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Forecasting long-term electricity demand for cooling of Singapore's buildings incorporating an innovative air-conditioning technology

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ABSTRACT

In an effort to accurately plan for investment on energy production and distribution, this paper proposes a long-term electricity consumption forecasting model for buildings' cooling by employing a high energy conservative scenario. The key aspect of the high energy conservative scenario is to adopt an innovative adsorbent-based dehumidifier and an indirect evaporative cooling (AD-IEC) technology as opposed to conventional mechanical vapor compression system. Bottom-up equations were developed to identify the cooling load and electricity consumption of both residential and non-residential buildings for the period 2002–2013. Based on the time-series electricity consumption, a multiple linear regression model is developed to forecast electricity demand for the future period of 2014–2030. It is found that the electricity demands for cooling in the building sectors account for 31 ± 2% of the total electricity consumption in Singapore, This study concluded that the high conservative scenario realizes the best potential of electricity saving of 21,096 GWh until 2030. Using a CO_2 emission factor of 4.49×10^{-4} metric tons CO_2/kWh, the total carbon footprint saving from all power plants is estimated to be 9491,264 t of CO_2. This work evolves a new forecasting methodology to predict buildings' cooling energy consumption involving the use of novel cooling technologies.

1. Introduction

Since air conditioner was first introduced to the Singapore's market by Carrier in 1950's, ownership of air conditioners has been increasing steadily up to 76% in 2013 [1,2]. In addition, all-year round air conditioning is also inevitable necessity for residents' comfortable due to the hot and humid tropical climate where the ambient temperatures range from 25 °C to 33 °C with an annual mean relative humidity of 85%. Hence, Singapore has been spending significant amount of energy and capital on air-conditioning by increasing the total electricity demand in tandem with the rapid expansion of the Singapore's economy since the 1970s [3–6]. Singapore government have been conducting building energy benchmarking by retrofitting existing buildings with the aim to reduce carbon intensity by 36% from 2005 levels by 2030 [7]. A large portion of the electricity savings is found to be a result of replacing or upgrading to a more efficient central air-conditioning system [8].

As a city-state with little land mass, one of the promising solutions for Singapore's energy saving and carbon emission reduction in air-conditioning is the implementation of a large-scale tri-generation based district cooling system (DCS) [9]. In such a DCS system, electricity, heating and cooling production are co-located at the same site, exploiting the economy-of-scale of larger chiller plants to improve chiller efficiency. Therefore, DCS is an energy-efficient air-conditioning system as it consumes 35% and 20% less electricity when compared with respective traditional air-cooled air-conditioning systems and individual water-cooled air-conditioning systems [10–12]. Many developed countries have adopted district energy system [13–16]. Paris developed Europe's first and largest district cooling network, of which a part used the Seine River for cooling the plants. It services the equivalent of 500,000 households, including 50% of all social housing as well as all hospitals and 50% of public buildings [13]. Dubai developed the world's biggest district cooling network, meeting a demand 3510 MW annually [14]. In 2004, Toronto integrated a district cooling system with the city's drinking water system, providing the equivalent of 263 MW (75,000 Rton) [15]. As far as Singapore is concerned, it has piloted a district cooling in Marina Bay by providing a cooing capacity of 57 MW for commercial buildings. For various reasons, however, the actual chiller plant efficiency is not

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able to reach as originally planned [16]. In addition to the DCS concept, this paper proposes a hybrid adsorbent-based dehumidifier and an indirect evaporative cooling or simply known as the AD-IEC cooling technology in an attempt to improve chiller plant efficiency up to 0.6 ± 0.05 kW/Rton. The underlying principle is to decouple moisture removal from the sensible cooling of return air in air handling units (AHUs) of buildings. The higher chilled-water grid is meant for sensible cooling only at load destinations. The moisture removal function is decoupled in this district cooling design and the thermal-lift between the evaporator and the condenser of the chiller plants is reduced by about 20%. Consequently, the kW/Rton of the plant is lowered. Such a cooling technology of has not been studied by any researchers so far, and few researches have been conducted on long-term energy forecast demand models for cooling in a tropical climate region.

Energy forecast models help in planning and drafting policies for the future energy demand with diverse scenarios. It also helps to assess the effects of specific policies and measures on energy efficiency. A number of energy demand forecasting models have been developed using various approaches. Joakim et al. developed domestic lighting demand model in Sweden [17], and Braun et al. predicted electricity and gas consumption of a supermarket [18]. J.S park et al. proposed energy model to estimate the energy saving potential of residential buildings [19]. Zaid et al. used economic and demographic factors to develop electricity consumption forecast model in New Zealand [20]. Household electricity consumption in Australia was established using a linear regression model [21], in which authors focused on demographic, household behavior and building appliance usage.

In this study, the proposed cooling technology is used as a predictor for forecasting energy consumption with a high conservative scenario, which is then compared with the technology under the business-as-usual (BAU) scenario where conventional chiller systems are used to meet the country's cooling demand. Based on both scenarios, electric energy demand for cooling is forecasted and analyzed in order to identify potential energy saving and carbon footprint reduction. Thus, this paper covers the estimation of cooling load of buildings at the national level, and the prediction and the forecast of the electric energy demand for cooling from 2002 to 2030.

2. Methodology

There are two available approaches employed to estimate energy consumption in regional or national level. The first one is top-down approach, which is based on macroeconomic modelling principles and techniques and is intended to include all important economic interactions of the society [22]. In contrast, a more tedious but accurate bottom-up approach has been widely used within energy analysis and planning that includes energy demand divided into end-use demands [22].

The bottom-up approach is initially employed to estimate the annual electricity demand for air conditioning in the building sector for the time period 2002–2013. This study investigates gross floor area (GFA) of assorted building categories and districts, hourly cooling load profiles (% of peak load) represented by each building categories, as well as average the cooling load indices (Rton/m^2) per finite floor. The annual electricity demand for the time period of interest is obtained by using a national average chiller's efficiency (kW/Rton) that is extrapolated from the known values such as the historical data, benchmarking and an actual district cooling plant's efficiency. The top-down approach is, in turn, adopted to develop a multiple regression model with appropriate econometric and technological variables. Thus, the electric energy demand for cooling is forecasted for the period 2014–2030 with two different scenarios so as to identify the eventual energy savings and carbon footprint reduction.

2.1. Cooling load and electricity demand

Firstly, we begin by examining the primary and statistical cooling demand data of built areas in Singapore's major sectors. After identifying the major consumers of electricity for air conditioning in Singapore, a total of three building sectors were examined, namely (a) residential building, (b) commerce/service-related building, and (c) industrial related building. They were grouped according to Energy market Authority (EMA)'s classification based on energy consuming sectors in connection to their principal activities – Singapore Standard Industrial Classification 2010 (SSIC 2010).[1] As the most influential factor, the GFA is directly related to the cooling load and hence the air-conditioning space required for occupant's comfort. The gross floor area is the total area of the covered floor space measured between the center line of party walls, including the thickness of external walls but excluding voids. The GFA data was collected from the Jurong Town Corporation (JTC) for all the commerce and service-related and industrial buildings [23]. On the other hand, the number of built residential units was provided by Urban Re-development Authority (URA) and Housing Development Board (HDB) [24,25]. Thus, GFA for residential buildings was deduced by multiplying the total number of units by the average room sizes based on flat types.

The following assumptions are used to simplify the bottom-up models for cooling load of Singapore's building sector: (a) Cooling load and electricity consumption in buildings are significantly affected by the building usage area that is considered as a space being cooled by air-conditioning systems at a given time. (b) Normalized cooling load profiles that are expected of each building types and can be applied to aggregate the total cooling load of buildings in the same category. (c) Detailed building physics properties and occupants' behaviors are ignored in estimating cooling load in national level. The total cooling load represented by residential can be expressed in the following equation.

$$CL_{residential} = \sum_{j=1}^{j=N} \left\{ \sum_{i=1}^{i=N} \left\{ \overbrace{(N_i)_{no.ofunits}(F_i)_{A/C}}^{unitswithA/C} \overbrace{(U_i)_{size}(F_i)_{floorsize}}^{fractionofunitair-cond} \overbrace{P_{\%dailycoolingload}}^{hourlyfrequencyof\%load} \right\} \right\} \quad (1)$$

where $(N_i)_{no.ofunits}$ is the number of units in flat type (i) which can be classified into 1-bedroom, 2-bedroom, 3-bedroom, 4-bedroom, 5-bedroom, executive, studio and Housing and Urban Development Company (HUDC) in accordance to flat sizes. $(F_i)_{A/C}$ is the fraction of air-conditioner installed in the flats. $(U_i)_{size}$ is the gross floor area (GFA) of each flat type (i), and $(F_j)_{floorsize}$ is the fraction of the air-conditioned area found in the units. $P_{\%,hourlycoolingload}$ refers to the hourly frequency of cooling in a day for all flats in Singapore. The first summation term represents the total daily cooling load in dwellings in a district, refers to as (j), and in the present study, there are 28 districts at assorted locations of Singapore.

[1] EMA's classification of electricity consumer: residential, commerce and service-related, industrial, transport and others.