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FORMULATION OF SUSTAINABLE TRIGENERATION SYSTEM DESIGN FOR HIGH-RISE COMMERCIAL BUILDINGS IN HONG KONG

RESEARCH SUMMARY

Construction Industry Council

Formulation of Sustainable Trigeneration System Design for High-rise Commercial Buildings in Hong Kong

Research Summary

Author

Ir Dr Square K.F. FONG
City University of Hong Kong

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Enquiries

Enquiries on this research may be made to the CIC Secretariat at:

CIC Headquarters
38/F, COS Centre, 56 Tsun Yip Street, Kwun Tong, Kowloon

Tel.: (852) 2100 9000

Fax: (852) 2100 9090

Email: enquiry@cic.hk

Website: www.cic.hk

FOREWORD

There is a growing trend that renewable energy is used in power generation for buildings. The Construction Industry Council (CIC) had successfully pioneered the Zero Carbon Building (ZCB), in which photovoltaic panels and a trigeneration system using biofuel made of waste cooking oil were used to produce energy for the building, to achieve zero net carbon emissions. The successful operation of the ZCB in the past few years demonstrates that the trigeneration system is an energy-efficient technology and can help reduce carbon dioxide emission.

Most of the buildings in Hong Kong are high-rise and the required energy density is high. The application of the trigeneration system in Hong Kong is quite challenging. With this in mind, we engaged a research team from the City University of Hong Kong to investigate the feasibility of applying the technique of trigeneration system to high rise commercial buildings in Hong Kong.

The research work was funded by the CIC Research Fund, which was set up in September 2012 to provide financial support to research institutes/construction industry organizations to undertake research projects which can benefit the Hong Kong construction industry through practical application of the research outcomes. CIC believes that research and innovation are of great importance to the sustainable development of the Hong Kong construction industry. Hence, CIC is committed to working closely with industry stakeholders to drive innovation and initiate practical research projects.

In the report, the supply of fuel sources in Hong Kong, the possible system configurations for different kinds of buildings and their energy performance, as well as their economic viability are presented. Although it was found that the technology was not economically feasible at this moment in Hong Kong, the CIC would continue to collaborate with all stakeholders to refine and promote the technology.

The research team is led by Dr Square FONG. I would like to thank the dedication and devotion of the members in the research team. The research findings lay a solid foundation for further investigation on the topic in the future.

Ir Albert CHENG

Executive Director of Construction Industry Council

PREFACE

It is very pleased that the CIC Research Fund supports this research project on formulation of sustainable trigeneration system design for high-rise commercial buildings in Hong Kong. Around the globe, trigeneration is an enabling technology used to simultaneously generate cooling, heating and electrical power for district applications. If the trigeneration system can be widely applied down to the building level, its merits in energy efficiency and carbon emission cuts can be certainly penetrated into our society.

To properly explore the potential of trigeneration application in Hong Kong, a thorough technical evaluation is of primary importance. In the course of study, the research team has conducted extensive system design and dynamic simulation works on various trigeneration configurations for different building types. To explore the feasibility of zero carbon design, the availability of biofuel in Hong Kong has been explored. A big challenge is found that the price of biofuel is much higher than that of conventional fossil fuel, incurring a tangible economic hurdle in the biofuel-driven trigeneration at the present day. However, it opens a door to rethink about the infrastructure of natural gas provision to the public, in particular for the distributed power supply like trigeneration.

The research outcomes are expected to let the building stakeholders acquire the appropriate system design of trigeneration; appreciate its energy and environmental merits; and widen the economic analysis by accounting for carbon reduction in building application. In view of climate change mitigation, sustainable trigeneration is clearly one of the effective distributed energy sources for continual economic and population growth in Hong Kong.

Prof. C.M. TAM
Division of Building Science and Technology
City University of Hong Kong

RESEARCH HIGHLIGHTS

Trigeneration systems are considered as energy-efficient form of distributed power systems which helps reduce the carbon dioxide emission and hence relieves climate change in the world. This is particularly attractive for a density-populated city like Hong Kong in which the electricity demand from buildings contributes the major portion of energy consumption. However, it is challenging that most of the buildings in Hong Kong are high-rise and the energy density is high. Hence, in this research project, the energy, environmental and economic feasibility of trigeneration systems are investigated for building applications in Hong Kong.

Fuel sources

- For the available fossil fuels in Hong Kong, the most common liquid fuel is diesel oil; while the major gas fuel is towngas. Diesel oil is commonly used by the emergency generator sets and/or boilers in buildings; it is delivered through trucks and stored in tanks. Towngas is directly supplied to the end users from the gas plants through a central gas pipework.
- The supply of biofuel in Hong Kong generally falls into two categories, biogas and biodiesel. Biogas is mainly generated from the landfill sites and the sewage treatment plants, but the amount is generally used up for the on-site electricity generation and thermal treatment. Some landfill gas is delivered for production of towngas. However, the provision of landfill gas is not unlimited, particularly when the landfill site is saturated and closed. There may be an opportunity of biogas supply through the large-scale organic waste treatment facilities commissioned in 2017, but it is necessary to develop an infrastructure of pipe network for biogas delivery in advance.
- Biodiesel is the current biofuel available in the market, as produced by three companies in Hong Kong. The supply mainly aims at automobiles in a form of blended fuel. The main obstacle to the use of biodiesel is its much higher price than that of conventional diesel oil, especially in the recent collapse of oil price. The Mainland also produces biodiesel, but its biodiesel industry is still facing continual loss due to the non-competitive price level as compared to conventional diesel fuel.

Building types and trigeneration systems investigated

- To allow a broad range of building load characteristics (power-to-cooling-to-heating ratio) to be investigated, five types of high-rise or multi-storey buildings, namely office, hotel, retail, hospital and sports centre were covered in this study.
- For each building type (except the sports centre), four feasible options of prime movers for trigeneration were considered, including diesel engines; gas engines; gas turbines with recuperators; and combined gas turbine cycle. For the sports centre, only the diesel and gas engines were involved due to the relatively small design power load. An absorption chiller was chosen to be the thermally-driven cooling equipment, while an auxiliary vapour-compression chiller was needed.
- In view of the availability hurdles of biodiesel and biogas in Hong Kong, conventional types of fossil fuels were adopted in the performance evaluation of trigeneration. As such, diesel oil was used for diesel engine, while natural gas was applied in gas engine; gas turbine with recuperator; and combined gas turbine cycle. The use of towngas was not considered since it incurred both higher prices and carbon emission as compared to natural gas.

Energy and environmental performances

- By performing year-round dynamic system simulation using TRNSYS, the primary energy consumption (PEC) and the carbon dioxide emission (CDE) of the various trigeneration systems for different building types were computed and compared with those based on the conventional design.
- Among different building types, the hotel building offered the highest PEC reduction among all kinds of prime movers investigated, which exceeded 23% with a diesel-engine-primed trigeneration system. The hospital building had the second highest reduction in PEC. Both hotel and hospital buildings demonstrated that high year-round space and water heating demand were essential to achieve the good energy performance in trigeneration.
- Reduction of PEC was the lowest in the office building. This was because the major usage of the recovered waste heat from the prime mover was for space cooling. Space heating and water heating demand, however, was minimal in office building. The benefit of primary energy saving was diminished substantially by the much higher coefficient of performance of the conventional vapour-compression chiller as compared to the absorption chiller.

- Among the various kinds of prime movers considered, the diesel engines offered the highest reduction in PEC followed closely by the gas engines. The main reason was that they had better part-load performances as compared to the gas turbines and the combined gas turbine cycle systems. This highlighted the advantage of using internal combustion engines (i.e. diesel engine and gas engine) as prime movers in trigeneration for building application.
- Despite the better energy performances, diesel engines generally yielded the lowest CDE savings among all the prime movers. This is because the carbon dioxide emission index of diesel oil is 27% higher than that of natural gas. On the other hand, gas engines offered the largest CDE savings which measures up to 37% when applying to the hotel buildings.

Economic analysis

- An initial economic analysis showed that only the use of gas engines could guarantee a reduction in running energy cost. In consideration of both energy and environmental performances, the use of gas engine was deemed to be the only possible choice for building use in Hong Kong.
- In further economic evaluation of the gas-engine-primed trigeneration systems, it was found that the payback periods were not encouraging with the lowest being 13 years for use in the hotel buildings. The value could even rise to more than 400 years for application in the office buildings.
- To improve the payback, various scenarios were considered. The first scenario was to include a carbon tax; the second one took into account the social cost of carbon dioxide emission; and the third one was to reduce the gas cost by introducing an electricity-to-gas price ratio of 3 (similar level as adopted in many developed countries). It was found that the adoption of the carbon tax would reduce the payback periods but still unsatisfactory. The consideration of the social cost of carbon cut the payback periods down to less than 8 years in all cases. The adoption of a lower gas cost also yielded significant reduction in the payback periods to less than 10 years in most situations.
- If biogas was available, the CDE saving became more substantial as biogas was assumed to be carbon-neutral. This should help reduce the payback periods if the carbon tax or carbon social cost was implemented. With a supply of biogas and the adoption of carbon tax, the payback periods dropped to less than 7 years for all the building types. In case social cost of carbon was considered, the respective payback periods would fall below 4 years.

Recommendations

- From this study, it can be concluded that the trigeneration systems are energetically and environmentally feasible for building application, but economically infeasible under the present conditions in Hong Kong. In order to have successful promotion of trigeneration, a city supply of natural gas with a reasonable electricity-to-gas price ratio is a pre-requisite. Effective incentive schemes are needed which include subsidy on fuel and investment, feed-in tariff scheme and incentive on CDE reduction.
- At present, there is no direct city supply of natural gas to the public in Hong Kong, although natural gas is being imported by the power and the gas companies. Studies have been conducted on the feasibility of introducing natural gas or liquefied natural gas into Hong Kong's market for decades, but no progress has been made since then. Being the greenest fossil fuel, the quest for natural gas is crucial for realisation of distributed power supply like trigeneration in Hong Kong.

CONTENTS

1 INTRODUCTION

1.1 Background

Since 2010, the HKSAR Government has proposed to reduce carbon intensity by 50-60% by 2020 compared with 2005 (EB, 2010). In the building sector, zero carbon building is an effective strategy to support this. We proudly have the CIC Zero Carbon Building (ZCB), which is a showcase to integrate various passive and active sustainable means in order to achieve zero carbon emission for building in hot-humid climate (Li, 2012). However, it is not straightforward to transfer the know-how of those green designs to the high-rise buildings, which are featured with great energy intensity in a congested urban area. In order to attain zero energy target for the entire building, self-sustained energy resources should be available. Renewable technologies, like solar and wind power, would demand large spatial requirement and unobstructed environment, so it is not easy to be widely adopted in a crowded city.

Trigeneration, or called combined cooling, heat and power, is a centralised plant used to simultaneously generate three essential provisions for buildings – electrical power, air-conditioning, space and water heating. The traditional approach of electricity generation is difficult to have efficiency exceeding 40%. Meanwhile, trigeneration can have remarkable overall efficiency up to 80% (Wu and Wang, 2006) since the waste heat is captured for cooling and heating production. The existing trigeneration plants are largely energised by natural gas, which is still fossil fuel. If the target of zero carbon emission is set, the use of sustainable fuel source becomes critical. The biofuel can be in the form of solid (e.g. fuelwood, stalks, municipal solid waste), liquid (e.g. methanol, ethanol, raw vegetable oil) and gas (e.g. pyrolysis gases, landfill gas, sludge gas). According to the Intergovernmental Panel on Climate Change, the biomass has already contributed to 10.2% of the total global primary energy supply in 2008 (IPCC, 2011). In fact, bioenergy will continuously play a significant role among various renewable energy resources in the coming decades. In the CIC ZCB, biodiesel generated from the waste cooking oil is used to feed the trigeneration plant (Li, 2012). Landfill gas has already been captured and utilised to generate electricity for on-site use (EPD, 2015). These are examples of biofuel utilisation at present in Hong Kong. Nevertheless, the supply of biofuel in Hong Kong is still limited with the major application in automobiles. Hence, the capability of providing sufficient biofuel locally for building use is uncertain.

In the past, the design of trigeneration/cogeneration is generally in district scale, like the 250 MW cogeneration plant in Massachusetts of the US (KITT, 2011) and the 381 MW trigeneration plant in Tokyo of Japan (JFS, 2009). In pursuit of holistic energy efficiency for the building sector, much attention has been paid on the design strategies of trigeneration in recent years. The US has advocated a modular prototype of trigeneration plant since 2006 in order to facilitate the installation and construction for buildings (USDOE, 2006). Exemplary projects of trigeneration/cogeneration using biofuel are blooming in the UK, Germany, Japan, Finland, Cyprus and Poland (COGEN, 2015). The manufacturers of trigeneration/cogeneration are getting more (Dresser-Rand, 2016; Enercon, 2016, etc.).

European Union currently generates 11% of their electricity using trigeneration/cogeneration, reducing carbon emission of an estimated amount of 35 Mton/year in Europe. The expansion of trigeneration/cogeneration in France, Germany, Italy and the UK alone would effectively double the existing primary fuel savings by 2030 (EU, 2004). A newly issued report of the US Department of Energy has an aggressive goal of setting 40 GW of new and cost-effective cogeneration/trigeneration in US by 2020, this implies an increase of its total capacity by 50% in less than a decade (USDOE and USEPA, 2012). The City of Sydney has committed to trigeneration using waste-derived renewable feedstocks. They have developed a master plan of trigeneration utilisation to align the policy to be off coal fired electricity by 2030 (Kinesis, 2012). It is obvious to have a global trend in the deployment of trigeneration. Therefore, it is the right time to identify the extent and potential of sustainable trigeneration in Hong Kong through this research project.

1.2 Objectives

The objectives of this research project are:

a. To survey the available types of biofuel supply for trigeneration system in Hong Kong;

b. To identify the potential system designs of trigeneration according to the available biofuel types;

c. To conduct energy, environmental and economic evaluation for the trigeneration system designs; and

d. To generate recommendations on biofuel-driven trigeneration design for high-rise commercial buildings in Hong Kong.

1.3 Scope

To achieve the research objectives, the scope of work of this project covers the following 5 phases.

Phase 1 – Survey on biofuel supply;

Phase 2 – Development of various potential designs of trigeneration;

Phase 3 – Model development of potential trigeneration systems;

Phase 4 – Energy, environmental and economic evaluation of trigeneration systems;

Phase 5 – Development of recommendations on sustainable trigeneration design.

2 RESEARCH METHODOLOGY

The related methodologies and details of the 5 phases of work are described as follows.

Phase 1 – Survey on biofuel supply

In order to achieve zero carbon emission from buildings, it is natural to shift the energy source from the conventional electricity supply to a sustainable one. In the Asia-pacific region, Hong Kong has high potential in biofuel demand, since we consume only 95,000 m^3/year or 0.01 m^3/year per capita (Gumartini, 2009). Currently, there are three production plants of biodiesel already available. In this stage, more local and overseas possible bioenergy sources will be explored. Since the type of energy sources would directly affect the prime mover of trigeneration, the available feedstocks would determine the alternatives of system design. Both the environmental and economic factors of the possible biofuel sources would be focused on. In addition, the reliability and choice of supply will also be discussed.

Phase 2 – Development of various potential designs of trigeneration

A trigeneration system can be divided into six components as follows:

a. Fuel source;

b. Prime mover for electricity generation;

c. Generator set;

d. Heat recovery equipment;

e. Thermally driven and auxiliary air-conditioning (AC) equipment;

f. Control and operation.

In fact, there are a number of design alternatives in items (a), (b) and (e). The conventional trigeneration system design uses natural gas as the fuel source, internal combustion engine as the prime mover and absorption chiller as the thermally driven AC equipment. In the CIC ZCB, biofuel, diesel engine, adsorption chiller and solid desiccant wheel are designed.

The design alternatives of fuel, prime mover and thermally driven AC can be:

- Fuel: biofuel (solid, liquid, or gas), diesel oil, towngas, natural gas, petrol gas;
- Prime mover: internal combustion engine, gas turbine, steam turbine, Stirling engine, microturbine;
- Thermally-driven AC equipment: absorption chiller, adsorption chiller and desiccant cooling.

In addition, the system design of trigeneration would depend on the loading characteristics of the building. Therefore, more factors have to be considered:

- Load priority;
- Configuration of electricity and heat generation: topping cycle or bottoming cycle;
- Hybrid use of conventional electrical chiller and thermally-driven AC equipment for fuel match.

As a result, it is necessary to have a systematic approach to generate the potential trigeneration designs for the commercial buildings based on the aforesaid alternatives. In this study, the commercial buildings will cover the types of office, hotel and retail. In addition, other types of non-commercial buildings with high hot water demand like hospital and sports centre will also be considered. This phase will be linked up to the subsequent phase in order to identify the feasible trigeneration system designs.

Phase 3 – Model development of potential trigeneration systems

In order to evaluate the performance of trigeneration that includes a cluster of components and alternative designs, component-based system modeling is an effective tool. Moreover, the key components of trigeneration, particularly the prime mover and the thermally driven AC equipment, would be under part-load performances due to the changing loading and climatic conditions. Dynamic simulation is therefore necessary to provide a complete picture of the trigeneration operation throughout a year in Hong Kong. The academic dynamic simulation platform TRNSYS (2010) and its component library TESS (2010) will be used for this study. TRNSYS offers many standard components which are required in formulating the trigeneration system including conventional vapour-compression chillers (if necessary), fans, pumps, heat exchangers, building zones, etc. Meanwhile, new component models will be developed for the prime movers and the thermally driven AC equipment. The typical meteorological year for Hong Kong (Chan *et al.*, 2006) will be used to represent the hourly change of various weather data in Hong Kong. Model development of the conventional provisions of electric power, air-conditioning and heating will also be included for benchmarking purpose. This stage will demand most of the project time, since model development and system verification are involved for such numerous alternatives of trigeneration system designs.

Phase 4 – Energy, environmental and economic evaluation of trigeneration systems

Through the developed model of each trigeneration design, the year-round primary energy consumption and overall plant efficiency can be determined. These are the key metrics of energy evaluation. In addition, the part-load performances of different components of trigeneration can be observed and analysed. This would help refine the sequence and interlock controls among the components involved. In the environmental evaluation, carbon dioxide emission reduction and air quality impact of each potential trigeneration system would be accounted for. Those trigeneration designs with both energy and environmental advantages will be brought forward to the life cycle economic analysis. Economic benefit of trigeneration will include the surplus of electricity selling back to the grid when appropriate. This phase will go in parallel with the previous phase of model development, and form an iterative process to generate the feasible designs. Five types of buildings, namely office (OF), hotel (HT), retail (RT), hospital (HP) and sports centre (SC) are selected for analysis in view of the different power-to-cooling-to-heat demand ratios offered which allow the performances of the trigeneration systems to be investigated over a wide range of loading characteristics. The design guidelines from EMSD (2007) are adopted wherever applicable to determine the loading profiles for the various types of buildings.

Phase 5 – Development of recommendations on sustainable trigeneration design

Based on the simulation results and analysis from Phase 4, recommendations will be made on the types of buildings which offer the best potential for the implementation of trigeneration designs according to their energy, environmental and economic merits. Should the current situations do not favour the adoption of trigeneration designs, suggestions will be proposed for the promotion of the system. This includes incentive schemes from the government on the space and fuel cost as well as the revision of particular statutory requirements. Meanwhile, the availability, delivery, storage, safety and security of the associated fuel type will be discussed. The coordination with architectural layout, structural loading, fire services, water supply, emergency power, noise reduction will also be suggested in order to let the stakeholders understand the merits and the constraints, and the implication to the building design and construction. The available suppliers of various equipment and fuel supply will be mentioned as well. Figure 1 depicts the procedures and methods adopted in this research.

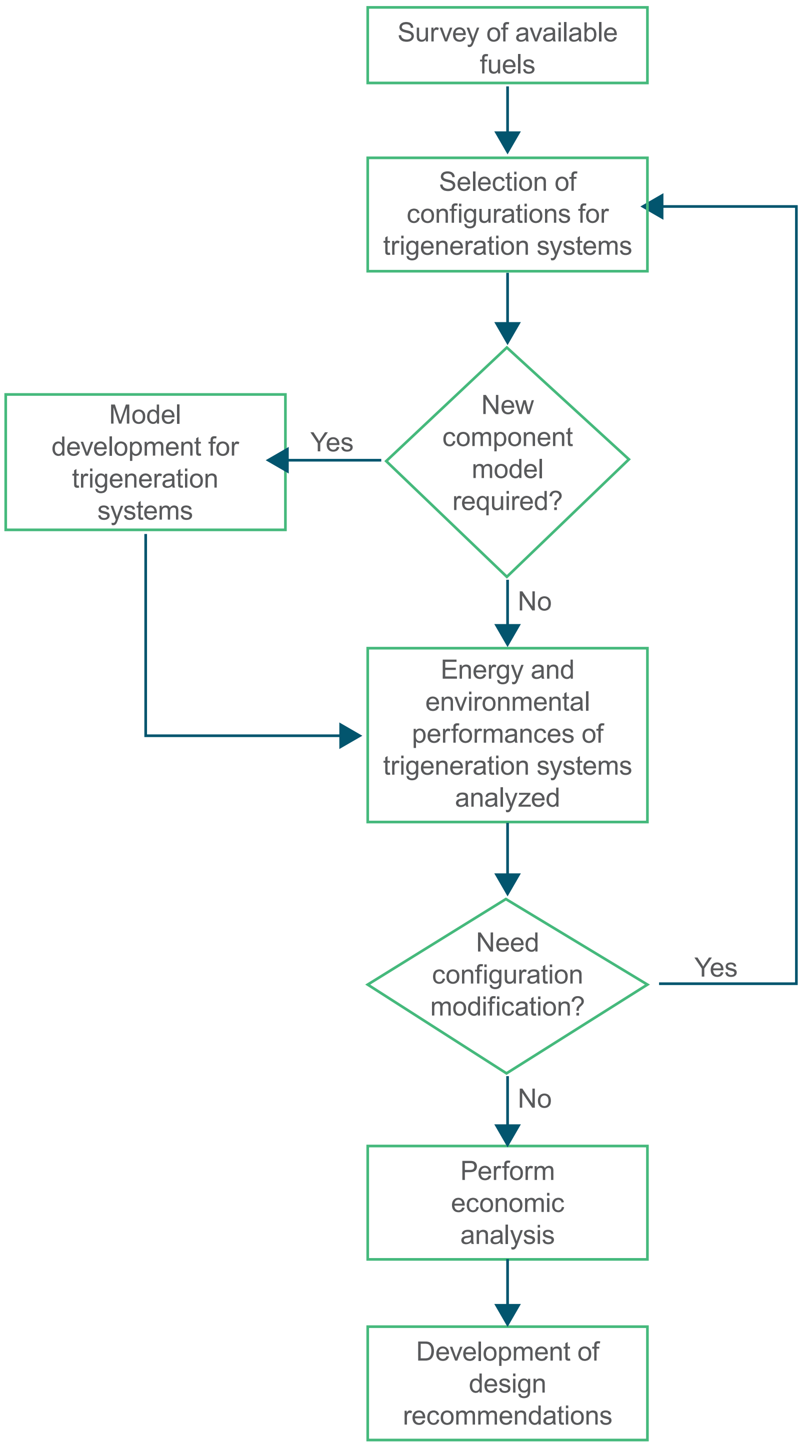

Figure 1 Flowchart for the analysis of trigeneration systems

3 RESEARCH FINDINGS AND DISCUSSION

3.1 Trigeneration in context

3.1.1 Basic principle of trigeneration

Figure 2 depicts the basic principle of a trigeneration system. Fuel is supplied to a prime mover for generating electricity. Meanwhile, the waste heat delivered from the prime mover through the casing and/or the flue gas is recovered to provide space cooling and/or space/water heating to the building zone. With this design, usually more than 70% of the energy released from the fuels can be utilised. A thermally-driven cooling device is employed to serve the cooling demand in the building zone.

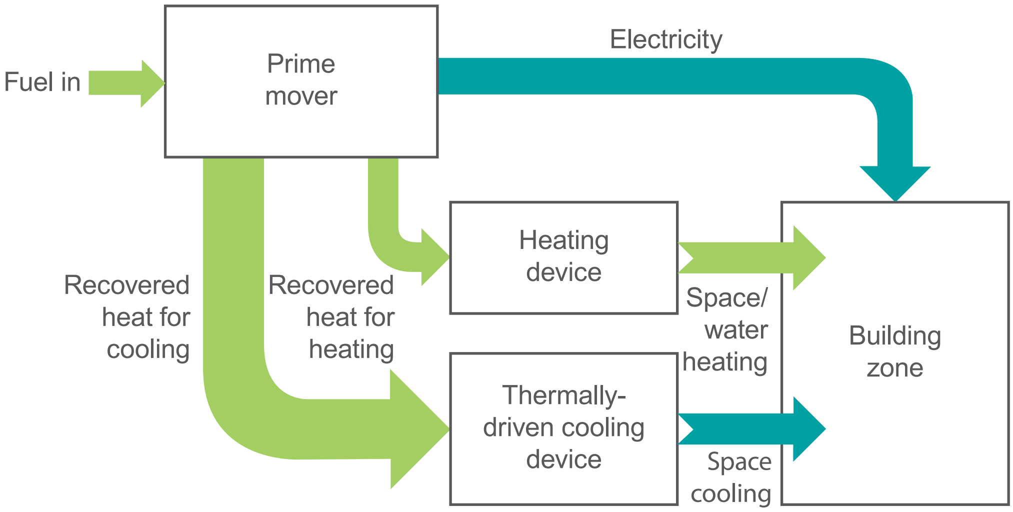

Figure 2 Symbolic diagram of a trigeneration system

3.1.2 Choices of system configuration

Depending on the choice of prime movers and the building demands in power, cooling and heating, there are numbers of ways to configure a trigeneration system. For the method of recovering the waste heat, the use of a single regenerative water stream to capture the recovered heat is the most common method as shown in Figure 3. The benefit of this arrangement is that the distribution of the recovered heat for cooling, space heating and water heating can be very flexible through the control of the regenerative water flow to the respective systems, but the effect of the temperature level of the flue gas may not be fully utilised.

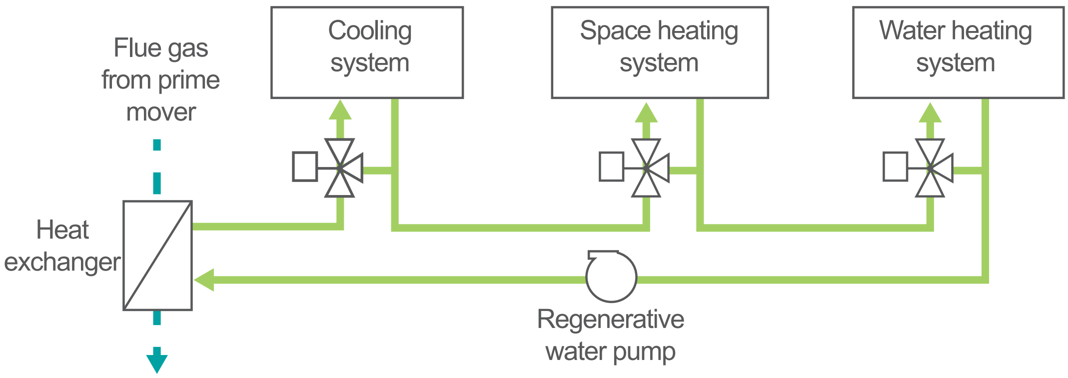

Figure 3 Regenerative water pipework with a single circuit

Another method is to adopt individual water circuit for the cooling, space heating and water heating system as shown in Figure 4. In case there are various sources of waste heat from the prime mover at different temperature levels, the adoption of individual water circuits can optimise the utilisation of the waste heat. However, the main drawback of this configuration is that if any of the cooling, space heating and water heating systems is not in use, the unrecovered waste heat from that system cannot be totally transferred to other systems even if the demands in the other systems are high.

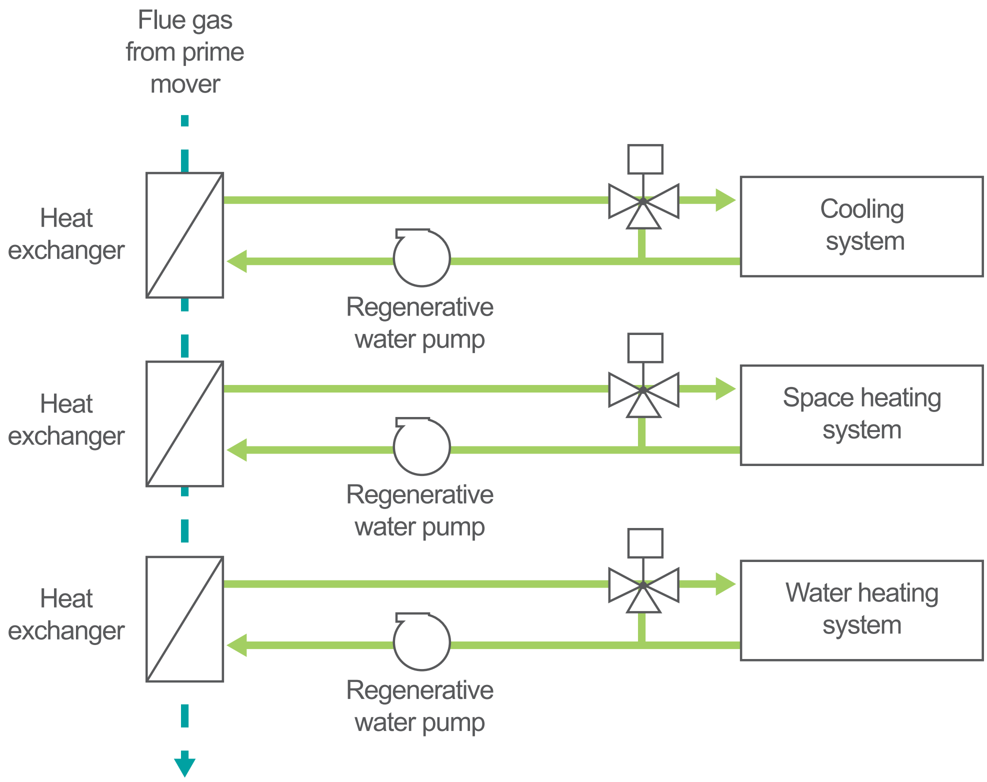

Figure 4 Regenerative water pipework with individual circuit for each system

To enhance the electrical output of a trigeneration system, a bottoming cycle may be added which utilises the hot flue gas from the prime mover to energise another power cycle to harvest more work/electrical output. The most common selection is a steam or an organic Rankine cycle as shown in Figure 5 depending on the temperature of the flue gas.

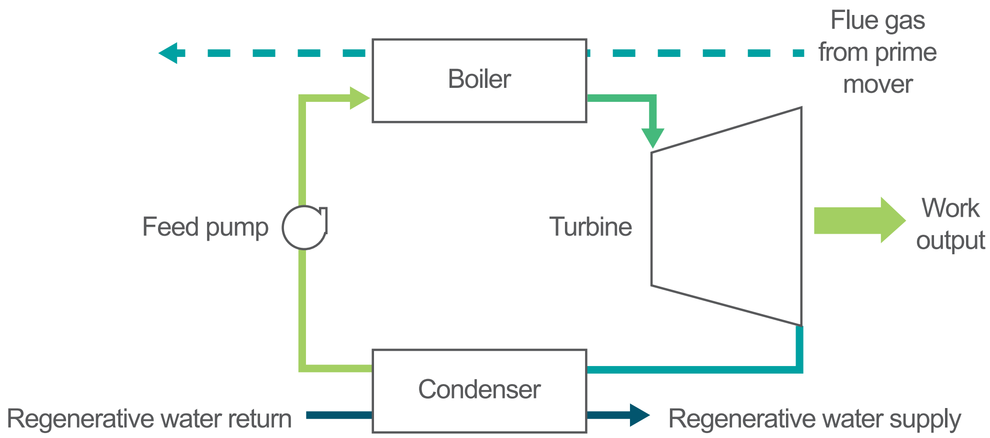

Figure 5 Configuration with a bottoming Rankine cycle

3.2 System description of feasible trigeneration system for high-rise commercial buildings

3.2.1 Load characteristics of cooling, heating and power

The load characteristics of cooling, heating and power can vary widely among different types of buildings and the climate of the applied location. In particular, except in the tropical regions, the air-conditioning demand (both cooling and heating) fluctuates significantly throughout the whole year. As a sub-tropical city, the air-conditioning load in Hong Kong is cooling-dominated, and space heating is only required within a short period of time. In fact, space cooling is usually required throughout the whole year at the internal zones of most commercial buildings. The energy demand for hot water as well as the consumption is the highest in winter and lowest in summer due to the fact that the make-up potable water is the coldest in winter and warmest in summer. However, the year-round fluctuation is less severe than that of the space cooling demand. The power demand from the building is generally stable throughout the year when the consumption from the air-conditioning system is excluded.

3.2.2 Fuel sources and handling

The availability of fuels for building use is a critical factor for the successful application of trigeneration systems. The most common liquid fuel is the diesel oil (DO) as commonly used by the emergency generator sets and/or boilers in buildings. Diesel oil is shipped to Hong Kong by vessels and stored at oil tanks of the oil companies. Trucks are used to deliver the fuel to the end users. Stores which comply the related statutory requirements are to be built at the buildings to accommodate the oil.

There are currently two types of gas fuels available in Hong Kong, namely towngas and liquefied petrol gas (LPG). Towngas is supplied by the Hong Kong and China Gas Company (HKCGC) which is produced through the steam reforming of naphtha at the Tai Po and Ma Tau Kok plants. Recently, natural gas from mainland China and landfill gas is also utilised in the production of the towngas. The gas is directly delivered from the plants to the end users through the gas pipework installed by the gas company and no storage facility is required in the buildings.

Petrol gas is a derived hydrocarbon gas which can be pure propane, butane or most commonly a mixture of both. It is transported to Hong Kong by vessels in liquefied state. For large demand at buildings, a local storage and distributing pipework system should be erected at site. LPG is then transported from the gas company's place to the end users' local storage facility by lorries.

At present, there is no direct supplier of natural gas (NG) in Hong Kong although natural gas is being imported by the power and the gas companies. Being the greenest fossil fuel, the more use of natural gas is the general trend nowadays to help improve the air quality particularly in China. Besides, the carbon dioxide emission index of natural gas is also the lowest among the various fossil fuels. Hence, the quest for natural gas supply in Hong Kong is crucial for future development.

The supply of biofuel in Hong Kong generally falls into two main categories, biogas and biodiesel. Biogas can be generated through various sources, namely the landfill sites, sewage treatment plants and food waste treatment plants. According to the information provided by the Environmental Protection Department (EPD) (2015), there are several sites which provide landfill gas to HKCGC for further treatment before delivery to the users through the pipework of the gas company. However, the provision of the landfill gas at each landfill site is not unlimited, particularly when the landfill site is closed. This incurs extra consideration of the expected supply period and amount of landfill gas at each landfill site when judging the economic merits of utilising the landfill gas for building use.

According to the Drainage Services Department (DSD) (2015), biogas is generated during the sludge treatment process which contains 65% methane and the rest being carbon dioxide. However, the biogas is primarily used to serve the sewage treatment works only and there is no surplus that can be supplied to other places.

Biogas can be produced and utilised for power generation from large-scale organic waste treatment facilities being built (EPD, 2010). At present, it is not clear if the biogas can be directly exported besides used to generate electricity. Unlike the landfill gas, the supply of biogas from the organic waste treatment facilities can last through the operating life of the plant.

Biodiesel is the most common biofuel available in the market. Currently, there are three companies in Hong Kong. They collect waste/used cooking oil, animal fat and grease trap oil as feedstocks from the restaurants. The main application is for automobiles usually in the form of a blended fuel (say B5 with 5% biodiesel mixed with 95% conventional diesel) although non-blended biodiesel (B100) is also available by individual manufacturer.

As a liquid, the supply of the biodiesel to buildings can be easily done by using lorries or trucks. Of course, suitable storage facilities at buildings which fulfil respective statutory requirements are then needed. The main obstacle to the use of biodiesel is its higher price as compared to conventional diesel oil, particularly in view of the collapse of the oil price between 2014 and 2016.

3.2.3 Prime mover for electricity generation

There are various types of prime movers available in the market, namely internal combustion engines, external combustion engines such as Stirling engines, Rankine cycle engines (whether steam or organic), gas turbines, micro-turbines, combined gas turbine cycle systems and fuel cells. However, in view of the capacity required for a high-rise commercial building and the maturity of the technologies, only the internal combustion engines, gas turbines (GT) and combined gas turbine cycle systems (CGTC) are usually considered. To be more specific, there are two types of internal combustion engines available, namely the Diesel engines (DE) based on the Diesel cycle and the gas engines (GE) based on the Otto cycle as shown in Figure 6. For medium-capacity gas turbines which are based on the single Brayton cycle, the thermal efficiencies are lower as compared to the internal combustion engines. To improve the situation, a recuperator is added as shown in Figure 7. However, this reduces the flue gas temperature of the gas turbine which impairs the performance of the bottoming cycle in a combined gas turbine cycle engine. Hence, no recuperator is used in the combined gas turbine cycle systems as shown in Figure. 8.

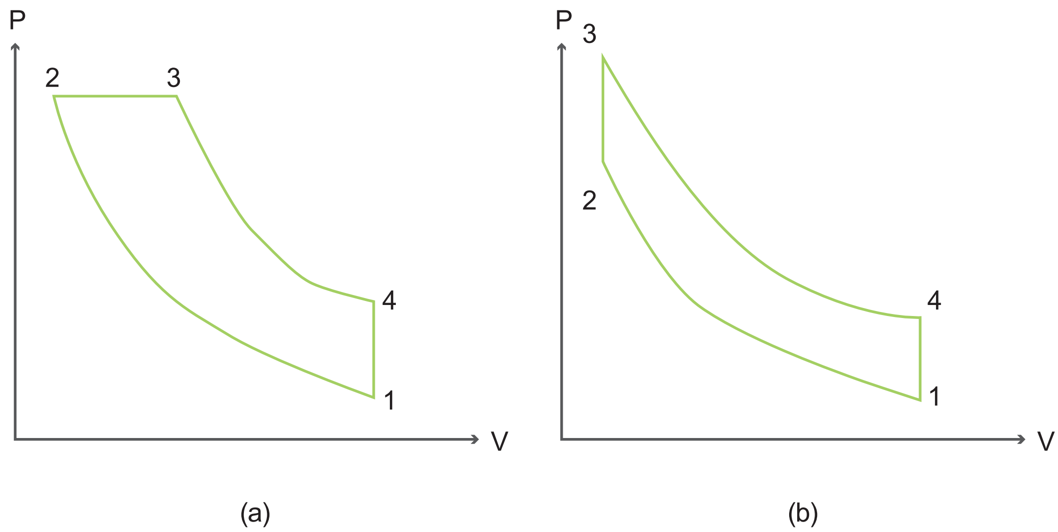

Figure 6 P-V diagram of the (a) Diesel cycle and (b) Otto cycle

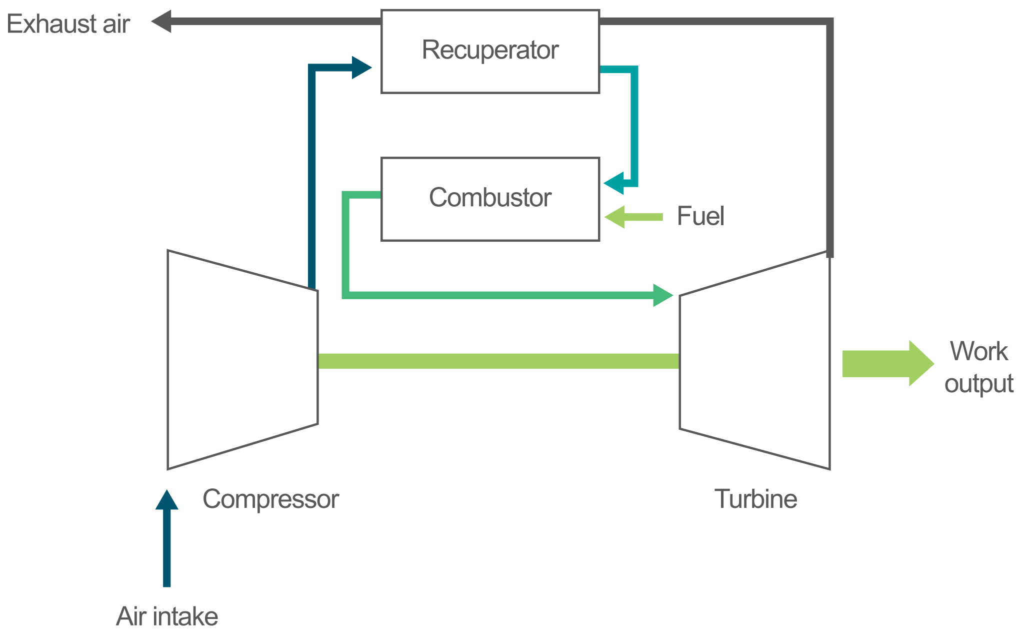

Figure 7 Schematic diagram of a simple gas turbine cycle with recuperator

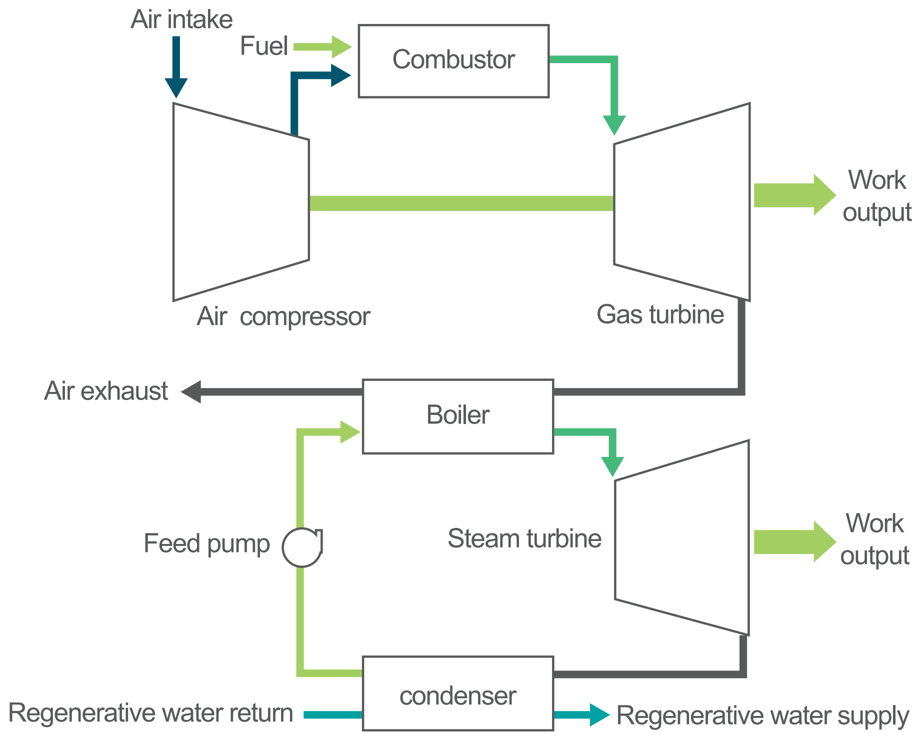

Figure 8 Schematic diagram of a combined gas turbine cycle system

3.2.4 Thermally driven air-conditioning and its system design

There are various thermal cooling systems available in the market, namely the absorption chillers, adsorption chillers, desiccant cooling systems and hybrid desiccant cooling systems. According to previous study from Fong *et al.* (2010), the absorption chillers yield the highest coefficient of performance (*COP*) as compared to the rest thermal cooling systems, which is important in trigeneration systems as more cooling capacity can then be developed from the recovered waste heat. As absorption chillers are also more common in the market, they are thus preferably used. Figure 9 depicts the schematic diagram of a lithium bromide (LiBr) absorption chiller as detailed by Fong *et al.* (2012). To facilitate the use of the recovered heat from the engine casing (normally less than 90°C) when internal combustion engines are used as the prime movers, the hot-water-driven type absorption chiller is used.

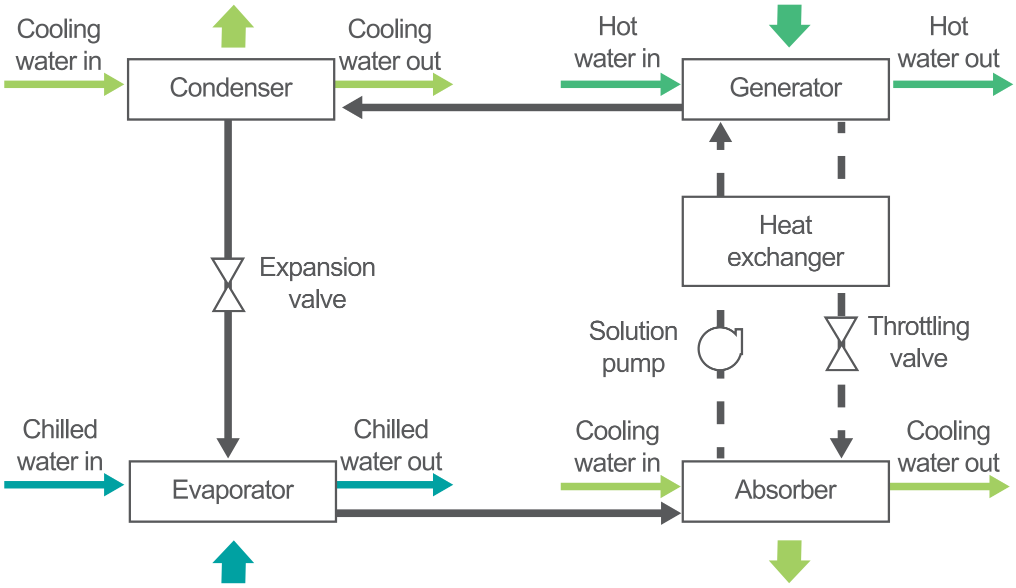

Figure 9 Schematic diagram of a LiBr absorption chiller

3.2.5 Configuration of entire system

Based on the fact that the space cooling/heating demand varies significantly throughout the year, a single-circuit regenerative water pipework system as previously shown in Figure 3 is adopted. Respective three-way valves are used to control the regenerative water flow to the absorption chiller, the space heating heat exchanger (SHHX), the water heating heat exchanger (WHHX) and the auxiliary water cooler (if necessary). In case the waste heat from the prime movers cannot provide sufficient cooling capacity through the absorption chiller, auxiliary vapour-compression chiller needed to be provided. Each chiller is equipped with a cooling tower, a condenser water pump, a primary chilled water pump and a secondary chilled water pump (where necessary). Fan coils each comprising a supply air fan (SAF), a supply air cooling coil (SAC) and a supply air heating coil (SAH) are used to provide air conditioning to the building zones. Meanwhile, auxiliary heaters may be needed to ensure that the required water temperatures in the space heating and water heating circuits can be maintained.

Figure 10 illustrates the waste heat recovery approaches for the various prime movers, and Figure 11 shows the general arrangement of the trigeneration system with auxiliary vapour-compression chiller. For the internal combustion engines, two heat exchangers namely the engine jacket heat exchanger (EJHX) and the exhaust heat exchanger (EHX) are used to collect the waste heat. The regenerative water first passes through the EJHX due to its lower temperature level before entering the EHX. For the gas turbine, only the EHX is used. Regarding the combined gas turbine cycle system, the heat exchanger is integrated as the condenser of the prime mover. Auxiliary water cooler is not required for the gas-turbine-primed trigeneration system. As discussed in the later section, more than one set of prime mover are normally used. Hence, each unit of prime mover is equipped with one set of regenerative hot water pump (RHWP) and all the regenerative water systems will be connected in parallel before supply to the space cooling/heating and water heating systems. Meanwhile, one set of the engine jacket water pump (EJWP) is provided for each unit of DE or GE.

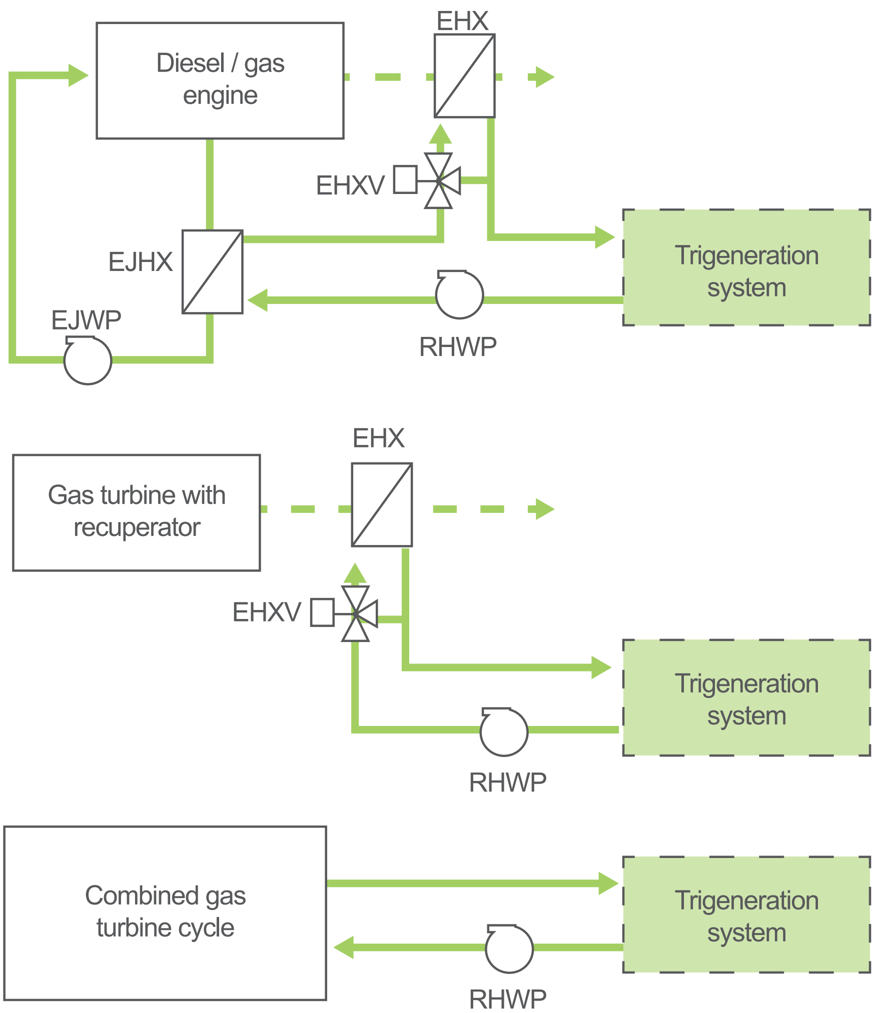

Figure 10 Schematic diagram of prime movers using DE/GE (top), GT (middle) and CGTC (bottom) together with the associated equipment for trigeneration systems

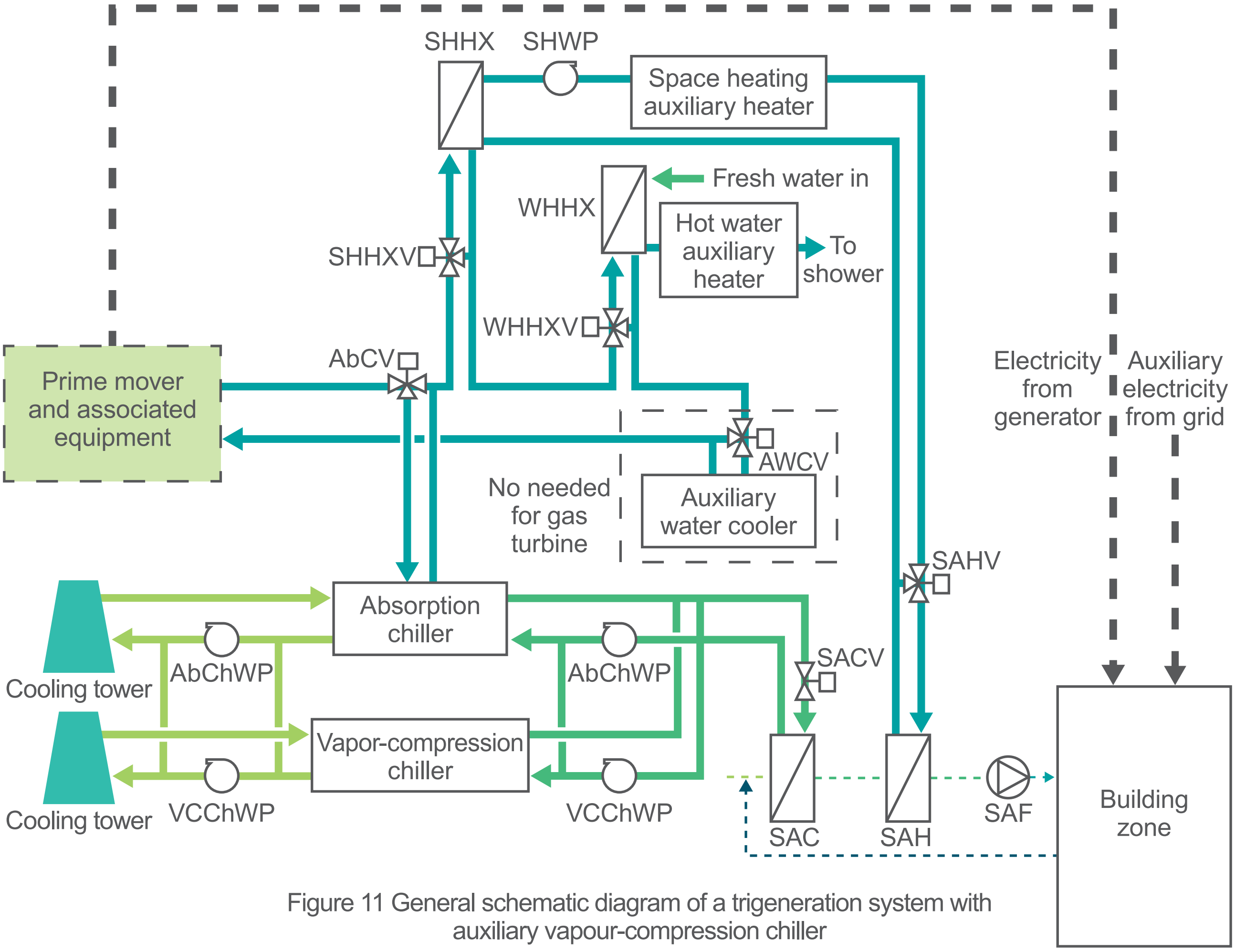

Figure 11 General schematic diagram of a trigeneration system with auxiliary vapour-compression chiller

3.3 System design and coordination

3.3.1 Design procedures

To design a trigeneration system for use in Hong Kong, the various building loads have to be predicted first according to the guidelines (EMSD, 2007) and the code of practice (EMSD, 2012) issued by the Electrical and Mechanical Services Department (EMSD) wherever applicable. With all the building loads evaluated, the capacity of the trigeneration system can be set based on the peak electrical demand. However, the process is not a simple explicit approach as the capacity of the trigeneration system limits the amount of recoverable waste heat. This governs the maximum capacity for the absorption chillers that can be provided by the trigeneration system. In case auxiliary vapour-compression chillers have to be included, the total building power demand will be affected. Besides, the power demands from the cooling towers and the water pumps serving the absorption chillers also depend on the capacity of the absorption chillers. Hence, repeated trials have to be conducted in order to get the optimal design.

To demonstrate the design procedures and considerations for the trigeneration systems, five reference buildings types are selected as previously stated in the “Research Methodology”, namely the office, hotel, retail, hospital and sports centre. The year-round cooling, heating and power patterns differ substantially among the five types of buildings. The analysis with these five building types allows the performance of the trigeneration systems to be compared at different loading ratios of cooling, heating and power in order to assess the application potentials of trigeneration systems in Hong Kong.

3.3.2 Determination of cooling, heating and power

The air-conditioning demand (including both space cooling and heating) is determined by applying the respective internal load densities and schedules as detailed in EMSD (2007) for the various building types together with the typical weather data in Hong Kong (Chan *et al.*, 2006) for calculating the heat transfer across the boundary walls and windows. By using suitable system simulation software like TRNSYS (2010), the complete year-round air-conditioning profile can then be generated. There is generally no straightforward guideline to calculate the hot water demand as it depends readily on the building type and system design. For the reference hotel building adopted with no dining facilities provided, most of the hot water demand comes from washing and bathing in the guestrooms. For the reference retail building, hot water is to be provided at the restaurant floor for washing and cleaning. Hot water demand in the reference hospital building comes from the shower heads. Only shower heads are considered in the reference sports. The electrical power demand for lighting and equipment can be determined from the EMSD guidelines (2007). Regarding the power demand for the air-conditioning equipment, it depends on the system design.

3.3.3 Multi-unit design

In practical design considerations, several units of prime movers are normally used. The main reason is to avoid the prime movers from being operated at a very low part-load ratio throughout the year when the power demand is low. Another reason is the security of the operation. The number of prime movers selected should thus be based on the fact that any prime mover will not be operated at a part-load ratio below a presumed minimum (say 50%) throughout the year. For buildings like hotels and hospitals in which the power demand at night is still substantial, the adoption of unit quantity should allow the operation of at least one set of prime movers throughout the whole year so that the part-load ratio of the trigeneration system is still above the presumed minimum. To facilitate the subsequent system design, the number of absorption chillers used is the same as the number of prime movers employed. Depending on the capacity for the auxiliary cooling system (if required), multiple vapour-compression chillers may be used.

3.3.4 System control

With the adoption of multiple prime movers, the switching mechanism is based on the instantaneous power demand from the building with a minimum start-up threshold of 50% of the rated capacity for one set of prime mover. Whenever one set of prime mover is in operation, the respective EJWP (if applicable), RHWP and the exhaust heat exchanger valve (EHXV) (not for the CGTC system) are switched on. To allow part-load control for the prime movers, the fuel injection rate of the trigeneration system is modulated according to the required part-load ratio.

The operation of the whole chiller plant, including both the absorption chillers and the auxiliary vapour-compression chiller(s), is controlled by a return chilled water thermostat. For the chiller step-up sequencing, the absorption chillers will be switched on first but the number of absorption chillers in operation should not exceed that for the prime movers. The auxiliary vapour-compression chiller(s) is energised only when all the available absorption chillers have been functioning. In case of step down operation, the auxiliary chiller(s) will be stopped first. Within the daily operating schedule of the air-conditioning system, at least one set of the chilled water pump for the absorption chiller should be in operation.

For optimal use of the recovered waste heat, part-load control to the absorption chiller is offered through the absorption chiller valve (AbCV) provided that the absorption chiller is in operation. The space heating water pump (SHWP), space heating heat exchanger valve (SHHXV) and the auxiliary heater for space heating (if required) are energised within the daily operating schedule of the air-conditioning system when the outdoor temperature is below a presumed level. Meanwhile, the water heating heat exchanger valve (WHHXV) and the auxiliary heater for water heating are switched on within the daily operating schedule for water heating. The operation of the auxiliary water cooler is controlled by a return regenerative water thermostat. To minimise the duty of the auxiliary water cooler when the DE or GE is employed, the EHXV is closed in this circumstance. Moreover, the regenerative water flow rate to the auxiliary water cooler is regulated by the auxiliary water cooler valve (AWCV) in case the auxiliary water cooler is in operation. Both the supply air cooling coil valve (SACV) and the supply air heating coil valve (SAHV) are controlled by a room thermostat with dual set points.

3.4 Performance metrics of energy, environmental and economic evaluation

The energy merit of employing a trigeneration system is assessed by determining the saving in primary energy consumption of the building. For the grid electricity, the corresponding primary energy consumption is calculated by dividing the electrical energy output by the overall efficiency of the power plant (η_{grid}). The present value is 36% according to the information from the major power company in Hong Kong (CLP, 2015).

An indicative parameter, the fuel energy saving ratio (*FESR*) may be used to evaluate the primary energy saving potential of a trigeneration system according to Li *et al.* (2006) as defined by

$$FESR = \frac{\frac{W_{out}}{\eta_{grid}} + \frac{Q_{ab}COP_{ab}}{COP_{vc}\eta_{grid}} + \frac{Q_{SHHX}}{\varepsilon} + \frac{Q_{WHHX}}{\varepsilon} - m_f LHV_f}{\frac{W_{out}}{\eta_{grid}} + \frac{Q_{ab}COP_{ab}}{COP_{vc}\eta_{grid}} + \frac{Q_{SHHX}}{\varepsilon} + \frac{Q_{WHHX}}{\varepsilon}} x100 \qquad (1)$$

$$\varepsilon = \begin{cases} \eta_{grid} \text{ for electric heater in conventional system} \\ \eta_{ph} \text{ for primary heater in conventional system} \end{cases} \qquad (2)$$

Here, W_{out} is the electrical output of the prime mover, Q_{ab} is heat power recovered to drive the absorption chiller, Q_{SHHX} is the heat power recovered for space heating and Q_{WHHX} is the heat power recovered for water heating. *FESR* measures the percentage saving in the primary energy consumption for the trigeneration system as compared to that for a conventional system. ε in Eq. (2) reflects the equivalent primary energy input in the conventional system for the recovered heat power for space and water heating where η_{ph} is the efficiency of a primary heater. As the coefficient of performance of the absorption chiller (COP_{ab}) in the trigeneration system is much less than that of the vapour-compression chiller (COP_{vc}) in the conventional system, the required capacity of the auxiliary equipment in the cooling water system (say cooling tower and water pump) is higher in the trigeneration system.

Besides the *FESR*, there are also other parameters usually found in the literature for measuring the energy performance of the trigeneration systems, namely the energy utilisation factor (*EUF*) and energy efficiency (*EE*) as defined below:

$$EUF = \frac{W_{out} + Q_{ab} + Q_{SHHX} + Q_{WHHX}}{m_f LHV_f} x100 \quad (3)$$

$$EE = \frac{W_{out} + Q_{ab}COP_{ab} + Q_{SHHX} + Q_{WHHX}}{m_f LHV_f} x100 \quad (4)$$

EUF represents the amount of energy from the fuel that is being utilised to provide power, space cooling/heating and water heating. *EE* differs from *EUF* by accounting the cooling capacity developed by the absorption chiller rather than the heat absorbed by the absorption chiller.

Table 1 Carbon dioxide emission index of various fossil fuels

Fuel	*CDEI* (kg/kWh)
Diesel oil [1]	0.252
Natural gas [2]	0.198
Towngas [3]	0.236
Petrol gas [4]	0.235

[1] Based on decane
[2] Assumed to be methane.
[3] Based on BEAM (2013).
[4] Based on 60/40% by volume of propane/butane.

The environmental merit of adopting a trigeneration system is assessed by the reduction in carbon dioxide emission. This depends readily on the carbon dioxide emission index (*CDEI*) of the fuels used by the trigeneration system and the grid power plant. Based on the information from BEAM (2012), the *CDEI* of the grid electricity is 0.7 kg/kWh of supply electricity. Table 1 summarises the *CDEI* for various common fossil fuels used in trigeneration systems based on unit energy content of the fuels.

A simple way to investigate the economic feasibility of a trigeneration system is to adopt the simple payback (*SP*) as defined by

$$SP = \frac{Additional\ initial\ cost}{Annual\ running\ cost\ reduction} \quad (5)$$

SP represents the number of years that the saving in the running cost can outweigh the additional initial cost. The space cost is not taken into account when determining the additional initial cost. A value of HKD1.232/kWh is adopted for the electricity cost based on the 2015 tariff scheme from CLP. Regarding the fuel costs, the choice of suitable reference values is difficult in view of the recent volatility of the oil price. Here, the average import prices for 2015 according to CSD (2015) are taken as the reference level for the diesel oil with the inclusion of an infrastructure cost of 5% and a markup factor of around 33% which measures around HKD0.621/kWh rather than the direct retail price. There is currently no direct retail price for natural gas. Hence, a reference price for landfill gas (SCMP, 2015) is adopted which is two-third of the retail price for towngas, i.e. around HKD0.534/kWh.

3.5 Comparative energy, environmental and economic analyses with different building types

For the four types of prime movers considered, the diesel engine is fuelled by diesel oil, while the others are fired by natural gas which is assumed to be methane. Only diesel and gas engines are considered for the reference sports centre due to the low electrical load requirement which makes the use of gas turbine and combined cycle system unfavourable or even impractical.

By performing year-round dynamic system simulations, the respective total primary energy consumption (*PEC*) and carbon dioxide emission (*CDE*) of the trigeneration systems are compared with those based on the corresponding conventional systems. Tables 2 to 6 summarise the major simulation results for the various systems considered for the five building types. The electricity generating efficiency (*EGE*) of the prime movers is also included for comparison. The percentage reductions in the total *PEC* and *CDE* relative to the conventional designs are indicated in Figure 12 and 13 respectively. Here, the reduction in *CDE* is based on the employment of the same primary fuel for the water heaters in both the conventional and trigeneration systems. Only one value for the *CDE* is presented for the conventional system used in the reference office building as no water heating demand is considered.

Table 2 Performance comparison for the various trigeneration systems analysed for the reference office building

System	Average *EGE* (%)	Average *EUF* (%)	Average *EE* (%)	Average *FESR* (%)	Total *PEC* (MWh)	Total *CDE* (Ton)
Conventional	N/A	N/A	N/A	N/A	23362	5887
DE	39.6	75.7	67.2	19.9	19831	4992
GE	39.7	75.3	66.9	19.8	19838	4076
GT	33.0	66.5	60.4	4.60	*23728*	4841
CGTC	39.9	74.5	65.7	19.6	20270	4158

Table 3 Performance comparison for the various trigeneration systems analysed for the reference hotel building

System	Average *EGE* (%)	Average *EUF* (%)	Average *EE* (%)	Average *FESR* (%)	Total *PEC* (MWh)	Total *CDE* (Ton)
Conventional	N/A	N/A	N/A	N/A	13733	3460 (DO) 3357 (NG)
DE	37.0	84.1	74.7	25.9	10540	2653
GE	36.5	83.2	73.6	24.7	10705	2114
GT	28.6	73.9	65.8	10.2	13250	2617
CGTC	34.0	78.9	70.8	20.9	11343	2240

Table 4 Performance comparison for the various trigeneration systems analysed for the reference retail building

System	Average *EGE* (%)	Average *EUF* (%)	Average *EE* (%)	Average *FESR* (%)	Total *PEC* (MWh)	Total *CDE* (Ton)
Conventional	N/A	N/A	N/A	N/A	11796	2973 (DO) 2917 (NG)
DE	38.8	80.8	70.7	23.7	9716	2446
GE	37.7	79.7	69.3	21.5	9935	2026
GT	30.5	72.0	63.8	7.5	11602	2352
CGTC	35.1	74.9	64.4	16.0	10630	2158

Table 5 Performance comparison for the various trigeneration systems analysed for the reference hospital building

System	Average *EGE* (%)	Average *EUF* (%)	Average *EE* (%)	Average *FESR* (%)	Total *PEC* (MWh)	Total *CDE* (Ton)
Conventional	N/A	N/A	N/A	N/A	13583	3422 (DO) 3302 (NG)
DE	36.6	84.0	72.8	22.7	11027	2775
GE	36.6	83.6	72.6	22.7	11065	2186
GT	28.5	77.4	67.5	8.60	13194	2606
CGTC	32.9	80.0	68.7	17.1	11786	2328

Table 6 Performance comparison for the various trigeneration systems analysed for the reference sports centre

System	Average *EGE* (%)	Average *EUF* (%)	Average *EE* (%)	Average *FESR* (%)	Total *PEC* (MWh)	Total *CDE* (Ton)
Conventional	N/A	N/A	N/A	N/A	2198	554 (DO) 517 (NG)
DE	35.7	81.1	69.6	26.6	1846	465
GE	35.2	80.5	68.7	25.5	1867	385

From Tables 2 to 6, the year-round averaged *EGE's* are all lower than the rated values with the differences more pronounced for the GT and CGTC primed systems. This can be explained by the inferior part-load performances of the GT and CGTC as compared to those of the DE and GE systems. The degradation appears to be smaller for use in the office buildings. This is due to the fact that the power demand profile in the office buildings is maintained at a fairy stably high level during the day time which leads to higher averaged part-load ratios for the prime movers. On the other hand, the power demand in the hotel building fluctuates substantially throughout the day. Hence, the resulting averaged part-load ratios and *EGE's* are lower. For the CGTC primed systems used in the hotel, retail and hospital buildings, the averaged *EGE's* are even lower than those of the DE and GE systems although the rated *EGE's* of the respective CGTC systems are higher than the corresponding ones for the DE and GE systems. This highlights that the DE and GE systems are more suitable for applications in which the power demand is expected to fluctuate significantly during the operation of the trigeneration systems. Indeed, the year-round savings in *PEC* are also the highest for the DE and GE prime systems as shown in Figure 12.

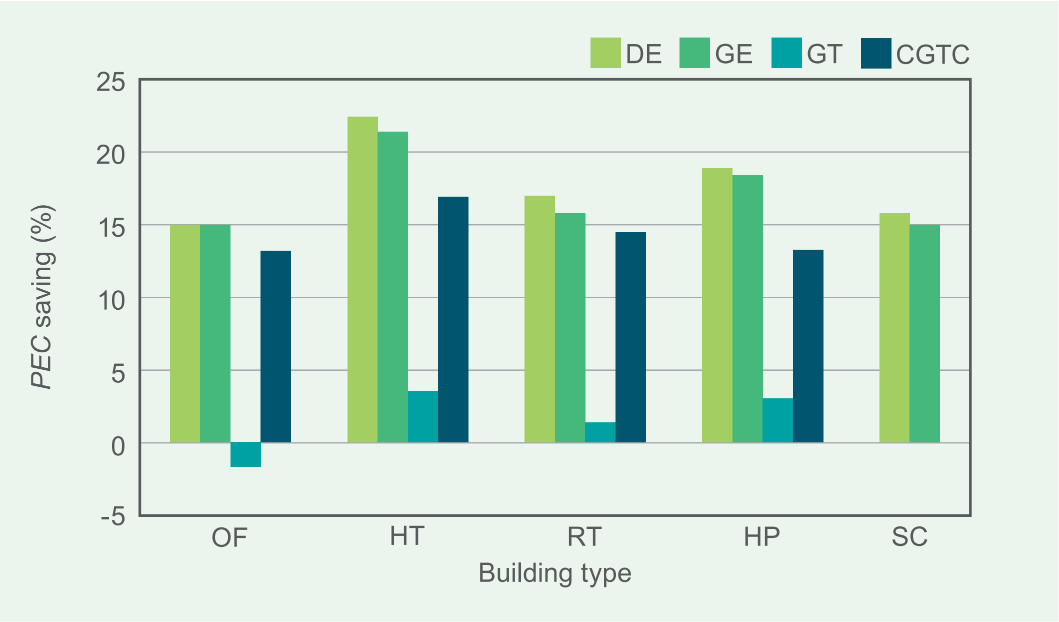

Figure 12 Summarised primary energy saving of the trigeneration systems investigated

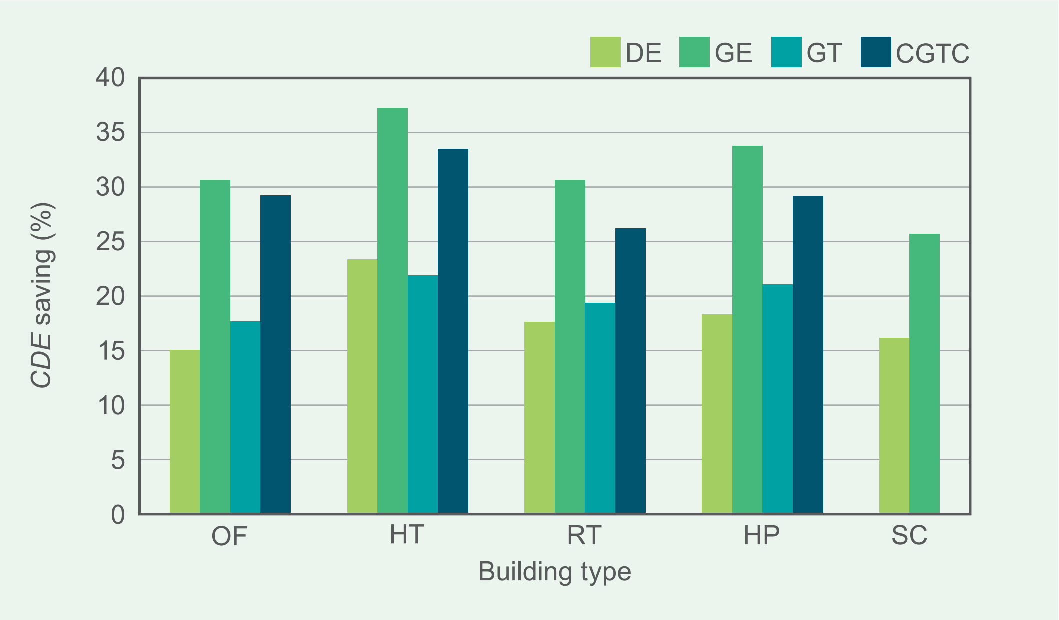

Figure 13 Summarised carbon dioxide emission saving of the trigeneration systems investigated

The averaged *FESR's* and the respective percentage primary energy savings are much lower than the corresponding *EUF's* and *EE's* for all the cases considered. For the GT primed trigeneration system used in the office buildings, there is even an increase in *PEC*. The main reason is that the merit of recovering the waste heat from the prime mover for space cooling is significantly reduced by the much higher COP_{vc} as compared to COP_{ab}. Meanwhile, the energy consumptions from the condenser water pumps and cooling towers of the absorption chillers are substantially higher than those for the vapour-compression chillers of the same capacity due to the lower COP_{ab}. This in turn reduces the saving in *PEC*. To worsen the situation, the averaged *EGE* for the *GT* primed trigeneration systems are even lower than the thermal efficiency of the grid electricity. For the reference office buildings, there is no water heating demand and that the space heating demand is very limited. Hence, most of the recovered waste heat is used for space cooling only. That's why no reduction in *PEC* can be achieved for the *GT* primed trigeneration system used in the reference office buildings.

The environmental merit of the trigeneration systems is promising as the year-round total *CDE's* are all lower than the respective conventional systems as shown in Tables 2 to 6. Clearly, the use of natural gas as fuel yields substantially lower *CDE's* as compared to the adoption of diesel oil thanks to the lower *CDEI* of natural gas as remarked earlier. Indeed, the total *CDE's* for the GT primed trigeneration systems are lower than those based on the DE primed ones even though their energy performances are inferior to the latter. The results reinforce the urge for provision of natural gas supply in Hong Kong for the sustainable development and fulfilment of the target for reduction of greenhouse gas as well as the provision of a better air quality in the city. Based on both the energy and environmental considerations, the GE primed trigeneration systems are the best among the various types of prime movers analysed.

Table 7 summarises the year-round energy cost for the different systems considered based on the unit energy cost for electricity and primary fuels as stated before. Two values are given for the conventional systems (except for use in the reference office building) according to the different types of primary fuels adopted for the water heater. It can be found that no reduction in the annual energy cost can be found for the DE and the GT primed trigeneration systems used in all the building types. The employment of the CGTC primed ones offer running cost savings only when applied to the reference hotel buildings. Meanwhile, the adoption of GE primed trigeneration systems can offer savings in the annual energy cost for all the building types considered. In combination with the energy and environmental merits, the GE primed trigeneration systems are deemed to be the most feasible choice among the various types of prime movers investigated.

Table 7 Comparison of year-round running cost for the various trigeneration systems investigated with those of the respective conventional systems

Case	Total grid electricity consumption (MWh)	Total primary fuel consumption (MWh)	Total running cost (HKD in Millions)
OF, Conventional	8410	0	10.36
OF, DE	1087	16812	*11.79* ↑
OF, GE	1041	16947	10.33 ↓
OF, GT	1020	20893	*12.41* ↑
OF, CGTC	1018	17442	*10.56* ↑
HT, Conventional	4255	1914	6.432 (DO) 6.263 (NG)
HT, DE	0	10540	*6.550* ↑
HT, GE	0	10705	5.712 ↓
HT, GT	0	13250	*7.070* ↑
HT, CGTC	0	11343	6.052 ↓
RT, Conventional	3877	1028	5.415 (DO) 5.325 (NG)
RT, DE	384	8650	*5.848* ↑
RT, GE	422	8762	5.195 ↓
RT, GT	399	10494	*6.091* ↑
RT, CGTC	389	9549	*5.574* ↑
HP, Conventional	4093	2213	6.418 (DO) 6.223 (NG)
HP, DE	0	11027	*6.852* ↑
HP, GE	0	11065	5.904 ↓
HP, GT	0	13194	*7.040* ↑
HP, CGTC	0	11786	*6.289* ↑
SC, Conventional	550	670	1.094 (DO) 1.035 (NG)
SC, DE	109	1544	1.094
SC, GE	106	1571	0.969 ↓

Although the use of GE primed trigeneration systems yields a reduction in energy cost, the magnitude is actually not high. In particular, the benefit is insignificant when applied to the reference office buildings. Even for the reference hotel buildings, the annual saving is less than HKD 0.6 million. This amount is unlikely to give a satisfactory payback period. One main reason is that the unit energy cost for the natural gas (landfill gas in this circumstance) is not sufficiently low as compared to that for the grid electricity. Indeed, in many countries of Europe (Eurostat, 2015) and in USA (EIA, 2016; Statista, 2016), the gas price is substantially cheaper and that the electricity-to-gas cost ratio can exceed three. This allows the energy cost saving to be increased significantly, and hence a reduction in the payback period. At present, there is no carbon tax in Hong Kong. Hence, the benefit of the large reduction in CDE for the GE primed trigeneration systems cannot be echoed. Sweden currently implements the carbon tax which is generally the most expensive one in the world [over USD105.0 per ton of carbon dioxide generated for non-industrial premises (Summer *et al.,* 2009)], and it ranges from USD 15.0 to USD 60.0 for other Nordic countries. Clearly, with carbon tax, the simple payback can be improved. The emission of carbon dioxide also incurs other latent impact to the society which can be expressed by a social cost (USEPA, 2016). According to a recent study (Moore and Diaz, 2015), this social cost can measure up to USD 220.0 or HKD 1,716.0 per ton of carbon dioxide emitted. In this regard, the accounting of the social cost can improve the economic merit of the trigeneration systems substantially.

To investigate, four scenarios are considered as shown below:

S1. Based on the normal electricity and gas cost as adopted in Table 7 without any carbon tax;

S2. Adoption of a carbon tax at HKD 200.0 per ton of carbon dioxide generated (an average level as exercised in France);

S3. Inclusion of a social cost at HKD 1,716.0 per ton of carbon dioxide released;

S4. Based on an electricity-to-gas cost ratio of three by reducing the gas cost to HKD 0.417/kWh.

Table 8 summarises the respective initial cost of the conventional and GE primed trigeneration systems for use in different building types and Figure 14 shows the corresponding *SP's* under different scenarios. For the first scenario, the calculated *SP's* are very high with the lowest value of around 13 years for use in the reference hotel building. Clearly, this is not considered to be feasible, particularly in view of the fact that the operation and maintenance cost has not been taken into account in the calculation of *SP*. With the implementation of the carbon tax in S2, the corresponding *SP's* reduce substantially particularly when applied to the reference office buildings. Still, they are not deemed to be satisfactory although it drops below 9 years for the reference hotel buildings. However, the inclusion of the carbon cost in S3 evidently reduces *SP's* to less than 8 years in all cases. Also, the adoption of a lower gas cost in S4 yields significant reduction in the *SP's* to less than 10 years in most situations. This indicates that a secure supply of natural gas with a reasonable electricity-to-gas price ratio is a pre-requisite for the successful promotion of trigeneration systems. Indeed, based on the *CDEI* as indicated in Table 2 for natural gas, the carbon cost is about HKD 0.34/kWh of natural gas consumption. This is substantially larger than the cost difference for the natural gas adopted in S1 and S4 (about HKD 0.117/kWh). This leaves room for the government to consider incentive schemes in order to make the trigeneration systems economically feasible as discussed in the later section.

Table 8 Summarised initial cost for the various conventional and gas-engine-primed trigeneration systems investigated with different building types

Building type	Initial cost (HKD in millions)	
	Conventional	Trigeneration
OF	12.2	27.8
HT	4.25	11.4
RT	5.60	13.3
HP	4.25	11.4
SC	1.50	3.60

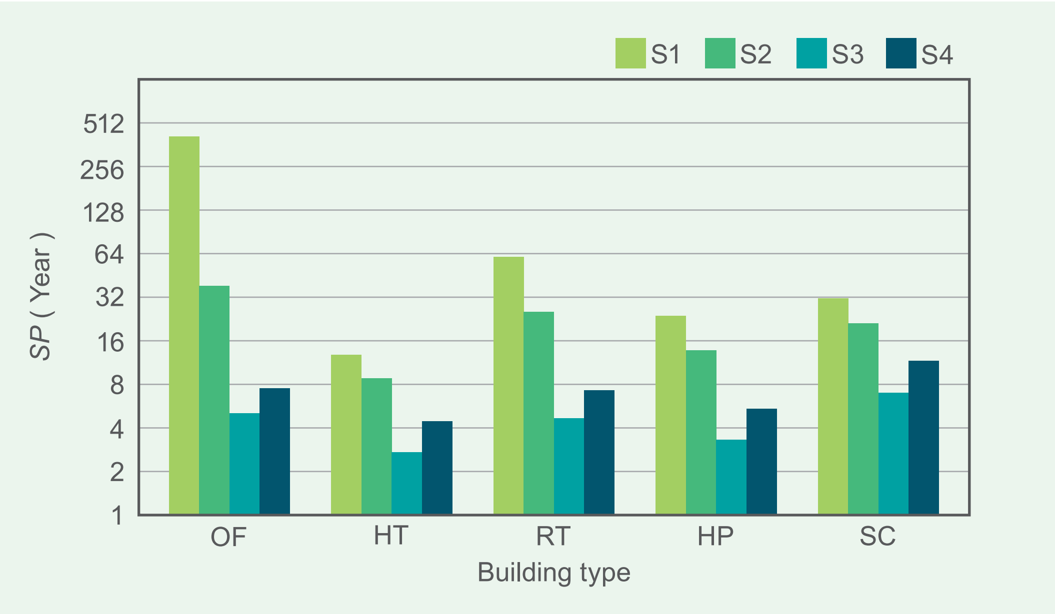

Figure 14 Summarised simple payback for the various building types under different scenarios

So far in the previous analysis, only the price of landfill gas is adopted in S1, S2 and S3. In case landfill gas is really accessible, the reduction in *CDE* can be more significant which offer a much better payback for the trigeneration systems for S2 and S3 as shown in Figure 15. Clearly, the respective *SP*'s drop substantially as compared to those indicated in Figure 14 which falls to around 6 years for the reference hotel building even when only the carbon tax is taken into account. In case the carbon cost is considered, the corresponding *SP*'s are below 4 years for all the building types investigated.

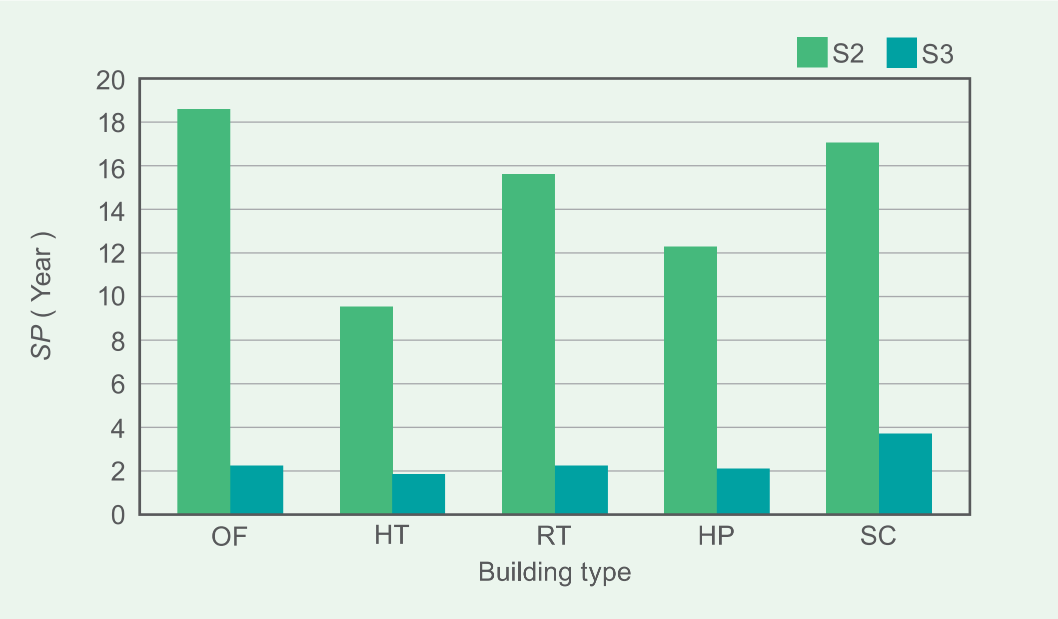

Figure 15 Revised simple payback for the various building types based on biogas

4 RECOMMENDATIONS

4.1 Design shift to distributed power supply

With the use of trigeneration systems at building level as distributed power supply, the quest for the expansion and new development of the centralised power plants to fulfil the increasing electricity demand can be relieved. This is helpful as the time from the planning to complete installation of this kind of infrastructure work is usually very long for the power companies. Moreover, many disputes have to be settled regarding the cost and environmental impacts to the society. Indeed, according to a recent report from HKCC (2014), it is suggested that the adoption of distributed power supply at building level can provide a healthy competition in the local electricity market. The prerequisite is that natural gas can be supplied to the buildings. The fulfilment of this requirement is not a short-term issue as remarked by HKCC (2014). Nevertheless, it highlights the possible trend for future development.

The provision of natural gas to buildings involves a lot of technical consideration and the government policy. One possibility is that it is supplied through the existing pipework of HKCGC. In this regard, the gas company will only provide natural gas, and the government may need to negotiate with the gas company in order to do so. Another possibility is to supply liquefied natural gas (LNG) to buildings in the way similar to that for the LPG, but then storage facility will be required at the buildings. Moreover, the price of LNG is generally higher than that of natural gas which will reduce the economic merit of the trigeneration systems. Nevertheless, as indicated in the Figure 14, reasonable payback periods can still be achieved should the cost difference between electricity and gas is reasonably high (like that in US and Europe), in particular for application in hotels and hospitals with a high hot water demand. In case the gas company can get the natural gas supply from the Mainland at the same price level as the power companies, it can be expected that the price gap between electricity and gas will widen to a favourable level. Of course, this is based on the assumption that the infrastructure cost for the gas supply is low. Meanwhile, as the electric companies are urged to use more natural gas for power generation, it can be expected that the electricity price should rise more in future.

4.2 Recommended incentive schemes for fuels and trigeneration installation

In spite of the recognised energy and environmental merits of trigeneration systems, the economic factor limits the higher application of this technology. In order to promote the green and new technologies in Hong Kong, the trigeneration systems should be supported by the government through promotion, subsidies or funding. Since the current capital investment on trigeneration systems is not attractive, incentive schemes should be adopted and promoted by the government so that the professionals can convince the building developers to adopt this green technology. These include:

- subsidy on fuel and investment;
- tangible feed-in tariff scheme; and
- incentive on reduction of carbon dioxide emission.

From the results shown in Figure 14, even if biogas is available, the unfavourable electricity-to-fuel price ratio is still fatal to the feasible use of trigeneration systems. Hence, the subsidy for the fuel price is crucial. On the other hand, investment subsidies and subsidies for demonstration projects help reduce the initial cost and hence the payback period. The ways of the investment subsidies include low interest loan, direct cash or financial support, tax exemptions and rebates.

A tangible feed-in tariff scheme should be worked out so that the local power companies would obligate to purchase the spill power generated from the trigeneration systems where appropriate. The feed-in tariff scheme is one of the common policies enacted in those countries (like USA, Europe, Japan, etc.) that are advocating the distributed power supply and the renewable energy installations.

Incentive on reduction of carbon dioxide emission can be in the form of a rebate to any users who can demonstrate a carbon emission cut. This is similar to the energy saving rebate promoted by the power company before. In fact, carbon dioxide emission imposes long-term cost to the community as reflected by the social cost mentioned in Research Finding and Discussion. Hence, the issue of rebate by the government to anyone who can help reduce the carbon emission would be a reasonable and effective motive force.

4.3 Proposed areas for further investigation

The present study reveals that the provision of space cooling through the recovery of waste heat from the prime movers is not beneficial, particularly if such kind of heat demand becomes a major part of the total usage of the recovered heat. To remedy the situation, cogeneration system can be considered in which the available waste heat is used primarily for water heating. Indeed, an actual installation is in progress for utilising landfill gas to drive a cogeneration system in a hospital in Tai Po (SCMP, 2015). In this circumstance, the sizing of the system will be based on the peak waste heat demand rather than the peak electricity demand and the grid electricity will supplement any deficiency in the power supply to the building.

The performance of a trigeneration system can be enhanced by adopting a prime mover with a higher EGE. The solid oxide fuel cell (SOFC), with EGE up to 60% based on the latest technology (Elmer and Riffat, 2014), can be a good choice. The main obstacle is the high initial cost at present as compared to the other kinds of prime movers. However, as the technology gets wider acceptance, it can be expected that the price of the SOFC can drop substantially so that a reasonable payback can be achieved. The technical concern is the long startup time of the SOFC. To maintain the temperature inside the SOFC at a sufficiently high level for rapid re-start during the part-load operation, a certain amount of fuel has to be consumed with no output from the SOFC. This will impair the performance of the SOFC, the extent of which has to be determined from an independent study.

In Research Findings and Discussion, a social cost for carbon dioxide emission is referred which is based on the situation in USA. The actual impact in Hong Kong may be different due to the different geographic and social structures. Hence, it is beneficial to investigate the actual social cost of carbon dioxide emission in Hong Kong which allows the policy makers to understand more clearly the consequences of carbon dioxide emission and hopefully push them to be more active in the promotion of green technologies in Hong Kong.

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Members of CIC Task Force on Research

Mr. Jimmy TSE
Prof. Christopher LEUNG
Ir Joseph MAK
Prof. James PONG
Prof. Sze-chun WONG
Ir Chi-chiu CHAN
Ir Tommy NG
Mr. Shu-jie PAN

Research Team

Principal Investigator

Ir Dr Square K. F. FONG

Co-investigator

Ir Francis LEE
Ir Dr Alan M. L. FONG

Research Fellow

Dr C. K. LEE

Senior Research Associate

Ir Vincent W. L. MA

Technical Assistant

Ms. L. N. WONG
Ms. T. K. IP

建造業議會
Construction Industry Council

Address 地址 38/F, COS Centre, 56 Tsun Yip Street, Kwun Tong, Kowloon
九龍觀塘駿業街56號中海日升中心38樓

Tel 電話 : (852) 2100 9000

Fax 傳真 : (852) 2100 9090

Email 電郵 : enquiry@cic.hk

Website 網址 www.cic.hk

cic_hk
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