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OPTIMAL DESIGN OF MULTI-UTILITY COMPLEX FOR A LOW CARBON CITY IN CHINA INTEGRATING RENEWABLE ENERGY

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ABSTRACT

There are many new city and district development projects ongoing in China, which are aimed at developing and building the low carbon emission cities of the future. The Energy Utilities sector is also facing new challenges from policy and regulations aimed at improving energy efficiency, adopting clean energy and mitigating environmental impact. As such, energy supply systems are becoming increasingly complex due to the installation and operation of multiple renewable energy systems. A Multi Utility Complex (MUC) has been proposed as a new and more effective way of constructing urban utility systems, in which facilities for utility services (e.g. energy supplies, water/sewage treatment and waste management plants) are physically installed at one site and managed by an integrated operating centre.

When designing a MUC to be ‘cleaner’, more efficient and economical, determining an appropriate capacity of each component constituting the MUC is an essential and not trivial task due to the complexity of resource /energy flows and constraints associated with energy policy and regulations. To address this, an optimization design methodology has been adopted on the basis of a population-base optimization algorithm in support of cost-effective investment. The methodology is implemented in a software tool, ‘*Plant Optimizer*’, equipped with an urban utility demand profile modeller, the MUC package with different installation scenarios, analysis modules and reporting facility. This paper describes the optimizing methodology and functions of the software tool, and presents a case study to demonstrate the applicability.

INTRODUCTION

In 2007, the combined population of China's cities and towns (those residing in cities and towns for half a year or longer) reached 593.79 million. This accounts for 44.9% of the country's total population, and represents an increase of 27% when compared to 1978 [1]. Since China is undergoing a rapid transition towards urbanization and industrialization, it is predicted that the total number of Chinese cities will reach about 1,000 by 2015 [2]. By 2050, it is likely that 75% of the Chinese population will live within the urban environment. This will account for 85% of China’s GDP and 90% of the service industry sector [3]. A policy of urbanization is regarded as an essential process to ensure continued, sustainable economic development in China over this period. Meanwhile, during the course of urbanization, there are critical issues to be addressed which include energy efficiency, and mitigation of CO_2 emission and environmental pollution. There are numerous new city development projects ongoing in China, which are aimed at developing and building low carbon emission cities with increasing levels of Renewable Energy (RE) systems deployment [3].

In this study, a Multi Utility Complex (MUC) has been proposed as a new way of constructing urban utility systems, in which facilities for urban utility services (e.g. energy supplies, water/sewage treatment and waste management plants) are co-located at the one site and managed by an integrated operating centre. The proposed MUC centre is designed according to the following devised strategies (see Fig. 1 for a schematic diagram presenting a conceptual image of a MUC).

- Maximizing the recovery of waste heat from sewage and waste by using renewable energy systems (such as a sewage heat pump, plasma gasification plant, or incinerator),
- Making profit by importing sewage and waste from neighboring cities (or community),
- Maximizing the utilization of utility facilities even vacant lots by installation of renewable energy systems (such as PV, solar thermal collector and wind turbine on a roof and vacant lots) and
- Co-operating with a renewable systems complex which is installed on wasteland, desert or offshore.

When designing the MUC to be cleaner, more efficient and economical, determining an appropriate capacity of each component in the MUC is not a trivial task due to the complexity of resource /energy flows and constraints associated with energy policy and regulations. There have been studies investigating the feasibility of utilizing renewable energy at the community or city level [4]-[8]. These studies were, however, limited in terms of number and type of RE systems selected to be part of the integrated energy supply system; and the optimization approach with only a single objective (e.g. identify the best combination or capacity towards lowest carbon emission). Identification of the economic feasibility of a MUC at an individual sub-system level could introduce conflicts between the services provided and result in uneconomical installation and operation of the system. Therefore, a holistic approach is required to deal with the optimization of the MUC. This has been addressed through the development of an optimization design methodology based upon an energy/resource flow model incorporating a multi-objective optimisation algorithm in support of identification of cost-effective investment strategy for MUC's. The methodology has been implemented in a software tool, '*Plant Optimizer*'. This paper reports the optimization methodology together with the functionality and applicability of the software tool when applied to a case study consisting of a Low Carbon city in China.

OPTIMISATION METHODOLOGY

The MUC package consists of controllable fuel-powered systems (i.e. combined heat and power, generators, boiler and chillers), uncontrollable RE systems (i.e. solar thermal, photovoltaic (PV) and wind turbine) and urban waste-to-energy systems (i.e. sewage heat pump, plasma gasification plant, incinerator, etc.). Within the MUC package, a combined heat and power (CHP) system has been selected as the main energy supply system for which the capacity is determined according to the operational mode (i.e. electrical following or thermal following) and peak demand. Figure 2 illustrates the configuration of the MUC package.

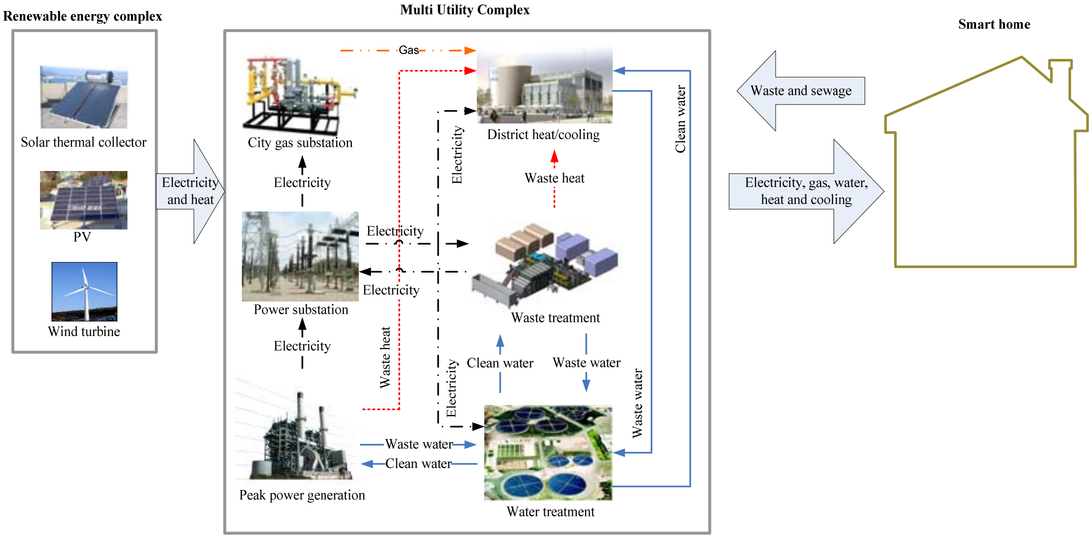

Figure 1 Schematic diagram of MUC.

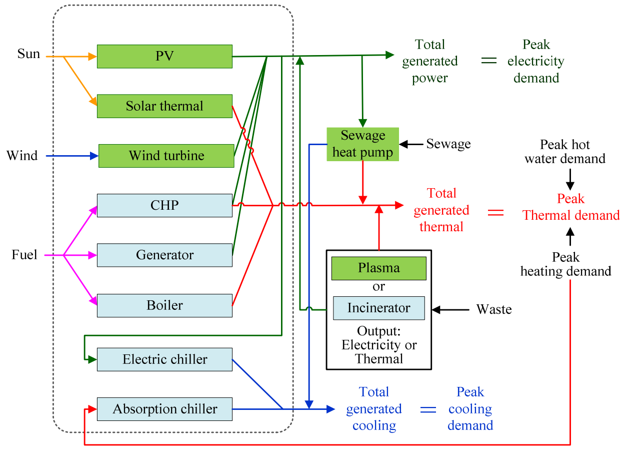

Figure 2 Resources/energy flow and components of the MUC package.

As illustrated in Figure 2, some components of the MUC package are interconnected with resource input/output relationships. For example, hot water required for an absorption chiller is supplied from thermal plant (i.e. CHP, boiler, solar thermal). To quantify the capacity of the peak heating load, the thermal demand of the absorption chiller needs to be taken into consideration. Due to inter-connections between such components, it is required to set up prioritization rules within an optimization process. The following lists the rules adopted within this work:

- ‘electrical following’: electrical supply systems (e.g. CHP, generator, PV, wind turbine etc) are examined to establish their optimal capacities before considering the demands of the thermal systems (e.g. boiler, sewage heat pump);
- ‘thermal following’ operation mode: converse to the above, the thermal supply systems are examined prior to the electrical;
- ‘with renewable systems’: renewable systems (i.e. PV, solar thermal collector and wind turbine) are examined to find their optimal capacities within the allowance of RE installation then remaining systems are examined for their capacities by following either ‘thermal following’ or ‘electric following’ rule;
- ‘with cooling systems’: cooling systems (i.e. electrical chillers or/and absorption chillers) are examined first followed by the remaining systems based on their capacities, by either ‘thermal following’ or ‘electric following’

A population-based optimizing approach, called Bees Algorithm is adopted [9, 10] to search for the best combination of matching components in the MUC package in terms of cost-effective investment against carbon emission reduction. In this study, a redefined Bees Algorithm with modifications has been employed to solve the multi-objective optimisation problem (MOOP) [11][12]. To compare candidate solutions to the MOOPs, the concept of ‘Pareto dominance’ and ‘Pareto optimality’ is commonly used. A solution belongs to a Pareto set if there is no other solution that can improve at least one of the objectives without degrading any other objective. Figure 3 illustrates the concept of Pareto optimality.

Its outcome is Pareto front represented by total capital cost (or/and running cost) against CO$_2$ emission. Each Pareto optimal solution obtains the optimal capacity of combined selected supply systems. Individual dots within Figure 3 represent the Pareto solution which has a combination of the components in the MUC package. The set of these Pareto solutions forms the Pareto front. The optimization engine finds all Pareto solutions through the objective space allowing decision makers to discard unpromising solutions which are out of range of either budget or CO$_2$ reduction ratio.

Those solutions can help decision makers to decide which systems could be selected to achieve cost effectiveness and carbon emission reduction.

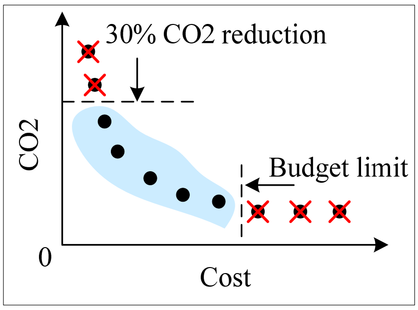

Figure 3 Pareto dominance and optimality with constrains of carbon emission and cost of the MUC package

SOFTWARE DEVELOPMENT: PLANT OPTIMISER

The Plant Optimizer is a software tool for the sizing of the MUC centre. Its main development objective is to assist urban energy planners and utility providers to determine cost–effectiveness and technical appropriateness of the planed centre in a time and cost effective manner. More specifically, the Plant Optimizer can be utilized to:

- provide 1) an optimal utility configuration package regarding the location and size of site coincided by utility providers, and 2) forecast of total capital cost, annual running cost, annual fuel consumption and CO2 emission; and
- assess and establish an operating strategy through simulation of each package by adopting a hourly-based matching analysis between energy supply systems (for electricity and thermal) and demand profile.

The Plant Optimizer is equipped with functionalities such as: demand modelling to forecast macro scale demands of energy/environmental options within a city; an optimization algorithm to identify the optimal design of utilities combination (electricity, heating & cooling, treatment of water, sewage and waste); supporting decision-making in terms of capital cost and running cost; and estimating ‘in-field’ application through virtual operations based on a 8,760 hours/ annum operating mode. The main functionalities of this application are:

- ‘city design’: design of city scale infrastructures in the context of location, size, climate and strategy of energy/environment treatment processes at specific sites;
- ‘demand forecast’: design at the city scale according to the site size and forecasts of energy/environmental demand by establishing standard profiles for energy/environment systems;
- ‘supply system design’: designs energy supply systems and environmental treatment processing systems;
- ‘system optimization’: identifies an optimal combination of the selected supply systems using the optimization algorithm in terms of capital cost, running cost and CO2 emission;
- ‘decision support’: shows total capital cost and annual running cost based on ‘optimized’ system performance; and
- ‘operation simulation’: examines generated energy by selected supply systems and fuel consumption under partial load through virtual operation with hourly based annual climate data.

CASE STUDY

The case study focused on a ‘medium-scale’ new city, with the population of 560,000 and a total area of 71,433,900m^2, and located in a hot-summer cold-winter climate near Shanghai, Figures 4, 5 show the urban plan and building blocks ratio for the city. Figure 6 illustrates the hourly outdoor dry bulb temperature profile in a typical meteorological year.

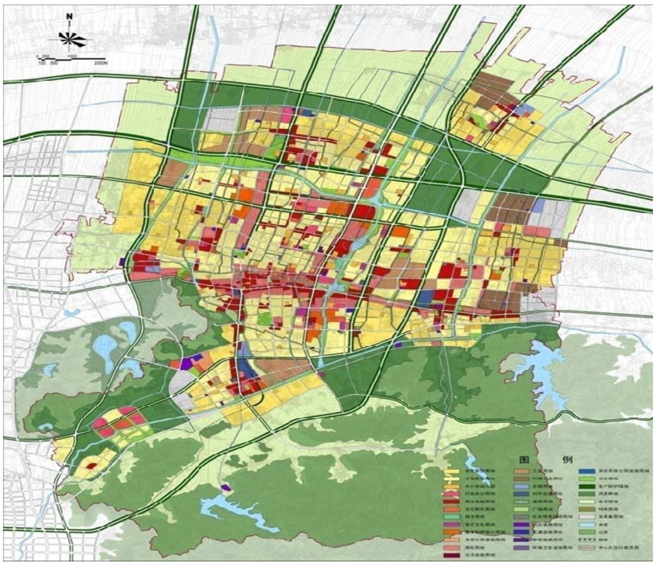

Figure 4 Urban plan of the new city

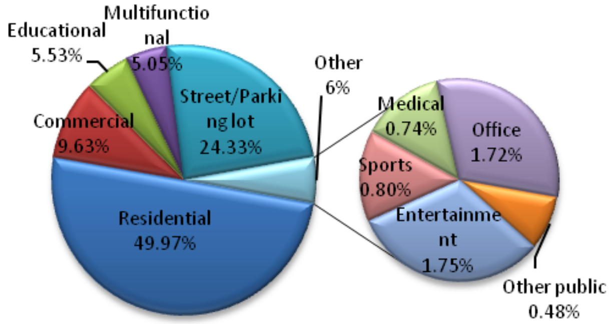

Figure 5 Proportions of building areas of various building stocks

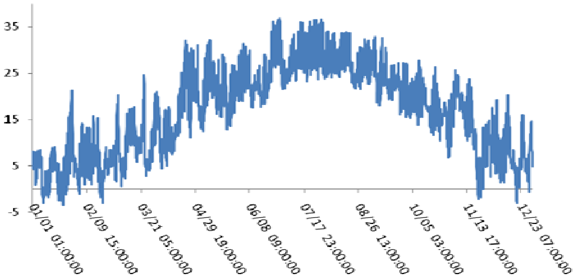

Figure 6 Hourly outdoor dry bulb temperatures (^{o}C).

Before carrying out an optimization analysis of the MUC, the database of demand profiles (i.e. electricity, heating/cooling, hot water) for different building stocks were established. The demand profiles of various building stocks (e.g. residential, commercial, industrial etc) were defined on the basis of government published literatures [13, 14] and statistical data of existing cities in China. The electrical demand profile of water treatment facilities (sewage and supply water) were also established from relevant literatures [14, 15]. Monthly data was collected from literatures. To obtain hourly heating/cooling demand patterns, virtual building models representing each building type were developed using a building simulation software program, ESP-r [16]. These virtual models were used to generate demand profiles for building stocks where there were no available statistical demand data. Typical Meteorological Year (TMY) weather data were used when running simulation. Figure 7 shows examples of the plan and zoning of standard office and residential buildings to establish representative virtual demand profiles.

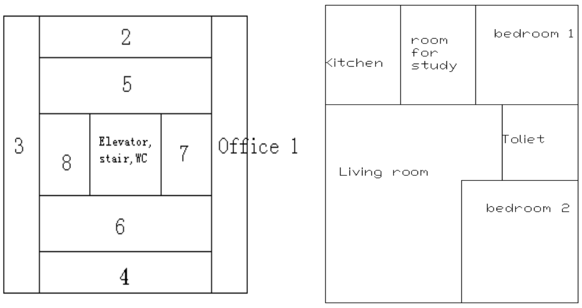

Figure 7 Plan and zoning of standard floor of office and residential building.

For office buildings, the floor-ceiling height is 4m, and the floor plan is 34m*34m with a 10m*10m core zone, while the depth of perimeter zones is 5m. The input data of envelope components, internal loads and operation schedules for office buildings is in compliance with GB50189-2005 (Public Building Energy Saving Design Standard) [17]. For residential buildings, the floor-ceiling height is 3m, and a floor plan of 9m*12m. The standard floor plan is divided into two bedrooms, one living room, one study room, one kitchen and one toilet. The input data of envelope components, internal loads and operation schedules for residential buildings were estimated according to the statistical data for China. Table 1 shows demand profiles of the city. It is assumed that the MUC covers 60% of electricity and water demand. The total demand of electricity includes the electrical demand of the service facilities (e.g. sewage heat pumps, water treatment, electrical chillers) in the MUC. The peak space heating demand is approximately 6 times higher than that of electricity.

Table 1 Demand profiles of the case city.

	Total demand	Supplied from MUC	Supplied from Grid	Peak demand
Electricity (Gwh)	12,059,542	5,844,384	3,896,256	1,606
Heating (Gwh)	4,908,026	4,209,467	0	8,582
Cooling (Gwh)	2,179,664	1,804,370	0	1,610
Hot water (Gwh)	1,688,601	1,435,266	0	307
Water (m^3/day)	224,000	134,400	89,600	n/a
Sewage (m^3/day)	191,620	191,620	0	n/a
Waste (ton/day)	823	823	0	n/a

The MUC package includes a range of renewable energy options (PV, wind turbine, solar thermal collector and sewage heat pump), an absorption chiller as a cooling system and incinerator as a waste treatment system to supply electricity. Using the plant optimizer, the MUC package was examined with different analysis aspects. Table 2 presents the input parameters used for the MUC optimizing algorithm. The followings are the results of the optimization analysis.

1) Capital cost vs. total (capital + running) cost

Optimization analysis was undertaken against two different cost conditions: capital and total (capital + running costs for 25 years). Figure 8 shows the Pareto fronts produced from the optimization analysis with a thermal-following operational mode. All Pareto solutions meet thermal, electrical and cooling demands. As can be seen in the Figure 8, diverse Pareto fronts are produced from the optimization analysis in terms of capital cost and carbon emission. If the 25 years running cost condition is applied, the number of Pareto fronts is limited. This indicates that the optimal capacity of the MUC is identified as the constraints of the optimal condition are applied.

2) Thermal following vs. electrical following method

Figure 9 illustrates Pareto fronts produced by the optimization analysis with two operational conditions: “thermal following” and “electrical following”. Pareto fronts from thermal following operations have greater diversity than electrical following. Pareto fronts by electrical following methods indicate that there are few options in determining the capacity of each component of the MUC package. This is because the MUC has to be optimized to meet both thermal and electrical demands. The MUC optimization is subject to the higher peak demand type.

Pareto fronts in Figure 9 also show the threshold point in terms of effectiveness of capital investment against carbon emission. For example, the Pareto front point ‘a’ and ‘b’ are placed at the same level of CO_2 emissions while the capital cost of the Pareto point ‘b’ is much higher. Figures 10 and 11 illustrate proportions of the components of the MUC package represented by ‘a’ and ‘b’ respectively. The MUC package ‘b’ contains a greater capacity of PV and wind turbine systems for which capital cost are higher than other energy systems. The Pareto fronts provide an insight for decision makers to identify the appropriate scale of capital investment.

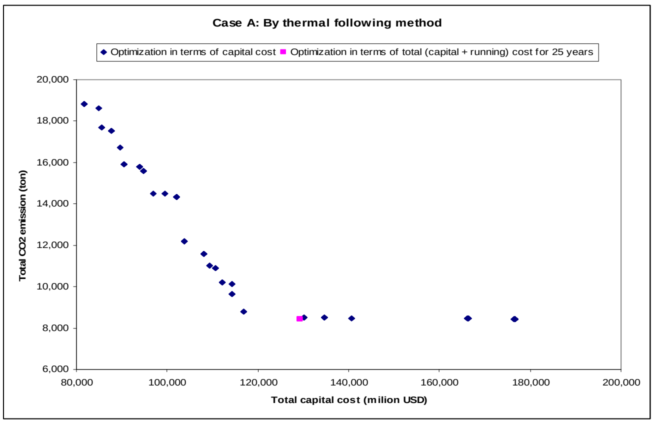

Figure 8 Pareto fronts (optimization in terms of capital cost vs. total cost for 25 years)

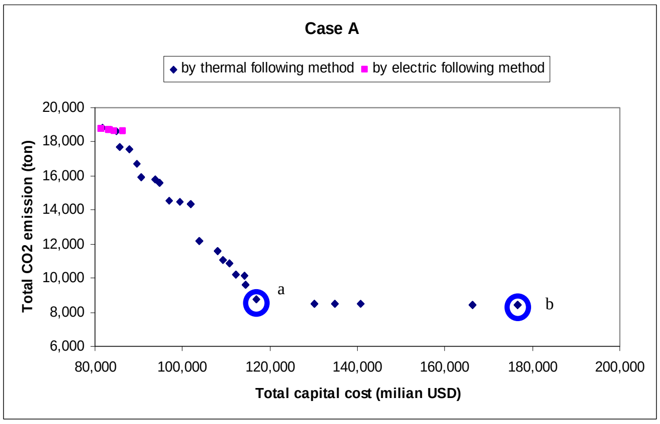

Figure 9 Pareto fronts (thermal vs. electric following method)

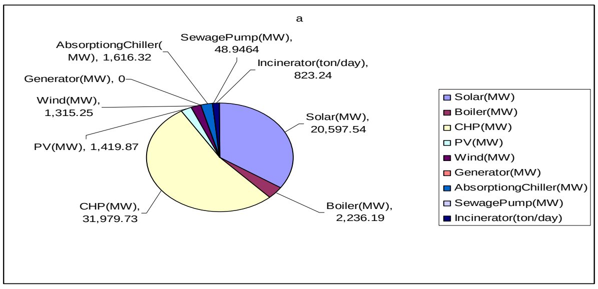

Figure 10 Individual proportions of the energy system (a Pareto solution in Figure 9)

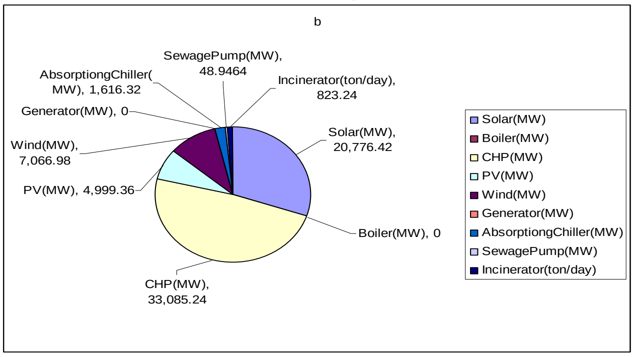

Figure 11 Individual proportions of the energy system (b Pareto solution in Figure 9)

3) 50% reduction of energy demand (i.e. when demand profile is changed)

When reducing thermal demand by 50%, Pareto fronts are formed within a much lower area compare to those of 100% thermal demand. Figure 12 displays Pareto fronts for 100% thermal demand (Case A) and 50% thermal demands (Case B). As can be seen in Figure 12, Capital costs of Pareto fronts of Case B are less than 10% of those of Case A. The capital costs falls significantly. It implies that adopting demand side measures such as 'passive house' levels and demand-side control can make significant impact on the capital investment for the city.

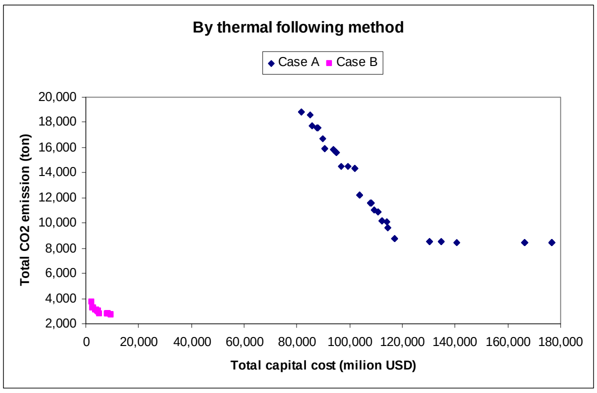

Figure 12 Pareto fronts (Case A vs. Case B(50% thermal demand))

4) Change allowance of RE deployment

If the percentage of utilization for renewable systems is increased from 0% to 70%, the capital cost and total cost is gradually increased as shown in Figures 13 and 14. Over a 25 years operating life, 30-50% of renewable utilization obtains minimum total (capital + running) cost and CO2 emissions reduction in electrical following case, as shown in Figure 15. However, in thermal following case, the lesser the utilization of renewable systems (i.e. 0% - 10%) obtains highest CO2 emissions but lowest total cost, and visa versa.

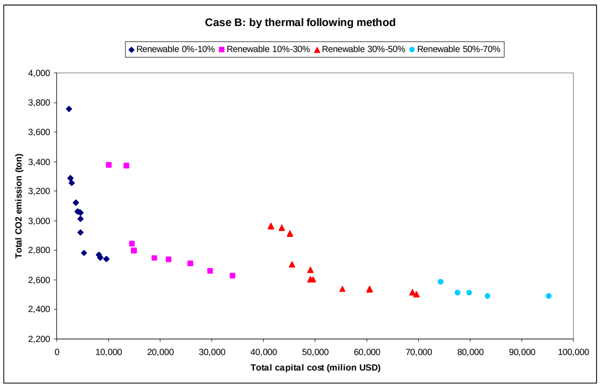

Figure 13 Pareto fronts on changing renewable usage percentages

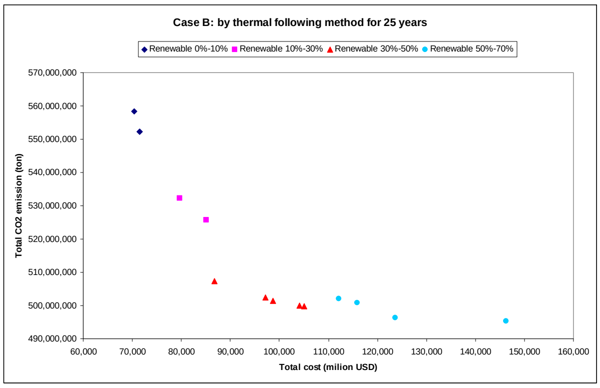

Figure 14 Pareto fronts on changing renewable allowance in terms of total cost for 25 years by thermal following method

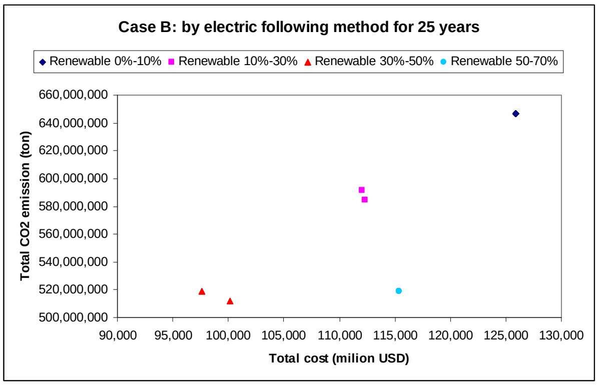

Figure 15 Solutions on changing renewable allowance in terms of total cost for 25 years by electric following method

CONCLUSION

This paper introduced a methodology for establishing an optimal design of a MUC when integrated with multiple renewable energy systems to service a city. A new city located in a hot-summer cold-winter area of China was selected as a case study to test the applicability of the methodology and the robustness of the software tool. Accordingly, the results of the case study has demonstrated that the proposed optimization method can provide decision makers (e.g. energy planners, city designers, investors etc) with quantitative information required to support the establishment of cost-effective, low carbon energy strategies. This includes demand-side management measures and RE installation/operation as an integral part of the MUC. To make a more realistic scenario-based study, hourly-based demand/supply operation of the MUC should be tested.

ACKNOWLEDGEMENT

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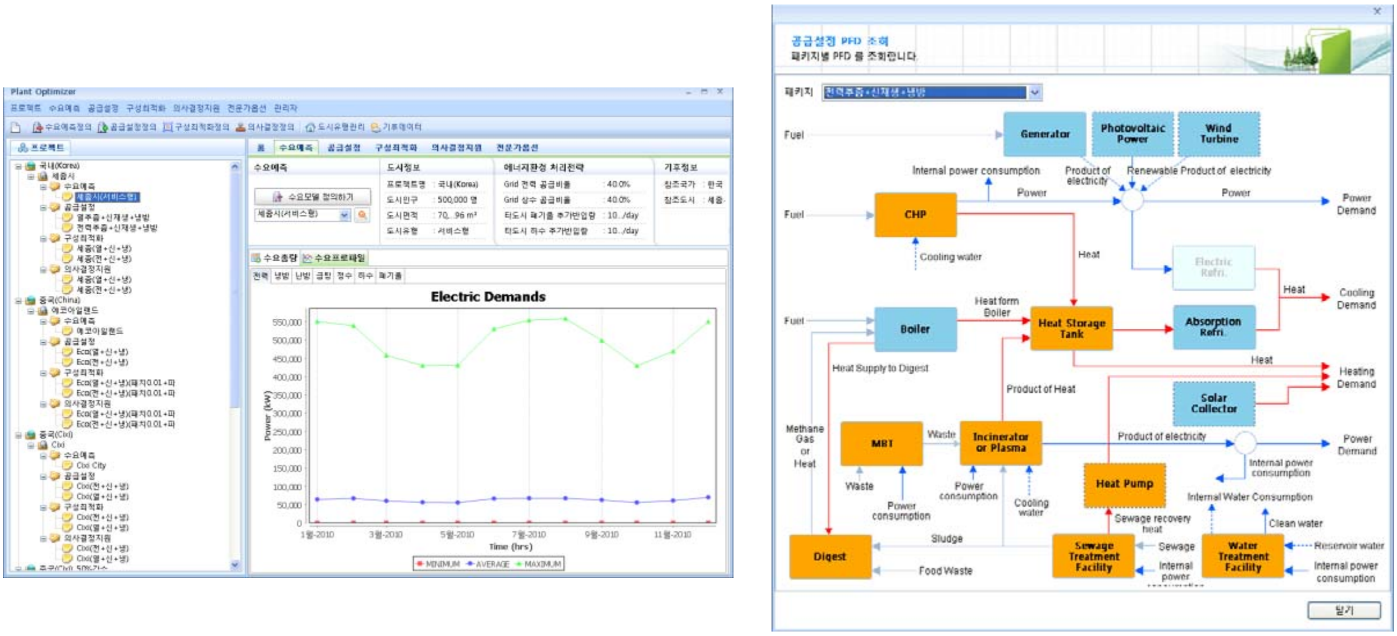

(a) Demand forecasting

(b) Configuration of the MUC package

Figure 4 Screen shots of Plant Optimizer.

Table 2 Parameters used for the MUC optimizing algorithm

System parameters	CHP	Generator	PV	Wind Turbine	Boiler	Heat pump	Absorption Chiller	Solar Collector	Incinerator
Fuel	Natural gas	Diesel	-	-	Diesel	Electricity	Thermal	-	Waste
Fuel consumption ratio (m^3/kW)	0.195	0.029	-	-	0.118	-	-	-	-
Fuel price (\$/m^3)	0.58	1.25	-	-	1.25	-	-	-	-
Fuel price increase (\$/m^3)	0.03	0.04	-	-	0.04	-	-	-	-
Operating hours (hour)	8,760	8,760	-	-	8,760	8,760	2,880	-	7,920
Unit capital cost (\$/kW)	1,369	204	8,815	4,583	125	971	93	2,620	833
Electric efficiency (%)	95	95	15	9.1	-	-	-	-	100
Thermal efficiency (%)	85	-	-	-	85	80	90	12	-
Power/Heat ratio	0.5	-	-	-	-	-	-	-	-
COP (thermal)	-	-	-	-	-	3.837	-	-	-
COP (cooling)	-	-	-	-	-	3.972	1.0	-	-
CO_2 factor	0.185	0.253	0	0	0.253	0*	0*	0	1
Possible maximum capacity boundary	Peak electric/thermal demand	Peak electric demand	City area	Peak electric demand	Peak thermal demand	Daily sewage **	Peak cooling demand	City area	Daily waste **

*: CO_2 factor for input source is already concerned in the supply source
**: Their capacities are fixed depending on sewage and waste