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# Investigation on potential applicability of subsurface cooling in Singapore

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## HIGHLIGHTS

- First attempt to study the potential applicability of subsurface cooling in Singapore.
- Three operation modes with different heat rejection methods were discussed.
- The hybrid mode of groundwater cooling shows a better option for Singapore.
- A good reference for other countries or cities in tropical areas.

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## ABSTRACT

The potential applicability of subsurface cooling in Singapore's condition was investigated. Three operation modes with different heat rejection methods were proposed. Mode 1 is an open-loop groundwater cooling system combined with cooling towers; Mode 2 is a pure groundwater cooling system without cooling towers; and Mode 3 is a surface water cooling system. Contrary to previous studies in many other areas around the world, the proposed modes are aimed for tropical areas and suitable for pure cooling purpose. The thermal effects, economic benefits, and water-consumption performances were analyzed theoretically by using the software "EnergyPlus". A conventional water-cooled air condition system was simulated as the benchmark condition. The results reveal that the proposed three modes have important advantages over the conventional air conditioning system in tropical areas such as Singapore. The amount of urban heat generated and water consumed can be significantly reduced although the electricity cost could only be marginally reduced because of the relatively high ambient temperature. A detailed comparison of the result showed that Mode 1 is a better option for application in Singapore.


## 1. Introduction

Singapore is close to the equator and its climate is characterized by a relatively constant high temperature and humidity. Cooling is considered as a basic necessity throughout the year. Traditional cooling systems use a large amount of energy and generate significant amount of carbon dioxide emissions. Moreover, the energy consumption of such air conditioning systems is finally released to the ambient environment, increasing the urban temperature and leading to the urban heat island effect. Researchers have found that the commercial and business areas are hotter than the green areas by about 4 °C in Singapore [1]. Such a problem is further aggravated by the increasing residential air-conditioning demand, which may cause over-consumption of energy and result in a higher risk of failures in the energy transport network. Therefore, in order to mitigate the urban heat problem, it is imperative to explore more effective and environmental-friendly air conditioning systems.

The ground source heat pump (GSHP) system has been widely used around the world due to its contribution to energy savings and environmental protection [2–4]. It uses the ground, groundwater or surface water as a heat source or sink. It is much more energy-efficient than traditional air conditioning system as the earth can provide a much better heat exchange medium. This is because ground temperature is more stable than air temperature around the year, and it is usually lower in the summer and higher in the winter. Currently the GSHP systems have been widely used in both residential and commercial buildings, and the majority of installations are in North America and Europe [5]. A report from the US Department of Energy [6] pointed out that the installed GSHP capacity in the United States in 2007 was equivalent to 10,839 MW with a capacity factor of 10%. In Europe, over 7300 MW of capacity have been installed by 2006 [7]. Most of these systems are used for space heating only or both heating and cooling in places where the climates have distinct weather

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changes. They are rarely used for pure cooling purpose since their use for cooling is not as efficient as heating [5,8]. This is because the heat rejected to the ground in the cooling mode is significantly higher than that extracted from the ground, given the same load in the heating mode [9]. The relatively high ground temperature is another obstacle of subsurface cooling in tropical areas [10]. Moreover, the ground temperature may continue to increase if the building is cooling dominated. Over a long-term operation, the ground would turn into a less favorable sink and the overall system efficiency may decrease.

However, it is still possible to use subsurface cooling systems in tropical regions if certain auxiliary measures are adopted to inhibit the increase of ground temperature [11]. For example, making a proper setting of operation or using supplementary device could offset the ground load. Yasukawa et al. [12,13] have conducted a number of experiments in Thailand to prove that geothermal heat pump could be continuously used in tropical regions for space cooling. Permchart and Tanatvanit [14] presented experimental results of 12,000-Btu/h cooling load system in Bangkok. They found that the soil could absorb and dissipate the heat rejected from a condenser without notably causing an increase of soil temperature near the buried pipes. Bi et al. [15] investigated the application of GSHP systems in different temperature zones in China. They pointed out that in the tropical zone (Qionghai) and subtropical zone (Guangzhou), GSHP systems can be applied for both cooling in the summer and heating domestic water in these districts throughout the year. Sagia et al. [16] studied a typical cooling dominated hybrid GSHP system using a cooling tower as a supplemental heat rejecter in Greece. Such system can also be found in Hong Kong, a subtropical area. Man et al. [17,18] pointed out that the hybrid GSHP system is a good option to reduce the accumulated heat under the ground in a cooling dominating area. Yik et al. [19] investigated three kinds of surface water cooled systems, which used sea water as the cooling medium, in Hong Kong. Their results showed that the water systems would significantly bring down the electricity consumption for air-conditioning buildings in Hong Kong.

Previous studies have made valuable attempt in using GSHP systems in tropical or sub-tropical areas. However, there are no studies that focus on Singapore's condition. As Singapore is a small city with very few natural resources, she imports most of her food and water, as well as the resources and materials needed for industries. Consequently, sustainable development is very important to the country. The Singapore government has unveiled a Sustainable Development Blueprint [20] to detail new targets and initiatives to improve resource efficiency and enhance Singapore's urban environment. In order to achieve these goals, GSHP system, which uses renewable, clean and sustainable energy sources, is required to reduce energy consumption and minimize environmental pollutions.

Therefore, as a first attempt, this study aims to investigate the potential applicability of subsurface cooling technology (i.e., GSHP) to Singapore's condition. First, a number of potential heat pump systems with different heat rejection methods are proposed. An extensive mathematical analysis on a typical building in the western part of Singapore is then conducted to evaluate different cooling modes. Finally, comparisons on energy consumption, heat released, and water consumption are given and the potential applicability discussed.

## 2. System design

In general, a ground source heat pump system can be subdivided into three key elements: (a) the load, which comprises the building, its controls, users and the resulting thermal load; (b) the heat transfer system, which includes the heat pumps, heat exchangers and associated control systems; and (c) the source, which encompasses the below-ground elements, such as boreholes, ground loops and associated infrastructure.

The load is determined by the type and details of the building. Among the heat transfer systems, it is found that direct cooling systems are usually more economical, but it is only possible if the temperature of the sub-surface soil or water adjacent to the intake pipe is lower than the desired indoor air temperature. This problem may be overcome by adopting indirect cooling systems, such as reversible heat pumps (chillers), where the ground serves as a heat sink [21]. In Singapore, the shallow groundwater temperature is estimated to be 27 °C [22], which is close to the average ambient air temperature. It is higher than the desired temperature of the building which is usually kept at about 24 °C. Therefore, active chillers are needed in order to reach the desired temperatures.

According to ASHRAE [23]: three different sources, namely, ground-coupled (GCHP), groundwater (GWHP) and surface water (SWHP) heat pumps are commonly used. Accordingly, we are proposing three similar operation modes (named as Mode 1, Mode 2, and Mode 3) to be applied in the indirect ground source cooling systems in this study.

Mode 1 refers to an open-loop groundwater cooling system combined with cooling towers. In this mode, ground water cooling can operate as an alternate source to meet the cooling tower water demand. If the amount of extracted groundwater is limited and/or cannot meet the requirement, the cooling tower will be used. The advantages of this mode include: (i) reduction of heat release to the atmosphere; (ii) easy installation and linkage to existing cooling tower system; and (iii) saving of water usage. However, there are also some disadvantages. The system design (or control) is relatively complicated and has a higher capital cost. Subsurface condition needs to be carefully examined in order to identify how much water can be extracted. Environmental regulations may also need to be considered for groundwater extraction and recharge.

Mode 2 is a pure groundwater cooling system without cooling towers. The water is used to cool the heat pump units before being discharged into the environment. The advantages of Mode 2 are: (i) it will significantly reduce the amount of heat released to the atmosphere; and (ii) as there is no need to use the water cooling tower or air cooling system, a considerable amount of city water will be saved. On the other hand, the limitations are: (i) the system is only applicable to sites with favorable subsurface conditions and the extraction and discharge of groundwater may be limited by environmental regulations; and (ii) the drilling of wells could be more expensive than the construction of a cooling tower.

Mode 3 is a surface water cooling system, which uses surface water such as pond and sea water as the cooling medium. The loop in this mode can either be opened or closed. The advantages of Mode 3 are: (i) it will reduce heat released to the atmosphere; (ii) surface water sources are relatively easier to withdraw than groundwater; and (iii) license of water usage is easier to obtain compared with groundwater extraction. Since Singapore is very close to the sea, sea water may be a good choice in this mode. However, the major limitations are: (i) the seawater system has a strict requirement of the pipeline material (e.g., Titanium); (ii) pre-treatment of water quality should be more stringent in order to prevent environmental contamination problems and protect the equipment.

A number of successful examples of Modes 2 and 3 in other countries have been reported, such as the groundwater heat pump system in London [24], and the sea water cooling system in Canada [25]. The major difference from these examples and our study is that the proposed two modes in a Singapore's context are only used for cooling purpose, and the temperature of groundwater (or surface water) is much higher than those in other areas. In such a condition, the chiller systems are essentially required in various modes. The hybrid modes designed in other cooling dominated area mostly combined the ground coupled heat pump with the cooling tower, such as the hybrid system application in Hong Kong [17]. However, Mode 1 in this study is a combination of cooling tower and groundwater heat pump system that has rarely been reported.

In fact, there are some other possible options such as the ground coupled heat pump systems [26]. However, the high ground temperature in Singapore may lead to the increase of the overall length of the ground-based heat exchangers or widening of the spaces between boreholes. This may greatly elevate the initial system cost. Moreover, the shortage of land area is usually restricting the placing of over-sized ground heat exchangers in dense urban lands [17]. Therefore, only the above three modes are taken into consideration.

## 3. Description of study case

### *3.1. Building details*

In order to analyze the subsurface water cooling system, we choose a typical building located in the western part of Singapore as a reference. It is the second floor of Block N1 in the Nanyang Technological University (NTU) campus because an independent air conditioning system is installed for this particular section. The floor is divided into three zones, separated by two lobbies (Fig. 1). The total floor area is about 3430 m$^2$ while the air condition area is about 2253 m$^2$. It is mainly used for research offices and laboratories. The present air conditioning system (i.e., cooling tower mode) for this floor is provided by three water cooled chillers, with a total capacity of 560 kW. These chillers are cooled using a cooling tower with a capacity of 1050 kW. The air conditioning systems operate from 8 am to 10 pm on weekdays, and the systems are turned off on weekends and public holidays.

### *3.2. Cooling load*

To simulate the thermal behavior of the building, EnergyPlus version 6.0 [27] is used to calculate the cooling load. EnergyPlus is a computer program (with graphical user interface) designed for simulating energy behaviors of buildings with the associated heating, ventilating, and air-conditioning systems [28]. Other software platforms such as DOE-2, BLAST and TRNSYS can also be used for building energy simulations. Crawley et al. [28] compared EnergyPlus with other software and showed that EnergyPlus integrated the best features of the BLAST and DOE-2 programs, and was also able to link to TRNSYS simulations.

The outdoor temperature and relative humidity data needed for the study are obtained from the EnergyPlus weather file as shown in Fig. 2a. Currently, more than 2100 locations including Singapore are now available in the EnergyPlus weather files. The weather data are arranged according to the region and country listed by the World Meteorological Organization, and the data source for Singapore is from International Weather for Energy Calculations (IWECs). These data are helpful to determine how much heat is needed. Table 1 lists the parameters used in the cooling load calculation.

Fig. 2b shows the cooling load of the three-zone building. The peak load is about 520 kW and average daily load is about 170 kW. The cooling load varies daily because the computers and laboratory equipment in the building may generate much more internal heat than solar radiation at certain time periods. Generally, when all these equipment are turned off after working hour, the load reduces significantly at night. However, the maximum or average load does not vary significantly as temperatures are almost the same throughout the year due to the special tropical climate condition. In addition, the internal heat, which occupies the largest percentage of the total load, is steadier and less affected by the climatic condition.

### *3.3. Subsurface conditions*

Subsurface conditions play an important role in the application of the GSHP system. The distribution of geological formation of Singapore is not favorable for groundwater occurrence. The majority of rain water drains into the sea without infiltrating into the ground [29]. According to previous monitoring results, the water table is estimated to be within 1.5 m of the surface in many of the low-lying areas of Singapore [30].

The amount of groundwater extracted is determined by the hydrogeological conditions. Soil permeability, which is defined as the ability of water to flow through the soil, has a notable influence on water extraction. Water is able to flow rapidly if the permeability of the soil is high, and vice versa. This usually relies on the soil types. Rahardjo et al. [31] have found that two thirds of Singapore's area is covered by residual soils. The study building is located in the Jurong formation area, which also comprises residual soils. Agus et al. [32] conducted a series of experimental tests to investigate the basic properties of the Jurong sedimentary soil in the NTU campus. They found that the soils are generally characterized as clayey silt, sandy clay of medium plasticity and clayey to silty sand, with coefficients of permeability ranging from $10^{-9}$ to $10^{-7}$ m/s.

## 4. Methodology of the study

### *4.1. Thermal analysis*

In this section, mathematical analyses on heat release and energy consumption of the three proposed modes are given with the aid of EnergyPlus. First, we need to simulate the current air conditioning system (i.e., the cooling tower system) and use its

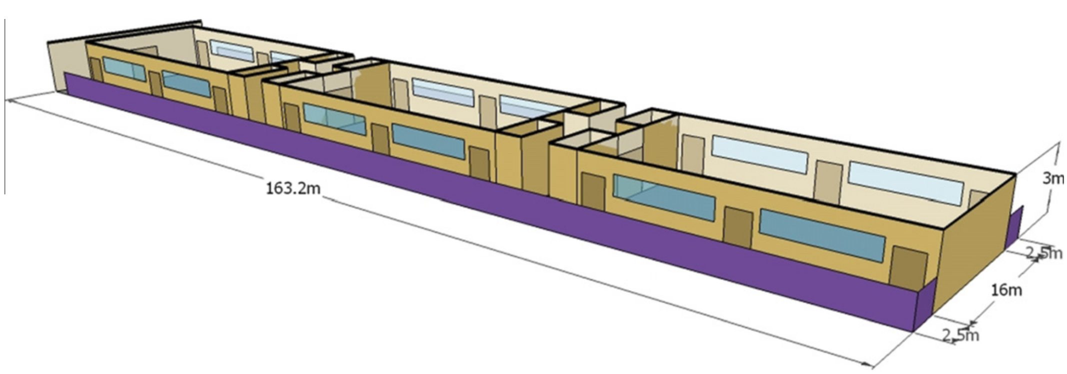


**Fig. 1.** A cut view of the analyzed building.

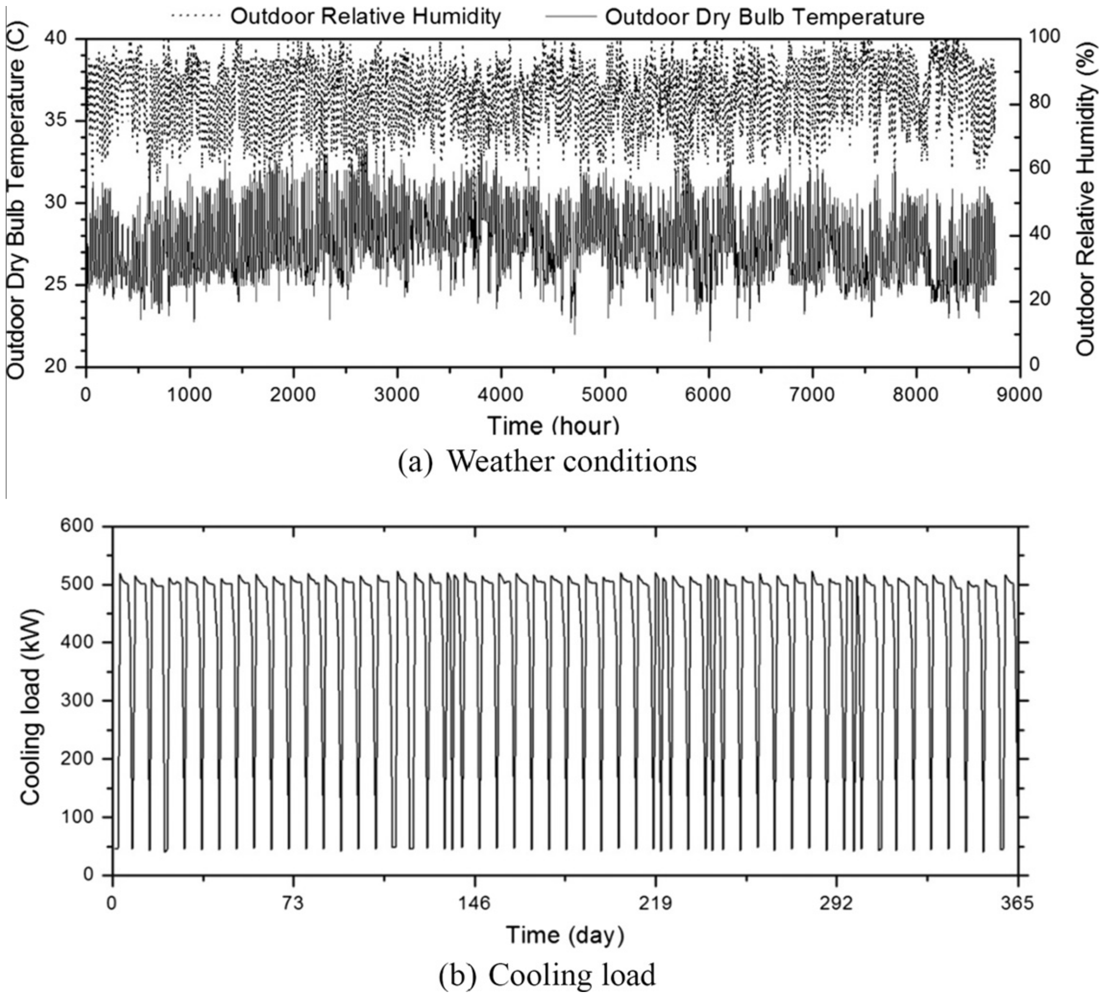


**Fig. 2.** Weather conditions and cooling load results.

**Table 1**
Basic parameters.

| Parameter | Value |
|---|---|
| Location of building | Second floor of Block N1 in NTU campus, Singapore |
| Application | Office building, laboratory |
| Building area | 163.2 m $*$ 21 m = 3430 $m^2$ |
| Air conditioned area | 2253 $m^2$ |
| Temperature set point | 24 °C |
| Humidity set point | 40–60% |
| Air conditioning open time | 8 am–10 pm |
| Number of people | 280 |
| Light | 12 $W/m^2$ |
| Equipment | 200 $W/m^2$ |
| Infiltration | 0.2 $m^3/s$ |

results as a reference for comparisons. The coefficient of performance (COP) of the chillers assumed in the simulation for these four systems are 3.2 for the cooling tower system, 4.0 for Mode 1, and 4.5 for Mode 2 and Mode 3 [33].

During the simulation, we discovered that EnergyPlus has not been programmed to simulate groundwater [34]. However, it is possible to connect the water source heat pump to a condenser loop with an additional cooling tower. If the water temperature at this cooling tower inlet node represents the groundwater temperature, we can configure the cooling tower to provide an outlet water temperature that is very close to the inlet water temperature. This would be equivalent to the condition where the groundwater is connected directly to the air conditioning system. However, we should try to minimize this cooling tower fan energy or disregard it completely when performing the simulation. Based on such a configuration, we will use a cooling tower to simulate the groundwater in Mode 1 and Mode 2.

In the hybrid mode (Mode 1), both the groundwater and tower water could be used as the cooling medium. There are two possible ways for system operation: alternative mode and simultaneous mode. In the former mode, the groundwater and tower water are used alternatively. A schedule should be given to control the operation time of the two media. Such a mode may cause variation of water flow rate in the loops due to the different water flow rate between tower water and groundwater. In the latter mode, the groundwater and tower water are used simultaneously. This may lead to issues such as unbalanced water pressure in the whole system. Attention should also be given to control the total water amount. In this study, we assume that the simultaneous mode is used. In order to simulate different subsurface conditions, we have designed three scenarios as shown in Table 2. The groundwater rate is 10 L/s, 20 L/s and 30 L/s in the three scenarios respectively, and the groundwater temperature is assumed to be 27 °C [22].

### *4.2. Subsurface analysis*

In order to determine the amount of extracted water, subsurface analysis is needed. Due to the lack of detailed geological

**Table 2**
Water flow rates for different modes.

| Modes | Tower mode | Mode 1–1 | Mode 1–2 | Mode 1–3 |
|---|---|---|---|---|
| Groundwater flow rate (L/s) | 0 | 10 | 20 | 30 |
| Tower water flow rate (L/s) | 40 | 26.3 | 16.3 | 6.3 |
| Maximum make-up water rate (L/s) | 0.52 | 0.39 | 0.25 | 0.14 |

*Note*: (i) tower mode represents an air conditioning system that only uses cooling tower to provide cool water; (ii) Mode 1 represents a hybrid ground source heat pump that uses both cooling tower and groundwater; (iii) Mode 1–1, Mode 1–2 and Mode 1–3 represent different scenarios of Mode 1.

**Table 3**
Estimation of installation costs.

| Mode | Installed cost (S$) | Data source |
|---|---|---|
| Tower mode | 562,500 | Naguib [36] |
| Mode 1 | 740,000 | Rafferty [37], Minea [39] |
| Mode 2 | 705,000 | Rafferty [37] |
| Mode 3 | 700,000 | Zhen et al. [40] |

parameters, estimation is made based on information found in the literature. Since there is no significant aquiclude above the aquifer, we assumed that it is an unconfined aquifer with a thickness of 30 m. Assuming a steady-flow pumping process, the Thiem–Dupuit method can be used to calculate the transmissivity of an unconfined aquifer [35].

$$Q = \pi k \frac{h_2^2 - h_1^2}{\ln(r_2/r_1)} \tag{1}$$

where $Q$ is the water flow rate ($m^3/s$), $k$ is the coefficient of permeability (m/s), $h_1$ and $h_2$ are water levels in the piezometers (m), $r_1$ and $r_2$ is the distance between the piezometers and pump well (m).

The mean coefficient of permeability is estimated to be $10^{-7}$ m/s [32], and the well diameter is set as 1 m. If the water level does not change at a distance 20 m away from the pumping well, then we have: $k = 10^{-7}$ m/s, $h_1 = 10$ m, $h_2 = 30$ m, $r_1 = 0.5$ m, and $r_2 = 20$ m. Substituting these parameters into Eq. (1) yields: $Q = 0.07$ L/s = 6 $m^3$/day.

## 4.3. Economic analysis

Usually, the total cost of air conditioning systems contains two components: initial capital cost and operation cost. The capital cost may include indoor installation, heat pumps, ductwork, water pumps, ground loop, and borehole excavation. The operation cost may include electricity, water and maintenance.

There are significant inconsistencies in terms of the capital costs considering various building and ground loop types. Another possible influencing factor may be related to the effort in borehole drilling and system installation due to selection of contractors that may have varied levels of experience. Since, very few data on these have been reported in Singapore, we will use data from published literatures to analyze Singapore's condition. Table 3 lists the initial cost of each mode. For consistency, the currency has been converted to Singapore dollars (i.e., 1 US dollar is assumed equal to 1.25 Singapore dollar, and 1 Chinese Yuan is equal to 0.2 Singapore dollar). The cost of Tower mode is about S$562,500 (US$450,000) according to Naguib [36], who also gave the cost of an air source heat pump (ASHP) system at S$300,000 (US$240,000). Rafferty [37] showed that the installation cost of a groundwater heat pump system is about US$3,300/ton (1 ton = 3.516 kW), and ASHP system is about US$2,060/ton. However, a report by Navigant Consulting Inc. [38] doubted Rafferty's [37] data for ASHP, and suggested the cost of US$1,400/ton to be more reasonable. Using the latter value, the cost of GWHP is 2.35 times of the cost of ASHP, and the cost of Mode 2 is then equal to 2.35 times the cost of ASHP. Minea [39] estimated the cost of a cooling tower to be around S$35,000 (US$28,000). The initial cost of Mode 1 is equal to the cost of Mode 2 plus the cost of the cooling tower. Zhen et al. [40] showed that the cost of a sea water heat pump system (RMB 296 million) is about 1.24 times of the conventional system (RMB 238 million). Thus, the cost of Mode 3 is estimated to be about 1.24 times the cost of cooling tower mode. It should be noted that the comparison here is only meaningful in a relative manner; the absolute value may vary significantly.

Electricity cost occupies the largest portion of the total operation cost. It varies according to several factors, including the cooling capacity of the air conditioner, temperature setting used, whether the fan is operated on "continuous" or "auto" mode, frequency of use, price of electricity, and the weather condition. We could use EnergyPlus to calculate the electricity consumption of each mode, and then evaluate the cost according to the electricity tariff (Table 4) in Singapore [41].

Water cost mainly depends on the make-up of water amount and tariff. Water loss in an air conditioning system mainly comes from the cooling tower because it uses evaporation of water to remove heat. The total make-up water amount could be simulated by EnergyPlus. According to the information from the Public Utility Board (PUB) [42], the tariff for industrial water in 2011 is 52 Singapore cents per cubic meter. Thus the water cost can be calculated accordingly. The maintenance cost of the mechanical systems varies widely depending on configuration, equipment locations, accessibility, system complexity, service duty, geography, and system reliability requirements. It can be a major factor in an overall life-cycle cost of a mechanical system. The maintenance cost is obtained from Cane and Garnet [43], which is shown in Table 5.

## 4.4. Novelty

The methodology of this study includes thermal, subsurface and economic analyses. The thermal and economic analyses mainly rely on the EnergyPlus software. Since EnergyPlus has hitherto not been programmed to simulate groundwater, the only way to connect the groundwater to a condenser loop is through an additional cooling tower. Therefore, we have attempted to use cooling towers to simulate the groundwater in Modes 1 and 2, where the

**Table 4**
Electricity tariff in Singapore in 2011.

| Usage charge | January–March | April–June | July–September | October–December |
|---|---|---|---|---|
| Contracted capacity charge (S$/kW/month) | 6.52 | 6.52 | 6.52 | 6.52 |
| Uncontracted capacity charge (S$/kW/month) | 9.78 | 9.78 | 9.78 | 9.78 |
| Peak period (S¢/kW h) (7.00 am–11.00 pm) | 20.87 | 22.98 | 24.85 | 24.50 |
| Off-peak period (S¢/kW h) (11.00 pm–7.00 am) | 13.36 | 14.69 | 15.87 | 15.70 |
| Reactive power charge | 0.48 | 0.48 | 0.48 | 0.48 |

*Note*: the rates are not inclusive of 7% GST; source: Singapore Power Services [41].

**Table 5**
Estimation of maintenance costs for different modes.

| Mode | Cost (US$/100 ft$^2$) | Cost (S$/m$^2$) | Annual cost (S$) |
|---|---|---|---|
| Tower mode | 45 | 6.05 | 13,640 |
| Mode 1 | 27.33 | 3.68 | 8285 |
| Mode 2 | 9.33 | 1.26 | 2830 |
| Mode 3 | 11.28 | 1.52 | 3420 |

*Note*: data from Cane and Garnet [43] in 2000.

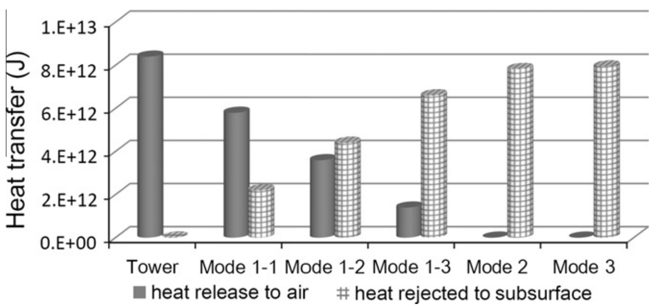


**Fig. 3.** Comparison of heat transfer energy for each mode.

cooling tower fan energy was minimized or even disregarded completely. Such a treatment has not been reported previously.

Subsurface analysis is simplified in this study and the Thiem–Dupuit method is employed to estimate the maximum water flow rate. This is very important to assess the feasibility of each mode. For real-world conditions, we need to use numerical methods, such as the finite-difference method, to solve the groundwater flow equation with different initial boundary conditions. The water consumption is also included, which is usually not considered in previous studies. This is because water conservation is a very important goal in Singapore. The water cooled air conditioning systems lose a large amount of water due to the makeup water consumption. With the aid of EnergyPlus, we can calculate the total make-up water amount and evaluate how much water can be saved. This has not been attempted in previous studies.

## 5. Results and discussion

### 5.1. Thermal effect

Fig. 3 shows the comparison of the heat transfer energy for each mode of operation. The heat transfer energy refers to the heat that is removed from the condenser water loop by the tower or other exchangers. Since the cooling tower causes heat exchange with the ambient air, the cooling tower heat is eventually released to the surrounding air and aggravates the urban heat effect. According to our calculation, the annual tower heat transfer energy of the tower system is about 8400 GJ. Using the subsurface cooling system can significantly reduce the direct heat release to the atmosphere.

The total heat released is divided into two parts: one is absorbed by the cooling tower and the other is re-injected into the subsurface. According to the first law of thermodynamics, the total amount of heat must be conserved. If the amount of heat released to the air reduces, that re-injected into the subsurface must correspondingly increase. A large amount of heat reinjection may cause an increase in the ground temperature hence, reducing the system efficiency. Fig. 4 shows the temperature of the surface water around the heat pump pipes, indicating an increase of about 2 °C after a year. As a result, the system COP reduces from 4.5 to about 4.2, and asymptotes to 4.4 for Mode 3 (see Fig. 5). The system efficiency does not reduce sharply after a year because we have controlled the system operation time. The subsurface cooling system operates 14 h per day and is turned off from 10 pm to 8 am, which gives time for the temperature of the surface water to recover.

### 5.2. Electricity consumption

Fig. 6 shows the comparison of electricity consumption for each mode of operation. Although the annual electricity cost using the ground source heat pump systems is lower, the difference is not significant. The saving is about 25% compared to that of the conventional tower system. The reason is that we only use the indirect cooling systems, and the subsurface water is used to cool the condenser water rather than to cool the room directly. Chillers that consume the largest percentage of electricity exist in all these modes due to the high water temperature. Fig. 6 shows that the annual electricity cost of the cooling tower system is about 84 SGD/m$^2$, while for the other three modes the cost is between 60 and 70 SGD/m$^2$.

### 5.3. Water consumption

Singapore is a small island with limited natural aquifers and lakes, and little land to collect rainwater, therefore water conservation is very important in the country. The water-cooled air conditioning systems lose a lot of water due to the use of cooling towers, because they use the cooling effect of evaporation to remove heat from the water circulating through the HVAC (Heating, Ventilating, and Air-Conditioning) chillers. The amount of water

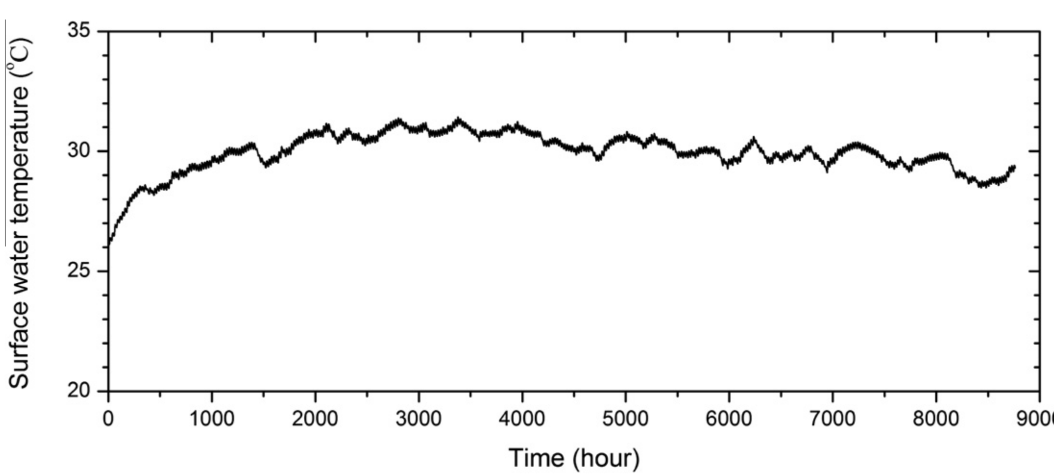


**Fig. 4.** Surface water temperature variations in Mode 3.

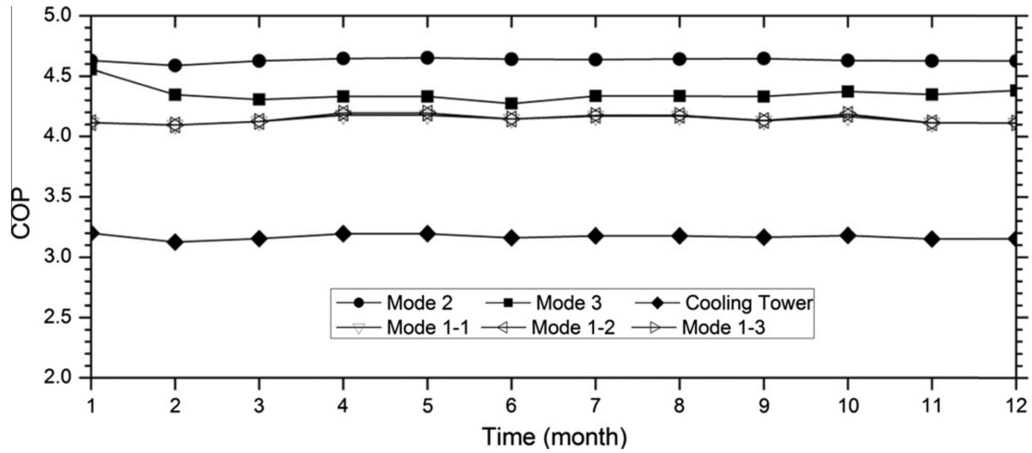


**Fig. 5.** Comparison of coefficient of performance (COP) for different modes.

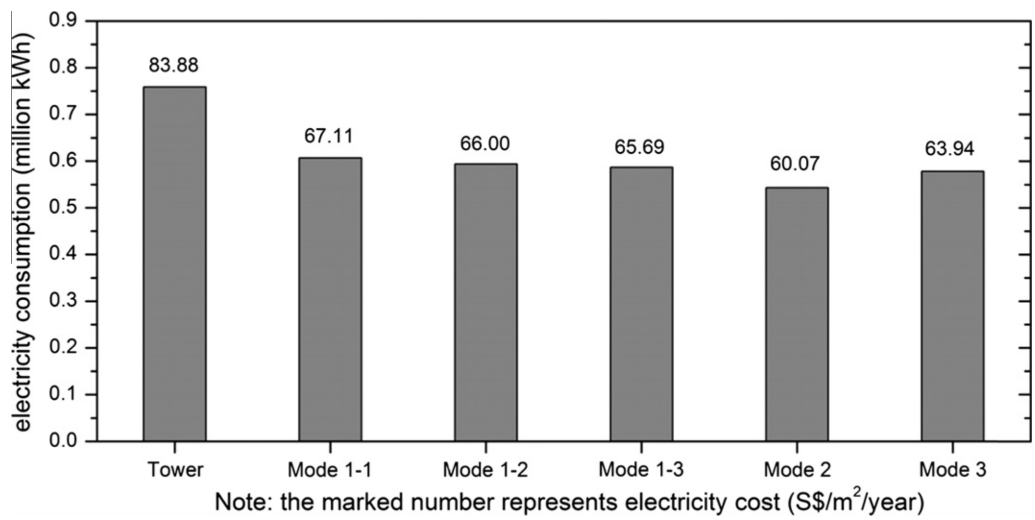


**Fig. 6.** Comparison of electricity consumptions for different modes.

loss depends on the tower water circulation rate. Using ground source heat pump instead of cooling tower is very helpful to reduce the make-up water amount. Fig. 7 shows that the annual water consumption of the cooling tower system is about 4430 $m^3$. The amount is linearly related to the groundwater rate. Fig. 7 shows that the water loss can be reduced by 27% by increasing the groundwater flow rate to 10 L/s (Mode 1-1). For Modes 2 and 3, water loss still exists due to water disposal, but the amount is lower than that of the cooling tower system.

### 5.4. Life-cycle cost analysis

Life-cycle cost is necessary to justify energy efficiency upgrades. Many alterative building technologies that result in energy savings may cost more in maintenance, compared with traditional solutions. In order to justify selecting these energy savings technologies, it is essential to combine both the initial and future costs in the decision making process. The results of the life-cycle cost analyses are shown in Table 6 and Fig. 8.

The simple pay back years are estimated by dividing the difference in the initial cost by the savings in the operating cost. It is defined as the period of time that is required to recover the initial investment in energy savings, namely the ratio of the initial cost to the yearly cost savings. The payback period of Mode 2 is the shortest (2.13 years), followed by Mode 3 (2.39 years). For Mode 1, the payback period, which is related to the groundwater amount, is about 4 years. The more groundwater used, the less the payback year is.

Another factor, namely the present value, is also included in Table 6. Present value provides a framework to combine initial costs and future costs into a single combined measure. It is a metric that combines all costs and reduces (or discounts) those costs that occur in the future. We have assumed a 3% discount rate without energy or maintenance cost escalation in the simulation. Fig. 8a shows the total cost of each mode. In the first year, the tower mode is cheaper than the other mode. However, the result is reversed 20 years later. The tower mode becomes the most expensive, and Mode 2 becomes the cheapest, followed by Mode 3.

It is important to highlight here that many of the data (e.g., the capital investment and maintenance cost) used in our simulation are based on the data found in published literatures for the purpose of theoretical analyses and preliminary evaluations; the values could be considerably different from the actual condition. For a real application, a detailed market survey for Singapore's condition is required.

### 5.5. Comparison of different modes

According to our study, Mode 1 can reduce the heat release and save energy consumption to some extent, depending on the

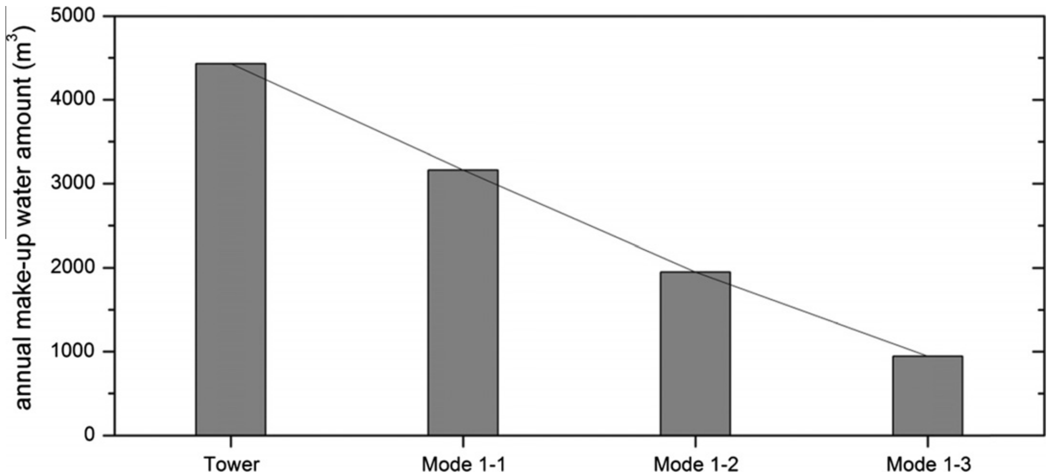


**Fig. 7.** Annual make-up water amount.

amount of extracted groundwater. If more groundwater is used, less heat is released to the air and more energy can be saved. On the other hand, more groundwater may require more pumping wells, resulting in a higher initial cost. In addition, the operation of Mode 1, which is a hybrid system, is complex.

Mode 2 is the most economical mode with the lowest initial cost and lowest energy cost. But this mode requires sufficient amount of groundwater in which the maximum flow rate should reach up to 40 L/s. It is limited to certain hydrogeological conditions and is only applicable to sites with favorable subsurface conditions. If groundwater is not sufficient, this mode cannot be used. According to the calculation in Section 4.2, the maximum well pumping rate of Jurong formation is only 6 $m^3$/day. It is impossible to provide the required flow rate.

Mode 3 can be a good choice only if surface water is close to the building. Otherwise the initial cost could rise notably and the efficiency may also be reduced. Moreover, we should pay attention to control the surface water temperature due to accumulated heat rejected. In our simulation, the surface water temperature increases by about 2 °C after a year. As a result, the system COP reduced from 4.5 to about 4.2, and become 4.4 in the end. The system efficiency does not reduce sharply after a year, due to discontinuous operation.

The above results demonstrated that the proposed three modes had advantages over the conventional air conditioning system in a tropical region like Singapore. Urban heat and water consumption could be significantly reduced by the proposed three modes. The water loss amount depends on the tower water circulation rate due to evaporation. In our study, water loss can be reduced by 27% by increasing the groundwater flow rate to 10 L/s. However, the electricity cost saving is not as significant as that documented in previous studies [44]. This is because the ambient air temperature is relatively high and the groundwater temperature is about 27 °C in Singapore. In such a condition, the chiller system which consumes a large amount of energy is still required in the system.

### 5.6. System applicability

Singapore is a tropical island. The air conditioning systems are the dominant energy consumers in buildings. Since the GSHP system has a good performance in reducing the energy cost, especially water usage in Singapore, it could be a competitive alternative to the current system. In fact there is already a successful application of sea water cooling system in a power company in Singapore, where a total amount of more than 2 million $m^3$/day of sea water is extracted for cooling purposes. However, groundwater-based cooling systems are not applied in Singapore presently due to regulatory and technical considerations (e.g., subsidence problem or sea water intrusion). With the increasing value of water resources in the future, it is important for Singapore to start looking into the feasibility of groundwater usages (e.g., drinking, cooling, or other industrial non-portable uses), examining the related policies and exploring possible engineering approaches. This study shows that Mode 2 is more suitable for a small scale system; Modes 1 and 3 are more desirable for large-scale applications in Singapore. Given the climatic and geotechnical conditions, similar analysis can also be conducted for other tropical regions. Special attentions should be paid on investigation of the subsurface condition, availability of groundwater extraction, regulatory requirements, environmental impacts and cost-benefit analysis.

## 6. Conclusions

This study investigates the potential application of ground source heat pump (GSHP) systems in Singapore. Three modes with

**Table 6**
Life-cycle analyses.

| Type | Tower mode | Mode 1–1 | Mode 1–2 | Mode 1–3 | Mode 2 | Mode 3 |
|---|---|---|---|---|---|---|
| Capital cost (million S$) | 0.5625 | 0.74 | 0.74 | 0.74 | 0.705 | 0.70 |
| Annual operating cost (million S$) | 0.205 | 0.161 | 0.158 | 0.157 | 0.138 | 0.147 |
| Simple pay back years | – | 4.05 | 3.78 | 3.69 | 2.13 | 2.39 |
| 20-year present value of annual cost (million S$) | 2.657 | 2.089 | 2.048 | 2.032 | 1.791 | 1.912 |
| Total 20-year life-cycle cost (million S$) | 3.219 | 2.829 | 2.788 | 2.772 | 2.496 | 2.612 |
| 20-year savings | – | 12% | 13% | 14% | 22% | 19% |

*Note*: (i) tower mode represents an air conditioning system that only uses cooling tower to provide cool water; (ii) Mode 1 represents a hybrid ground source heat pump that uses both cooling tower and groundwater; (iii) Mode 1–1, Mode 1–2 and Mode 1–3 represent different scenarios of Mode 1; (iv) Mode 2 represents a ground water heat pump system that only uses groundwater to provide cool water; (v) Mode 3 represents a surface water heat pump system that uses surface water such as lake, pond and sea to provide cool water.

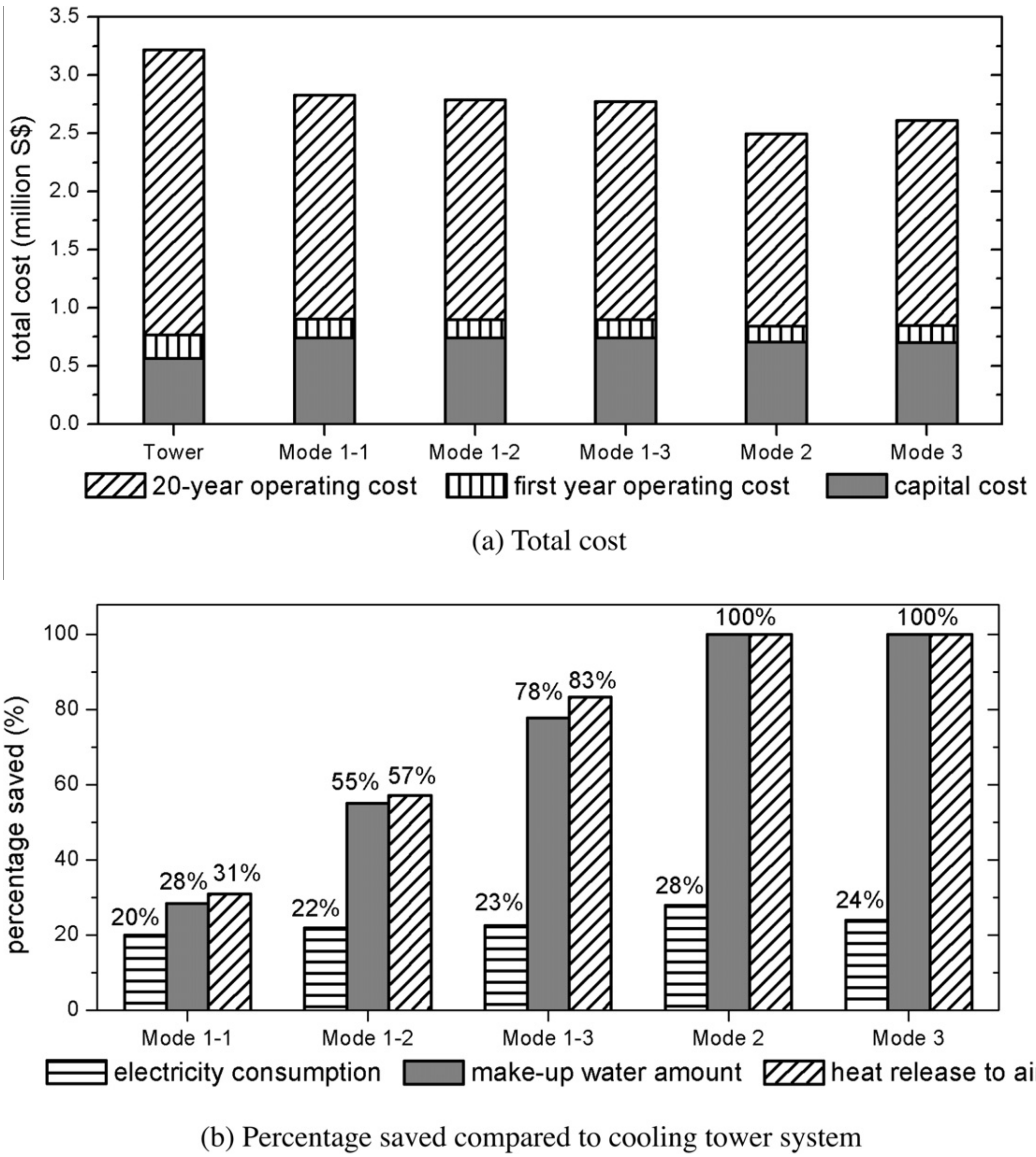


**Fig. 8.** Life-cycle cost analyses.

different heat rejection methods are proposed. Mode 1 refers to an open-loop groundwater cooling system combined with cooling towers. Mode 2 is a pure groundwater cooling system without cooling towers. Mode 3 is a surface water cooling system. Through a case study of a building (Block N1, second floor) in the Nanyang Technological University, it is found that the proposed three modes performs better than the conventional air conditioning system in the country. They significantly reduce the direct heat released to the atmosphere, which could mitigate the urban heat effect in Singapore. Compared to the cooling tower system, the percentage saving of electricity consumption is about 25%. It is relatively low due to the high groundwater temperature in Singapore. Water conservation is significant by using the proposed modes. As the groundwater extraction rate increases, the make-up water amount is reduced linearly due to the reduced use of cooling towers.

Modes 2 and 3 are more economical than Mode 1 with less consumption of electricity and water. However, these two modes highly rely on the geotechnical conditions. Since the subsurface condition is not favorable in providing sufficient water, Mode 2 is not recommended. Mode 3 could be a good choice only if the surface water is close to the building. Moreover, attention should be paid to control the temperature increase of the ground or surface water.

Finally, for those places where groundwater is not sufficient and surface water is not readily available, Mode 1 may be a better choice. In this case, groundwater cooling can operate as a supplementary source to meet the cooling tower water demand. Since the cooling tower and groundwater can be operated alternatively, it can provide enough time for groundwater temperature recovery.

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## References


[1] Jusuf SK, Wong NH, Hagen E, Anggoro R, Hong Y. The influence of land use on the urban heat island in Singapore. Habitat Int 2007;31:232–42.
[2] Banks D. An introduction to thermogeology: ground source heating and cooling. Blackwell; 2008.
[3] Omer AM. Ground-source heat pumps systems and applications. Renew Sustain Energy Rev 2008;12(2):344–71.
[4] Yutaka G, Yukihiro K, Atsushi I. $CO_2$ payback-time assessment of a regional-scale heating and cooling system using a ground source heat-pump in a high energy-consumption area in Tokyo. Appl Energy 2002;71(3):147–60.
[5] Lunda JW, Freeston DH, Boyd TL. Direct application of geothermal energy: 2005 worldwide review. Geothermics 2005;34:691–727.
[6] Cross J, Freeman J. 2008 Geothermal technologies market report. U.S. Department of Energy (DOE). Geothermal Technologies Program (GTP); July 2009.
[7] EurObserv'ER. Geothermal Energy Barometer. European Renewable Energy Council; 2007 September. p. 58–60.
[8] Chua KJ, Chou SK, Yang WM. Advances in heat pump systems: a review. Appl Energy 2010;87(12):3611–24.
[9] Pertzborn A, Nellis G, Klein S. Impact of weather variation on ground-source heat pump design. HVAC&R Res 2011;17(2):174–85.
[10] Li X, Chen Z, Zhao J. Simulation and experiment on the thermal performance of U-vertical ground coupled heat exchanger. Appl Therm Eng 2006;26(14–15):1564–71.
[11] Brandl H. Energy foundations and other thermo-active ground structures. Geotechnique 2006;56(2):81–122.
[12] Yasukawa K, Uchida Y, Tenma N, Taguchi Y. Groundwater temperature survey for geothermal heat pump application in tropical Asia. Bull Geol Surv Jpn 2009;60(9/10):459–66.
[13] Yasukawa K, Takashima I, Uchida Y, Tenma N, Lorphensri O. Geothermal heat pump application for space cooling in Kamphaengphet, Thailand. Bull Geol Surv Jpn 2009;60(9/10):491–501.
[14] Permchart W, Tanatvanit S. Study on using the ground as a heat sink for a 12,000-btu/h modified air conditioner. World Acad Sci, Eng Technol 2009;51:15–8.
[15] Bi Y, Wang X, Liu Y, Tian R, Chen L, Wu C. Applications of ground source heat pump systems in different temperature zones in China. Int J Ambient Energy 2009;30(2):63–72.
[16] Sagia Z, Rakopoulos C, Kakaras E. Cooling dominated hybrid ground source heat pump system application. Appl Energy 2012;94(6):41–7.
[17] Man Y, Yang H, Wang J. Study on hybrid ground-coupled heat pump system for air-conditioning in hot-weather areas like Hong Kong. Appl Energy 2010;87(9):2826–33.
[18] Man Y, Yang HX, Spitler JD, Fang ZH. Feasibility study on novel hybrid ground coupled heat pump system with nocturnal cooling radiator for cooling load dominated buildings. Appl Energy 2011;88(11):4160–71.
[19] Yik F, Burnett J, Prescott I. Predicting air-conditioning energy consumption of a group of buildings using different heat rejection methods. Energy Build 2001;33:151–66.
[20] Inter-Ministerial Committee on Sustainable Development (IMCSD). A lively and liveable Singapore: strategies for sustainable growth. Ministry of the Environment and Water Resources and Ministry of National, Development; 2009.
[21] Eicker U, Vorschulze C. Potential of geothermal heat exchangers for office building climatisation. Renew Energy 2009;34(4):1126–33.
[22] McQuay International. Application Guide 31–008 Geothermal Heat Pump Design Manual; 2002. p. 36.
[23] ASHRAE. Geothermal energy. In: ASHRAE Handbook—HVAC Applications, vol. 32, ASHRAE, Inc.; 2007. p. 10–29.
[24] Ampofo F, Maidment GG, Missenden JF. Review of groundwater cooling systems in London. Appl Therm Eng 2006;26(17–18):2055–62.
[25] Newman L, Herbert Y. The use of deep water cooling systems: two Canadian examples. Renew Energy 2009;34(3):727–30.
[26] Yang H, Cui P, Fang Z. Vertical-borehole ground-coupled heat pumps: a review of models and systems. Appl Energy 2010;87(1):16–27.
[27] U.S. Department of Energy. EnergyPlus Simulation Software; 2010.
[28] Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Huang YJ, Pedersend CO, et al. EnergyPlus: creating a new-generation building energy simulation program. Energy Build 2001;33(4):319–31.
[29] Wikipedia. Geography of Singapore. [Cited 2012]. <http://en.wikipedia.org/wiki/Geography _of_Singapore>.
[30] Pitts J. A survey of engineering geology in Singapore. J Southeast Asian Geotech Soc 1984;15:1–20.
[31] Rahardjoa H, Aungb KK, Leongc EC, Rezaurd RB. Characteristics of residual soils in Singapore as formed by weathering. Eng Geol 2004;73:157–69.
[32] Agus SS, Leong EC, Rahardjo H. Estimating permeability functions of Singapore residual soils. Eng Geol 2005;78:119–33.
[33] Milenić D, Vasiljević P, Vranješ A. Criteria for use of groundwater as renewable energy source in geothermal heat pump systems for building heating/cooling purposes. Energy Build 2010;42(5):649–57.
[34] EnergyPlus help file. Tips & Tricks for Using EnergyPlus; 2010. p. 20.
[35] Kruseman GP, de Ridder NA. Analysis and evaluation of pumping test data. Second Edition. Netherlands: International Institute for Land Reclamation and Improvement; 1994.
[36] Naguib R. Total cost of ownership for air-cooled and water-cooled chiller systems. ASHRAE J 2009;51(4):42–8.
[37] Rafferty K. An information survival kit for the prospective geothermal heat pump owner. Heatspring Energy 2008.
[38] Goetzler W, Zogg R, Lisle H, Burgos J. Ground-source heat pumps: overview of market status, barriers to adoption, and options for overcoming barriers. Final report submitted to U.S. Department of Energy. Navigant Consulting, Inc.; 2009 February 3.
[39] Minea V. Energy efficiency for two Canadian schools ground-source heat pumps. ASHRAE J 2006;48(5):28–38.
[40] Zhen L, Lina DM, Shua HW, Jiang S, Zhu YX. District cooling and heating with seawater as heat source and sink in Dalian, China. Renew Energy 2007;32:2603–16.
[41] Singapore Power (SP) Services. Tariff rates; [Cited 2011]. <http://www.singaporepower.com.sg/irj/portal/spservices>.
[42] Public Utilities Board (PUB). Water Tariff; [Cited 2011]. <http://www.pub.gov.sg/general/Pages/WaterTariff.aspx>.
[43] Cane D, Garnet JM. Update on maintenance and service costs of commercial building ground-source heat pump systems. ASHRAE Trans 2000;106(1):1–9.
[44] Chen C, Sun FL, Feng L, Liu M. Underground water-source loop heat-pump air-conditioning system applied in a residential building in Beijing. Appl Energy 2005;82(4):331–44.