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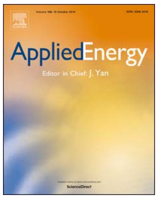

Potential of district cooling in hot and humid climates

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HIGHLIGHTS

- Operation of the large-scale district cooling grid was simulated.
- Proposed district cooling grid reduces CO2 emissions and energy consumption.
- Implementation of DC grid positively impacts the economics of the energy system.
- Singapore was chosen for a case study that represents hot and humid climates.
- The model is well suited for the other countries in the region.

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ABSTRACT

Efficiently utilizing energy that is currently being wasted can significantly increase energy efficiency of the system, as well as reduce the carbon footprint. In hot climates with large cooling demands, excess waste heat can be utilized via absorption chillers to generate cold. Moreover, cold from liquefied natural gas gasification process can further provide energy source for meeting the cold demand. In order to connect the large sources of waste heat and cold energy with customers demanding the cold, a significant investment in district cooling grid is a necessity. In order to deal with the mentioned issue, an existing energy balance model was complemented with Matlab algorithms in order to model the whole energy system, including the detailed representation of the district cooling grid. Singapore was chosen for a case study and several different scenarios were developed for the year 2050, with the main indicators being total primary energy supply, total CO_2 emissions and total socio-economic costs. The most beneficial scenario for the year 2050 had 19.5% lower primary energy demand, 38.4% lower total socio-economic costs and 41.5% lower CO_2 emissions compared to the business-as-usual scenario for the year 2050, although significant investment in the district cooling grid was included in the calculations.

1. Introduction

Climate change is impacting the Earth, posing a threat to sustainable development of different regions. Though agreement was reached during the COP21 [1] and COP22 [2] conferences in Paris and Marrakech, resulting in a now legally binding agreement upon curbing the CO_2 emissions, harmful consequences of climate change cannot be avoided and mitigation measures need to be adopted. Furthermore, rapid urbanization is taking place and it is expected that two thirds of world population will live in cities by the year 2050, increasing the complexity of energy supply [3]. Some regions will urbanize more rapidly than the others, presenting the need to detect the most efficient energy solutions early, in order to avoid a lock-in effect of investing in inefficient infrastructure [4].

Around the tropics, climate is dominated by humid air and high temperatures throughout the year, causing large energy demand for decreasing air temperature and dehumidifying the air [5]. Large and relatively constant energy demand for cooling throughout the year can be met by different sources. Although in more moderate climates heat sinks are better researched, either in terms of free cooling of rivers and lakes or in combination with chillers, there is a lack of possible heat sinks in regions being close to the thermodynamic equilibrium, where the climate is being dominated by small temperature differences of the air, ground and sea during the year [5]. The potential of ground source

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Nomenclature

Term	Remarks, units
WH_i	yearly waste heat potential of the i-th considered plant, kWh
η_{total}	total potential efficiency of the plant, kWh_{output}/kWh_{fuel}
$\eta_{electrical}$	electrical efficiency of the plant, kWh_e/kWh_{fuel}
$Fuel_i$	yearly consumed fuel energy in the considered plant, kWh
$C_{supply,LNG}$	cold extracted from LNG gasification process, kWh
LNG	amount of liquefied natural gas imported, kg
$C_{supply,i}$	cold potential of the i-th considered plant, kWh
$C_{supply,total}$	total cold potential in the considered area, kWh
A_{cool}	total buildings area that needs to be cooled down,
PR_i	plot ratio of the i-th land plot, m^2/m^2
$A_{land,i}$	i-th land plot area,
C_{demand}	yearly cooling energy demand per m^2 of the considered area, kWh/m^2
EUI_i	energy use intensity, $kWh/(m^2 * year)$
T_{loss}	thermal losses in the grid, kW
P_{loss}	power needed to overcome the pressure losses in the grid, kW
$E_{supply,t}$	power that needed to be supplied in each hour in order to satisfy the final energy demand in each hour and losses of the transmission and distribution grids, kW
c_p	specific heat of water, 4.187 kJ/(kg K)
U	overall heat transfer coefficient, $W/(m^2 K)$
A	area of the pipe surface,
ΔT_1	temperature difference between the water flowing inside the pipes and the ground on the outer wall of the piping, K
l	length of the considered pipe section, m
r	radius of the pipe section, m
Q	volume flow inside the pipe section, m^3/s
ρ	density of water 1000 kg/m^3
f_D	darcy friction factor, –
v	velocity of the flow, m/s
ΔT_2	temperature difference between supply and return line of the DC network, K
$\dot{m}$	mass flow inside pipe section, kg/s
l_i	length of the each pipe section, m
P_i	price per meter of each pipe section, USD/m

heat pump in western Singapore was assessed in [6]. The main detected benefits were potential reduction of heat island effect by removing cooling towers and reduced water consumption [6]. However, the authors of the paper acknowledged unfavorable ground conditions in Singapore and concluded that the latter is the main reason for relatively low electricity consumption reduction [6]. Bruelisauer et al. analyzed ground, seas, river and air temperatures of Singapore and concluded that they are not suitable sources for free cooling in any of the seasons during the year [5]. Hence, alternative cooling sources need to be selected for meeting the cooling energy needs.

Cooling demand can be met focusing on individual solutions or focusing on one solution for the whole building, cluster of buildings or the whole districts. Individual solutions usually involve air-conditioning split systems, technically called air-to-air heat pumps. In the tropical region, for the general cooling energy needs of buildings, split systems usually achieve coefficient of performance (COP) in the range of 2.5–3.25, electric chillers with dry air cooling tower achieve COP in the range of 3.5–5 and electric chillers with wet cooling tower achieve COP in the range of 6–10 [5].

Compared to individual split systems, more efficient solutions can be done using absorption or electric chillers. An absorption chiller uses waste heat at temperatures around 90–95 °C [7], while electricity is needed only for pumping the working fluid. Therefore, it is possible to expect total plant electrical efficiency ratio (EER) of 15–25, while thermal energy efficiency for single effect absorption units is typically 0.7 [8]. In order to be able to utilize absorption chillers, one must have steadily available streams of waste heat as otherwise electric chillers would be more viable. It was shown that despite the advances of electrically driven chillers, utilization of absorption chillers leads to the cost-effective CO_2 emission reduction, if there is availability of cheap excess heat [9]. Further research on upgrading cogeneration to trigeneration systems was presented in [10]. The authors showed that the trigeneration is beneficial for the northern European countries; however, they have pointed out that it would be very interesting to apply their research to tropical regions, where more steady demand for cooling occurs throughout the year [10].

One of suitable sources for district cooling is liquefied natural gas (LNG) regasification. In an advanced liquefaction process, about 2900 kJ/kg of energy is consumed; 2070 kJ/kg being dissipated as heat and 830 kJ/kg (0.23 kWh/kg of LNG) being stored in LNG as cold [11]. However, due to the cryogenic temperature of LNG, released cold is also suitable for air separation, material freezing, dry ice production and refrigeration in chemical industry. Thus, several solutions can compete for the same resource. According to the available literature, LNG cold from regasification can be utilized for air separation, power generation, cold storage and dry ice production, as well as for district cooling [12]. A very successful example of utilization of cold energy from LNG gasification is a cascade process developed at Osaka LNG terminal [13]. They have combined ethylene plant, air separation, carbon dioxide liquefaction, water chilling and the expansion turbine in order to utilize the cold, achieving exergy efficiency of 52% [13].

In tropics, although there is often a lot of waste heat available from industry and different energy plants, there is usually a lack of demand for it, as the temperatures are high throughout the year. Hence, in hot and humid climates, a district cooling grid is one of the potential solutions for distributing the waste energy in the form of cold to the customers. Although focusing only on municipal waste incineration plants as a potential heat source in tropical urban areas, researchers showed on the case of Thailand that absorption chillers are capable of introducing significant savings in the energy system, by reducing the electricity demand for compression chillers [14].

Most of the past large district cooling research projects, in terms of number of case studies, were carried out or are currently undergoing in Europe, where cooling demand is less steady and highly seasonal in comparison with tropical regions. The most significant project that was finished is the Rescue project [15], funded by the EU. Other important projects are Stratego [16] and International Energy Agency's advocated case study on district cooling in Stockholm [17]. The Rescue report advocates that the first step should be the identification of all possible sources of natural cooling and the second step should be locating the waste heat potential [15]. The Stratego report argued that the optimal level of district cooling is still unclear and recommended more research to be carried out towards the design of the district cooling network [16]. On the other hand, the largest projects on district cooling in terms of capacity took place in Qatar, Kuwait and United Arab Emirates. In Qatar, the district cooling plant at The Pearl-Qatar has the combined cooling power of 450 MW and it seems to be the world's largest integrated district cooling plant so far [18]. In Kuwait, the Shadadiyah University's campus will be cooled with 36 electric chillers with the combined cooling power of 252 MW [19]. However, the latter two projects are lacking of systematic scientific research on the operation of the systems. District cooling system was proposed for the South East Kowloon Development project in Hong Kong and the authors concluded that the proposed district cooling system for the region was feasible,