 06: One-day power plant scheduling for a summer day (28.07.) in "2014 unchanged" scenario with solar PV at 80 % utilisation ratio (own compilation)

DBNPS operates unaffected; solar PV generation substitutes coal and CCGT generation, coal generation at least at minimum stable operation limit.

On this sunny day, solar PV can supply a significant fraction of the load during on-peak hours. A comparison with Figure 02 shows, that generation from coal units is lowered down to the minimum stable operation limit. Generation from CCGT units is also significantly substituted. In the evening hours, coal and CCGT units ramp up again to compensate for the diminishing solar PV generation.

On sunny days like July 28th, coal units operate at their minimum stable operation limit for almost 16 hours. During this period, CCGT units cannot be fully utilised. This raises a crucial question: Given the solar PV infeed, is it now feasible to shut down coal units when they are not required after midnight and turn them on again in the early evening? Such daily cycling had been performed in US coal power plants built in the 1970s [28]. In this case, the benefit for Hong Kong would be a higher utilisation of the CCGT units on sunny days. On those days solar PV generation can supply a major share of the midday load peak so that coal units are only required in the late evening. However, this mode of operation would also lead to increased wear and tear and thereby higher maintenance costs.

For an answer, we look at the one-day scheduling on 23.9., when a substantial drop in global solar radiation occurred (Figure 07).

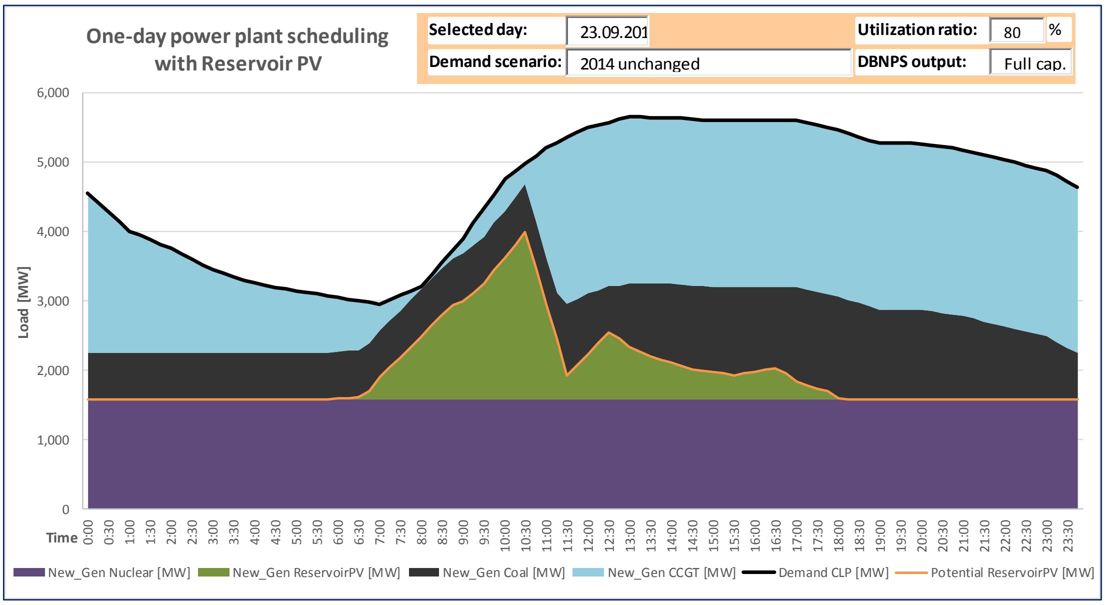

Figure 07: One-day power plant dispatching for 23.09. in "2014 unchanged" scenario with solar PV at 80% utilisation ratio (own compilation)

DBNPS operates unaffected; solar PV generation drops significantly after 10:00 and requires quick ramp-up of coal and CCGT units to avoid an outage.

This drop in radiation requires CCGT units to ramp up to full capacity within just one hour, which is within the technical ramp rate limits [18]. As CCGT capacity is not sufficient, coal units must be ramped up, too – on short-notice within 1.5 hours after the solar PV generation dropped. This ramp rate for coal units is also technically feasible [18], but can only be performed if the coal units are operating. If they were cycled and thus turned off, the hot start-up time of 3 hours [28, 29, p. 11, 30] would not allow coal units to be ramped up, resulting in a possible outage. Due to complex weather phenomena in locations sea-near like Hong Kong, day-ahead predicting of solar radiation is very difficult (i.e. cloud cover). To ensure supply reliability, sufficient capacity of conventional power plants (or storage systems) must be available at all times. As long as CLP's CCGT and storage capacities are not adequate, coal units can therefore not be cycled.

The direct result of these limitations is a deplorable constrain in CCGT utilisation, similar to the case presented in chapter 3.1.1. It further results in solar PV curtailment (see Figure 06), as the potential solar PV generation (orange curve) is higher than the actual possible infeed (green stacked area): DBNPS generates on a stable level, CCGT units are turned off, and coal units already operate at their minimum stable operation limit. As a result, 1.3% of the solar PV potential is lost. The more the electricity demand is reduced in the future, the more often curtailments of solar PV would happen.

3.3.2 Solar PV in the full-year fuel mix

Based upon our assumption on the area utilized for PV panels, the resulting 2.8 GW_{el} of installed solar PV capacity could supply around 12% of Hong Kong's annual electricity consumption (Figure 09) when aggregating all 15 minutes time steps. In comparison to the reference case (Figure 08), the generation from coal units is reduced only by three percentage points. This is because the coal generation can only be lowered to its minimum stable operation limit, but not further. As a result, solar PV generation reduces power generation from CCGT units by nine percentage points. As long as those technical restrictions of coal units cannot be overcome, the installation of solar PV cannot contribute to phase down the share of coal and to increase that of gas. Furthermore, there will be a conflict of investments: to support the fuel mix change, CLP has to invests in additional CCGT units. But if the company also invests in solar PV to further reduce emissions, the utilisation of CCGT units and thereby their contribution margin will decrease, while coal units will operate nearly unaffected.

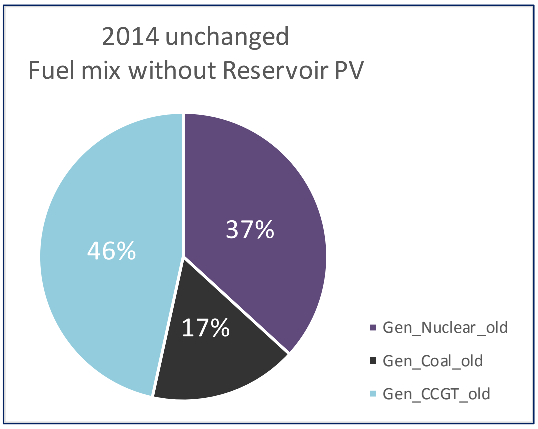

Figure 08: Full-year fuel mix at CLP in "2014 unchanged" scenario *without solar PV* (own compilation)

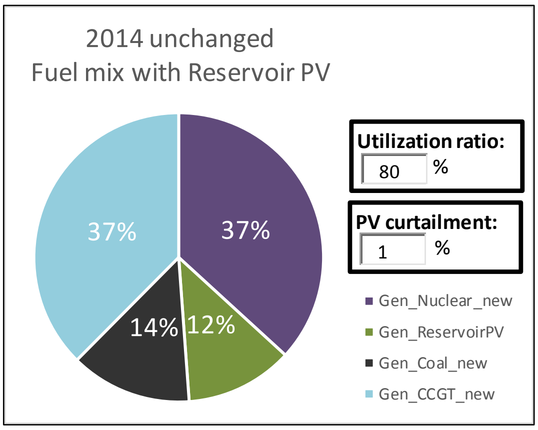

Figure 09: Full-year fuel mix at CLP in "2014 unchanged" scenario *with solar PV* at 80% utilization ratio (own compilation)

As solar PV generation substitutes rather CCGT than coal units, its effect on the GHG emissions will be only moderate. With 2.8 GW_{el} installed capacity in the “2014 unchanged” scenario, CLP’s emissions will be lowered to 10.2 x 10^9 kg CO_2e (Hong Kong’s total emissions to 29.0 x 10^9 kg CO_2e[6]), which means an absolute emission reduction of 29% (2005) or 5% additional reduction beyond the fuel mix change. For the other two demand scenarios, further analysis showed that 2.8 GW_{el} installed capacity would lead to slightly lower absolute emission reductions due to increased solar PV curtailment.

3.4 Summary and discussion of simulation results

To comply with the Paris Agreement, per capita emission in Hong Kong have to be reduced to 2.0 t [2, p. 17]. Table 1 summarises the results of the power plant scheduling simulation.[7]

The reference case showed that the fuel mix change with the currently installed CCGT units and the proposed additional 600 MW unit would lead to an absolute emission reduction of 24%, and thereby achieve only the lower bound of the target range (3.9 t CO_2e emissions per capita).

Implementing the proposals of the Energy Saving Plan could lead to another 10% additional absolute emission reduction beyond the fuel mix change. Thereby the upper bound could nearly be reached and the per capita emissions reduced to 3.4 t CO_2e per capita).

[6] 5.0 x 10^9 kg CO_2e from HKE.
[7] Hong Kong’s population is assumed to increase to 8.0 million by 2030 [31, p. 7].

	Reference case	Demand reduction		Solar PV installation
	Fuel mix change	Fuel mix change + Energy Saving Plan	Fuel mix change + HK3030 Vision	Fuel mix change + solar PV installation (80% utilisation ratio)
Absolute emission reduction (base year 2005)	24%	34%	49%	29%
Per capita emissions	3.9 t	3.4 t	2.6 t	3.6 t

Table 1: Comparison of emission reduction results for the reference case with scenarios of demand reduction and solar PV installation (own compilation)

A successful implementation of the HK3030 Vision could even add 25% of absolute emission reduction beyond the fuel mix change, lowering per capita emissions to 2.6 t CO_2e per capita.
In contrast to this, the installation of 2.8 GW_{el} of solar PV capacity (80% of the reservoir surface), would lead to only 5% additional absolute emission reduction, reducing per capita emissions from 3.9 t (reference case) to 3.6 t (see also **Figure 10**).

These figures clearly underline the importance of a substantial demand reduction for both achieving the domestic reduction target for 2030 and the 2.0 t per capita target by the Paris Agreement. In contrast to demand-side measures, the large-scale integration of solar PV into Hong Kong's current system would fail to achieve the desired effect due to the technical limitations of existing coal power plants and thereby unwanted substitution of CCGT capacities.

There are several entry points to improve the situation:

- Old coal power plants can and should be retrofitted to make them more flexible and allow operations below 40% of their nameplate capacity.

- Electricity storages can help to phase down coal generation. Electricity generated by vacant CCGT units during off-peak hours and from solar PV could be stored and shifted to the evening hours. On July 28th (see Figure 06), if CCGT units operate at their maximum capacity for the entire day, the aggregated generation from CCGT, nuclear, and solar PV would be sufficient to supply the aggregated demand. No coal units would be required. The Guangzhou Pumped Storage Power Station can already today be used to store electricity from vacant CCGT units during off-peak hours to reduce the generation from coal units during on-peak hours.

4 Barriers for electricity demand reduction in Hong Kong's energy politics

The scenarios presented in chapter 3 clearly showed the significance of a drastic reduction of electricity demand for a low-carbon future of Hong Kong's electricity system. Numerous suggestions for a sustainable transformation of Hong Kong's electric demand side have been made so far. E.g. [31, 32]. They all show significant potential for energy efficiency improvements of 20–40 %, even with already available technologies [33, 34, 35, 36, 37, 38, p. 103]. These potentials are not limited to a small number of individual buildings, but exist in a large scope throughout the city, as HKGBC revealed in its "HK3030 Vision". [7, p. 10]. HKGBC, therefore, suggests a 30% absolute electricity consumption reduction until 2030.

Despite these potentials, only little to moderate achievements have been made since then. The electricity consumption of the city increased on an annual average of 1.1% (2004–2014) despite a further shift from manufacturing to service-focused business [1, p. 22, 39, p. 104]. In 2003, the EMSD estimated potential electricity savings through water-cooled air conditioning systems at 1,170 GWh/a by 2020 [31, p. 28]. At the end of 2016, only 410 GWh have been realised [2, p. 44].

Barriers to a sustainable transformation exist both in politics and in business. A literature review shows that some of the obstacles in the political sector have repeatedly been discussed since 2008 [40, 41, 42].

For a holistic understanding of the specific institutional settings in the field of energy policy in Hong Kong, a framework was developed to group barriers towards a more ambitious transformation policy.[8] Following the concept of the "4Ts framework" by the Hong Kong government [2, p. 12], three central elements have been defined: "Target and Timeline", "Transparency", and "Together". For each element, essential requirements are clustered to successfully engage in sustainable transformation, so-called "building blocks", forming an "Essential Building Blocks Framework" (Figure 11, chapter 6.1).[9]

The barriers to Hong Kong's energy politics were identified through an extensive literature review and 19 semi-structured interviews of one to two hours length between April and September 2017. Interviewees had been government officials, engineers in governmental departments, engineers in the utility companies, managers in private companies, NGO/ council/ think tank representatives, university professors as well as independent energy consultants and engineers (see chapter 8 **Fehler! Verweisquelle konnte nicht gefunden werden.**).
The interview findings were supplemented by presentations and personal conversations with speakers at international conferences in Hong Kong, Singapore, and Mainland China. To protect the privacy of the interviewees and discussion partners, statements were mostly anonymised.

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[8] This framework was initially created during a "Climate Change Initiatives and Chinese Cities" study trip organized by the Hong Kong America Center and the Konrad Adenauer Foundation in 2017.

[9] The "building block" does not imply any claim to completeness.

4.1 Targets and Timeline

The following subchapters discuss the most critical barriers identified by the interviewees and scientific literature. They don't claim to be comprehensive.

4.1.1 Milestones and targets

4.1.1.1 Set targets are not ambitious

(1) Hong Kong's carbon emission intensity reduction target of 65–70% by 2030 was set according to the Chinese national targets [26, p. 6, 2, p. 11] (Interview 16). In contrast, internationally leading cities in climate change mitigation such as New York City, Seoul, and London have set much more ambitious goals than their national counterparts and outperform by far the national targets (Interview 16) [43]. Seoul, as for example, achieved 4% electricity consumption reduction between 2011 and 2014 despite the national consumption increase of 4% [43].

(2) The HKGBC further points out that for a service-oriented business city like Hong Kong intensity-reduction targets are inappropriate [7, p. 10], since GDP growth and carbon emissions are decoupled.

(3) The government's Energy Saving Plan 2015–2025+ leads to 12% electricity consumption reduction [4, 1, p. 22] from base year 2005. In comparison, saving potentials range from 20–40% and are achievable within economically viable payback periods in numerous buildings [8, 36, p. 275, 37, p. 64].

4.1.1.2 Lack of comprehensive targets and long-term perspective

(1) Besides energy consumption and emission reduction targets, Hong Kong lacks further objectives such as the installation of renewable energy [5]. The government only proposes "potentials" [2, p. 24].

(2) No targets are set for Hong Kong beyond the timeline of 2030, as the government describes this as "extremely difficult" [2, p. 17]. Countries like Germany committed to long-term targets until 2050, providing a higher degree of certainty to all stakeholders [44, p. 11&58].

4.1.1.3 Past (proposed) targets remained unachieved

(1) In 2010, the government "proposed" an RE target of 3–4% in the fuel mix until 2020 [45, p. 43]. This seems unachievable, given the fact that the share of RE in the fuel mix was a regrettable 0.1% in 2014 [1, p. 16] and an installed solar PV capacity of less than 5 MW in 2017 [2, p. 26]. The Climate Action Plan proposes a "realisable RE potential" of again 3–4%, this time until 2030 [2, p. 24].

(2) In line with this less than 50% of the in 2003 estimated potential savings through water-cooled air conditioning systems have been unlocked until 2016 [2, p. 44].

4.1.2 Roadmap

A strategic "Roadmap" must exist to supplement targets and milestones, including detailed actions and measures for achievement. In Hong Kong, both the demand and the supply side lack a clear roadmap.

4.1.2.1 Deficiencies in the supply side roadmap

(1) On the supply side, the fuel mix change was designed as the primary measure. However, essential information regarding economic, ecological, and social sustainability, such as required investments and potential challenges, had not been published. This proceeding was also criticized concerning the fuel mix consultation in 2014 [46].

(2) The "realisable RE potential" of 3–4% [2, p. 24] requires at least a 50-fold increase of the generation from PV in 2014. However, no dedicated action to increase the share of renewable energy was presented by the government so far.

4.1.2.2 Deficiencies in the demand side roadmap

The 40% target in the Energy Saving Plan, which is not further segregated into sectors, is not linked to any dedicated measures. Actions are only vaguely described, such as "require more frequent audit for air conditioning system" [2, p. 39]. An overview published in the South China Morning Post reveals that 39% of the targeted savings come from tightening regulations such as the Building Energy Code, for which no details are given in the Energy Saving Plan [4]. Moreover, the remaining 60% of the reduction have to come from "other measures to be rolled out at later stage" [4].
In contrast, the HKGBC elaborated potential electricity reduction measures along ten roadmaps already in 2012/2014 [7, 8]. However, the government only briefly summarised this document in its Energy Saving Plan [3, p. 45], but did not utilise any proposed measure, detailed information, and even less calculated potentials.

4.1.3 Institutional resources[10]

In Hong Kong, energy issues are handled primarily by the Environment Bureau (besides all other environmental topics), the Environmental Protection Department, and the EMSD. No dedicated authority with legislative power regarding "energy" has been set up so far.
Maria Francesch-Huidobro [41] described the actions of state and non-state actors as "rarely in any concerted fashion" [41, p. 3] and pointed out the "chronic lack of capacity for horizontal coordination" [41, p. 12], as the following examples show:

(1) Both the Census and Statistics Department and the EMSD publish energy consumption data, but with different sector definitions and granularity.

(2) The Water Services Department conducts the test of floating solar PV panels because it operates the reservoirs, although the EMSD has the technical know-how.

[10] In this context institutional resources in the government are understood as dedicated government departments and inner-governmental collaboration.

(3) While the Environment Bureau promotes the use of co-generation and tri-generation [26, p. 31], a property development firm had to experience that the Environmental Protection Department hampers the actual installation in new buildings (Interview 17).

In 2016, the Inter-departmental Working Group on Climate Change was replaced by the Steering Committee on Climate Change to promote collaboration. However, besides the Climate Action Plan, the only published document is a meeting minute from April 7, 2016 [47].

4.2 Transparency

Transparent, comprehensive energy data on sectors, segments, and fuels for different time periods will help the government in assessing the performance of all (sub-)sectors, creating local and international benchmarks, setting targets, defining corresponding roadmaps and drafting policies.
To support the government with stakeholder perspectives, technical and policy recommendations, and general independent research, NGOs, think tanks, and academia rely on comprehensive and transparent data (Interview 15). They further need data to critically review the government actions.

In Hong Kong, transparency issues are often overlooked (Interviews 16 and 18), although major barriers exist in data existence and availability:

(1) Data on energy end-use, published by the EMSD, is based on surveys instead of sectoral measurements (Interviews 13 and 14). Data is only available on an annual basis, no monthly information for sub-sectors/end-uses exists. Due to the different sector definitions, these data are not aligned with those published by the Census and Statistics Department.

(2) The latest comprehensive load profiles date back to 1999 [21, p. 4.2–4.5].

(3) Likewise, building energy consumption data is rare, as sub-metering and especially smart-metering is not widely rolled-out [35, 48, p. 516].

(4) Consequently, a comprehensive building benchmarking system does not exist. The one created by the EMSD in 2009 [49] cannot reach the requirements in terms of granularity and up-to-dateness.

(5) General information, for example on the distribution of different air-conditioning technologies, is not provided by the EMSD, even on request, further stating that it does not have the “full picture” and that “limited resources” hinder further analysis (Interview 14). They also reason that the large blocks of unidentified “others” (30–40%) in the energy end-use are a result of “follow[ing] traditions” (Interview 14).

Think-tanks and academia in Hong Kong cannot conduct research without published data. As Jing et al. [35] vividly describe: acquiring sufficient electricity consumption data from commercial buildings in Hong Kong is extremely difficult [35, p. 128]. They there-

fore highly recommend a “[s]mart sub-metering system and data recording in an appropriate manner” [35, p. 128].
Given this lack of data, it is not surprising that estimations of the energy saving potentials even for whole sectors rarely exist, not to talk about such for specific types of buildings. Likewise, electricity system models for Hong Kong depend on annual or rough monthly data but cannot consider essential characteristics such as load fluctuations [50, 51, 52].

Without much more detailed energy consumption data, neither the government nor any other institution can segregate the overall reduction targets and design realistic roadmaps. This needs a proper understanding of the potential impact of different measures and priorities to be given. How will the government be able to tighten the Building Energy Code as proposed in the Energy Saving Plan [3, p. 69] without detailed building data and a benchmarking system?

5 Conclusions

5.1 Prioritising actions

The results of the author´s simulations as well as results of other research clearly advice priorities for actions to transform the incumbent electricity system into a low-carbon system. *First*, a substantial reduction in electricity demand has to be achieved together with a change in the fuel mix. This helps to phase down existing coal-fired units and to reduce the impact of their technical limitations. This could lead to per capita emissions of 2.6 t CO_2e/a, which would be a major step towards the final target set in the city´s Climate Action Plan 2030+.
Substantial progress in optimising the utilisation of storage options could massively contribute to this end.

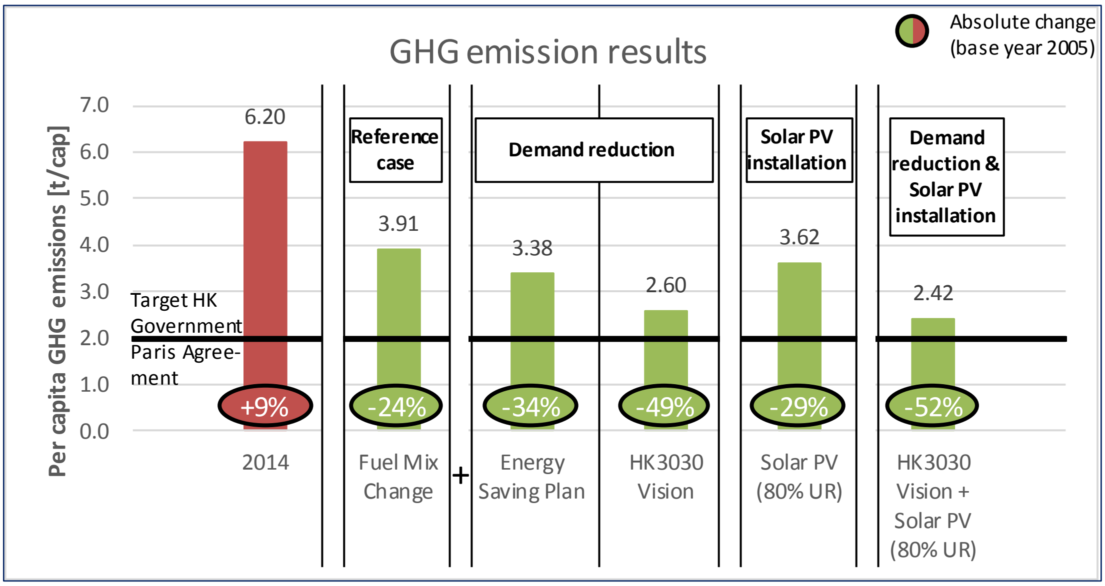

Figure 10: Greenhouse gas emission results in analysed scenarios as per capita and absolute reduction values (own compilation; 2005 and 2014 data from [27, p. 2, 2, p. 16]**)**

Impact of demand reduction by far outperforms impact of solar PV installation, among others due to the technical limitations in coal power plant operation. The HK3030 Vision can reduce emissions down to 2.6 t per capita.

Second, solar PV should be widely installed on reservoirs to improve the system further and reduce emissions. If solar PV is installed at an 80% utilisation ratio and the HK3030 Vision is successfully implemented at the same time, per capita emissions could be lowered to even 2.4 t/a. The remaining gap to the 2.0 t target can be closed by focusing on other emission sources.

5.2 Proposals for government actions

Major barriers in Hong Kong´s energy politics have been identified, ranging from unambitious yet unachieved targets and weak roadmaps over a lack of institutional resources and government leadership all the way down to deficits in transparency. Many interviewees expressed their hope that energy conservation becomes a primary field of action and that the Hong Kong government would act more decisively and ambitiously in this respect.

Following the structure of the Essential Building Blocks Framework, we suggest:

5.2.1 Transparency

Creating a comprehensive set of data and standardised measurements

- This database, linked with a benchmarking system, should comprise energy consumption data of segments, end-uses, and fuels along various time horizons; load profiles; energy audit and benchmarking reports.
- Requiring mandatory data monitoring and reporting by businesses and utility companies.

Enhancing accessibility

- Relevant information should be released (under consideration of privacy) to enable research by and advocacy of academia, NGOs, and think tanks.

5.2.2 Target and Timeline

Government Leadership

- The Hong Kong government should take the central leadership position. This includes a holistic planning process; formulating comprehensive regulatory and incentive policies; and acting as a role model through green building and leasing.

Institutional Resources

- An Energy Agency should be established, in which various energy specialists are involved. This agency should have wide-spread responsibilities and regulatory power in collecting and compiling data; in benchmarking; in defining targets and roadmaps; and in new energy efficiency initiatives.

Milestones and Targets

- The government should not slack off in its efforts to set ambitious and achievable milestones for absolute carbon emission reduction, energy consumption reduction, and renewable energy installation. The level of ambition should exceed that of the Mainland China and should instead follow the example of other global cities (i.e. of the C40 network).

Roadmap

- Dedicated measures to achieve the above-mentioned milestones and targets have to be developed and their potential and impact measured. This will only be successful if sufficient and comprehensive data is available.

It is also highly recommended to deepening international exchange. For some actions, reference cases already exist. I.e. high granularity load profiles exist in Germany [53, 54] and dedicated measures exist within the “One Less Nuclear Power Plant” policy in South Korea (Seoul) [55, 56].

5.3 Options for further research

This analysis has concentrated on the development of a power plant scheduling simulation for Hong Kong and fundamental analyses as well as on identifying major energy political barriers. It had to leave out numerous other important parts of the analytical framework presented. Regarding the *technical analysis*, the following items could be scrutinised in more detail:

- The estimated load profiles should be substituted by real data from CLP (if those exist and are available);
- Further prospective CCGT capacity could be simulated in various demand scenarios;
- Various storage options, e.g. pumped hydro storage, could be simulated to further optimise the utilisation of CCGT units and solar PV plants
- Simulating power plant scheduling for HKE and interconnection of the grids of CLP and HKE could identify further optimisation potential through joint electricity grid operations;
- Demand-side flexibilities could be simulated to assess further optimisation potential and challenges for power plant scheduling;
- The economic impact of each scenario could be assessed in detail.

In respect to the *political* analysis, further main elements of the Essential Building Blocks Framework had to be left out so far. Interviews indicate that several other barriers exist, in particular in the business sector.

The barriers that have already been identified in our analysis should be further analysed in depth to develop potential solutions and action plans.

6 Appendix

6.1 Essential Building Blocks Framework

In order to assess the complexity of climate change policy in Hong Kong and to set up an analytical framework, an "Essential Building Blocks Framework" has been developed. Different "blocks" comprise main factors (or a bundle of factors), which essentially influence the political decision-making processes in the city of Hong Kong. They are further used to analyse the performance of climate change mitigation in Hong Kong's electricity sector.

- "Target and Timeline" mainly describes concepts and actions by the Hong Kong government to formulate, implement, and monitor different measures to mitigate climate change.
- "Together" encompasses concrete actions by public or private stakeholders or individuals to share their efforts towards the target of emission reduction.
- "Transparency" serves the two other central elements in assessing the performance, increase accessibility, and provide the empirical basis for action.

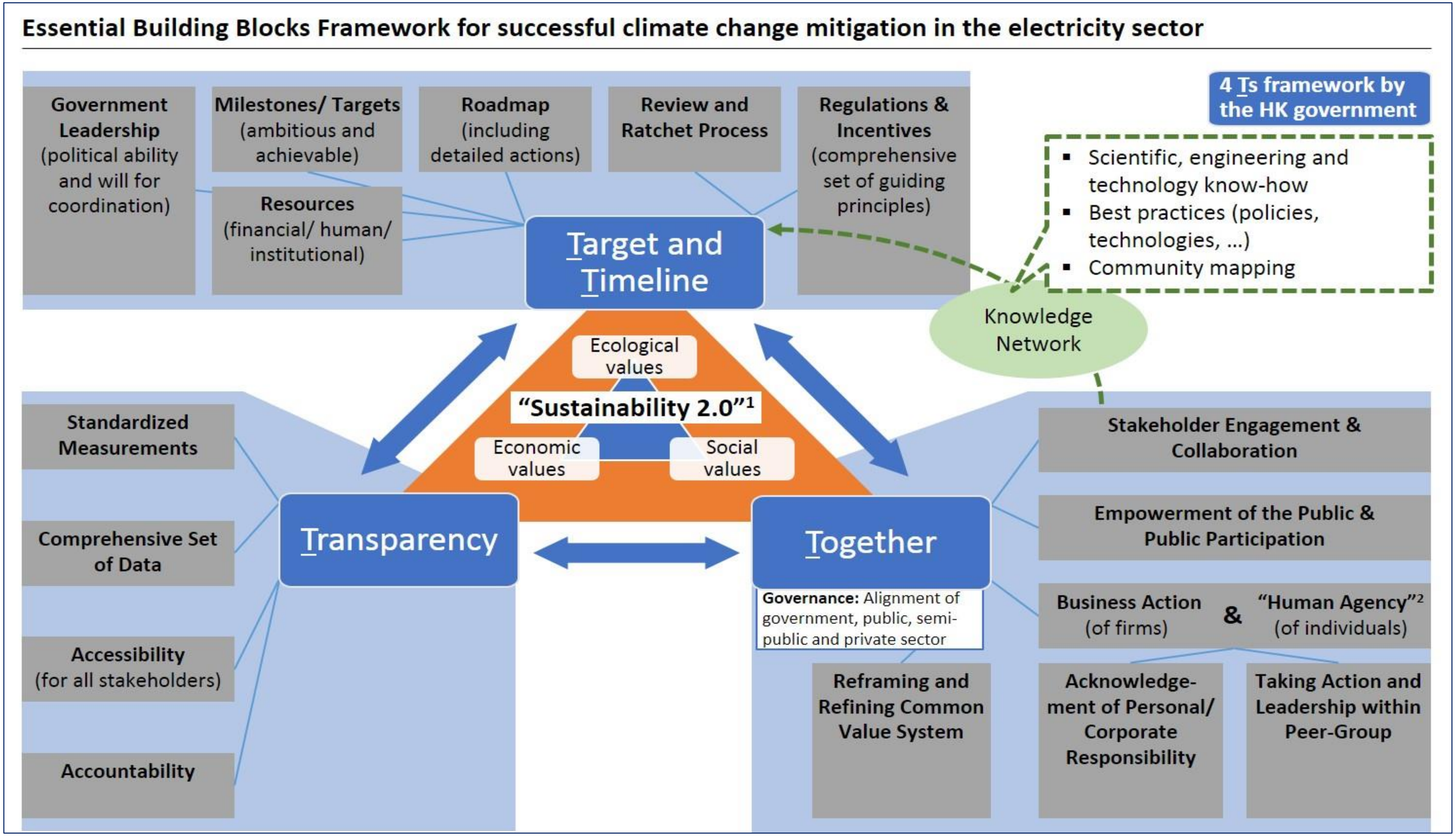

Figure 11: Essential Building Blocks Framework for successful climate change mitigation in the electricity sector (own compilation)

6.2 Scheduling algorithm flow chart

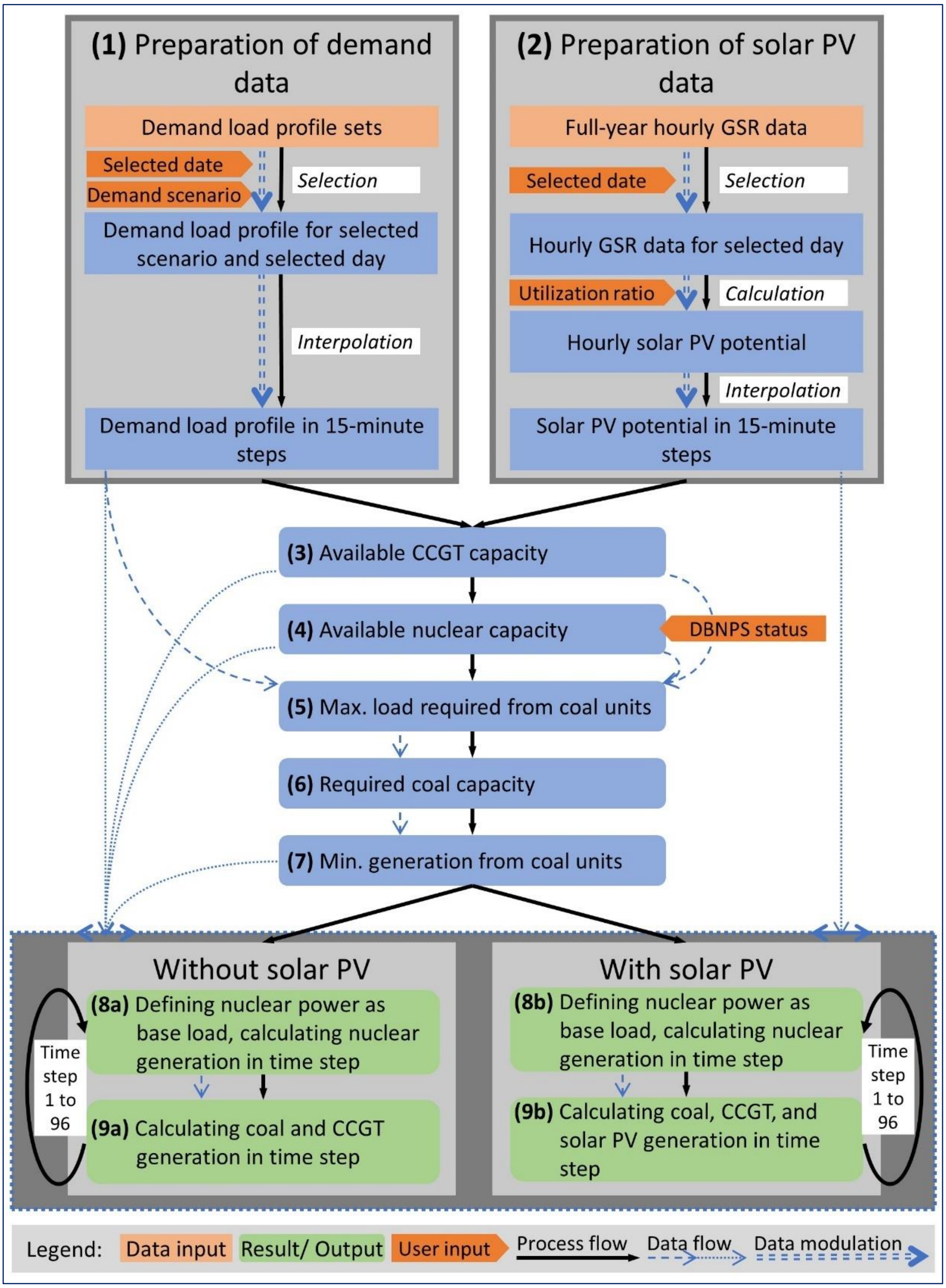

Figure 12: Flowchart of core code procedure steps (own compilation)

* Data flow means that the result is used as input for the following calculation. Data modulation means that data itself is forwarded and modified, for example through selection and interpolation processes.

6.3 Limitations in the power plant scheduling simulation

6.3.1 Limitations in the input data

The demand load profiles were derived on the basis of original profiles of 1999 comprising one average hourly profile per month. As a first step, a linear calibration process was made to derive profiles for 2014, followed by a second re-calibration towards the demand scenarios. No adjustments with respect to the relative course of the curves could be made as no newer or detailed information was available. However, as extreme changes in Hong Kong's electricity demand pattern have not been recorded throughout the last years, the assumed profiles should be a good approximation.

The hourly global solar radiation data, measured by the Hongkong Observatory, are of very good temporal granularity. Despite a spacial limitation (only one measurement station), we assumed no significant influence on the results of the simulation as effects on the very short time scale such as radiation peaks are not analysed.

In the process of assuming weather data from 2014 to 2030, changing weather patterns and climate change effects had not been considered.

6.3.2 Limitations in the scheduling algorithm

Limitations exist for very detailed information on CLP's power plants (i.e. exact start-up times, etc.) as only general information (i.e. capacities) is publicly available.

All parameters (power plant availabilities, minimum stable operation limits, minimum down times, etc.) have been carefully chosen and are based on well-researched, publicly available data sources on comparable power plants.

To keep the model computable, CCGT units are considered as fully flexible. The assessment showed that the impact of this simplification is very limited.

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8 Interview logbook

Code	Date	Interviewee
Interview 1	12.04.2017	PhD student, focus on Sustainable Development in Hong Kong
Interview 2	24.04.2017	Energy Economist and Climate Professional at The World Green Organization
Interview 3	25.04.2017	Principal Investigator & Consultant for Climate Change Policy
Interview 4	28.04.2017	Division Head at WWF Hong Kong
Interview 5	02.05.2017	Senior Manager at Business Environment Council
Interview 6	06.05.2017	Professor of Engineering Science and Economics
Interview 7	09.05.2017	Division Head at WWF Hong Kong
Interview 8	17.05.2017	Professor of Building Services Engineering
Interview 9	22.05.2017	Retired Engineer from Institution of Civil Engineers, Hong Kong Association
Interview 10	26.05.2017	Energy Engineer and Consultant
Interview 11	08.06.2017	Member of the Hong Kong Association of Energy Service Companies
Interview 12	08.06.2017	Environmental Consultant
Interview 13	09.06.2017	Manager at Hong Kong Electric
Interview 14	12.06.2017	Senior Engineer at Electrical and Mechanical Services Department
Interview 15	26.07.2017	Principal Investigator & Consultant for Climate Change Policy
Interview 16	28.07.2017	Professor for Energy Policy and Politics in Hong Kong
Interview 17	31.07.2017	General Manager at Property Development and Management Firm
Interview 18	05.08.2017	Senior Manager at Business Environment Council
Interview 19	08.09.2017	Expert in the field of Knowledge and Data

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