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Mid-term forecasting of urban electricity load to isolate air-conditioning impact

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ABSTRACT

Demand Side Management (DSM) is often one of the most cost-effective approaches toward energy conservation and efficient electricity infrastructure utilization. Identifying total air-conditioning load for assessing targeted interventions is a difficult task given the transient thermal response of buildings, the coupled interaction of multiple sub-systems and the high correlation of demand with weather and other perturbations. An hourly regression-model of electricity consumption was developed for the city of Abu Dhabi, UAE, using measured hourly substation-level data. The fit is exceptionally good, even in a prediction context: Root Mean Squared Error (RMSE) equivalent to 1.54% of the annual peak load and Mean Absolute Percentage Error (MAPE) of 2.01% for the training period (full-year 2010), RMSE of 1.84% and MAPE of 2.64% for the testing period (first-half of 2011). The regression-model was combined with information from Abu Dhabi Urban Planning Council and the National Central Cooling Company (Tabreed) to derive an accurate estimate of the urban cooling load, the main driver of electricity consumption in the region. It was determined that, although only 30% of the annual load is directly weather dependent, air-conditioning explains no less than 57% of the total annual electricity load and 75% of the peak summer demand.

1. Introduction

According to the 2008 World Wildlife Fund's Living Planet Report [1], the UAE had the world's worst ecological footprint per person, experiencing only minor improvements by the publication of the 2012 report [2]. Demand-side energy efficiency is undoubtedly one of the most cost-effective ways for achieving Green House Gas emissions reduction.

The first step in promoting energy efficiency, from a policy point of view, should be to incentivize those initiatives that have the potential of achieving the highest impact in terms of energy cost savings with the lowest investment, the so-called "low hanging fruits". Identifying such options and estimating savings is a notoriously difficult task given the complexity and dynamics of the systems involved, the uncertain role of energy prices, lack of information on driving variables, unpredictability of end-user behavior and weather variability. Abu Dhabi and most of the region has a high portion of its electricity demand dedicated to cooling, mainly due to the hot and humid weather as well as the low thermal efficiency of the current building stock. The objective of this study was to identify, using different methods and sources of data, the fraction of the electricity load that can be directly traced back to cooling, since a series of measures are available to curb this specific driver of load.

2. Problem definition

Given the generally unsatisfactory level of thermal insulation in existing buildings and the extreme weather conditions during the long summer season, electricity load in the UAE and in most neighboring countries is highly correlated with weather for most of the year. It is estimated that the weather dependent portion of the load within Abu Dhabi municipality reaches 30% of the total load for the year, and 49% for the year's peak load hour [3]. The weather dependent load provides an absolute lower bound for the air-conditioning load, since the latter also includes certain constituents that are not weather dependent (e.g., pumps, fans). This fact reveals air-conditioning load as the primary target of any systematic energy efficiency program. To better model electricity consumption and the impact of air conditioning, it is essential to distinguish sensible cooling from latent cooling. Sensible cooling load refers to the energy demand directly responsible for keeping the building's indoor dry bulb temperature within a prescribed comfort range

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Nomenclature

E	electricity load
Gl	linear growth
Gm	multiplicative growth
T	temperature
t	time
T_S	smoothed temperature
κ	forgetting factor
I	solar irradiance DNI_H
ω	solar irradiance coefficient
θ	composite temperature
α	ratio for composite temperature
$\widehat{Y}$	modeled hourly energy consumption
$\widehat{Y}_1$	modeled non-weather dependent fraction of load
$\widehat{Y}_2$	modeled weather dependent fraction of load
B	baseload
λ	coefficients for non-weather dependent parameters
F^a	Fourier series for annual seasonality
F^d	Fourier series for daily seasonality
D^f	dummy variable for Friday/Holiday
D^s	dummy variable for Saturday
D^r	dummy variable for Ramadan
θ	sensible cooling load proxy
γ	latent cooling load proxy
w	wind
$\widehat{\eta}\theta$	coefficient for sensible cooling
$\widehat{\eta}_\gamma$	coefficient for latent cooling
$\widehat{\eta}_w$	coefficient for wind
C	total load from chillers
P	Total load from pumps
F	total load from fans
$misc$	other sources of load
pC	percentage weather dependent chillers load
pP	percentage weather dependent pumps load
pF	percentage weather dependent fans load
$\bar{W}$	weather dependent load from regression model
$\widehat{W}$	weather dependent load from typical building
$\bar{B}$	non-weather dependent load from regression model
$\widehat{B}$	non-weather dependent load from typical building

(e.g., $24 \pm 2\,^\circ$C), while the latent cooling load is the energy required to keep the indoor air humidity within a prescribed comfort range (e.g., $55 \pm 5\%$). This is achieved through dehumidification of both the fresh air intake and the recirculating indoor air. The ultimate goal is to ensure that the indoor comfort conditions, usually defined in terms of temperature and relative humidity, are "acceptable" with reference to a certain standard (e.g., ASHRAE Standard 55 in North America).

The main objective of this study was to identify the energy consumed for indoor climate control, defined by heating, ventilation and air conditioning (HVAC) load. In order to identify such estimate a top-down mathematical model of the Abu Dhabi electricity consumption was developed and combined with information from a bottom-up model, which gives further information about the cooling load. The measured data provided by Abu-Dhabi's utility was separated in a way that two-thirds of it was used for the model training and one-third for model testing. We ensured that the low-complexity linear model (some light non-linearity explored) estimated coefficients are statistically significant and accurately represent the underlying physical phenomena.

In our model, temperature was used together with humidity, wind speed and solar irradiance to account for different weather influences. Regression analysis was the method chosen for combining and pondering the different effects, due to its relatively low computational cost and broad range of application. This approach also produces easily interpretable sensitivity coefficients for the different drivers of the load, facilitating the analysis of each component individually, as opposed to other top-down approaches where the physical significance of the coefficients is lost. The regression model was used to segment load into weather dependent and non-weather dependent component. In order to have a more detailed breakdown of electricity consumption, especially for identifying the base cooling load that is constant through the year (chiller base load, pumps and fans), the top-down model was combined with a bottom-up model representing the three main building types in Abu-Dhabi.

3. Literature study

There are two main classes of methods for predicting and analyzing aggregate urban energy usage [4], the bottom-up and the top-down approach.

A review of both classes of methods and comparison based on data requirements, pros and cons is presented in [5]. The traditional bottom-up approach to model urban energy use is usually based on data obtained from surveys and field measurements of the energy consumption profile and the characteristics of an individual unit or a statistically representative sample of units, identifying fixed demand per unit floor area or per household and extrapolating the results to infer global urban usage characteristics. This approach can give specific details on optimization potentials for a single building [6] but, by itself, usually fails to model the total energy use in buildings at urban level with sufficient resolution, due, among other shortcomings, to a non-linear relationship between load and floor area.

A more accurate approach, which can be combined with the top-down approach, consists of a series of typical building models used together in a way to represent the overall building stock. Individual simulation of each building focusing on energy use characteristics, are aggregated together based on the overall representativity of each building type in the studied area in order to predict urban energy use [7–9]. This approach can produce better results as compared to the traditional method, but some weaknesses arise. The results from the aggregate urban model are highly dependent on the precision of the individual building prototype models used, in the accuracy of the collected data on the representativity of each building in the urban building population, and in the assumptions made with regard to changing demographic factors, hours of occupancy, indoor climate control system in use etc. [10]. The work described in [11] shows the application of an urban energy model based on individual representative buildings combined into "building clusters" for specific districts and extrapolated to determine potential CO_2 emission reduction for Osaka city, Japan, considering different energy efficiency and energy saving measures. Because disaggregate data is usually obtained by surveys, precision and size of the underlying building database directly impact the precision of bottom-up models [12].

Due to the interaction between buildings and the heat stored in the urban canyon, an urban microclimatic phenomena known as the Urban Heat Island effect cannot be properly accounted for and estimated only by using isolated building models, since in practice the overall urban energy consumption is different from the sum of all its constituent building loads [13,14]. Given the complex dynamics of the system, the non-linearity and coupling of sub-systems and the high correlation with weather and other random perturbations, the bottom up approach has many limitations when applied to urban/district energy models. On the other hand, it does not