Carnegie Mellon University

Master Thesis

Dynamic Energy Mapping

Author:
Yujie Xu

Supervisor:
Prof. Nina Baird

A thesis submitted in fulfilment of the requirements for the degree of Master of Science

in the

Building Performance and Diagnostics
School of Architecture

August 2015

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Abbreviations

CMU	**C**arnegie **M**ellon **U**niversity
GHG	**G**reen**H**ouse**G**as
EPM	**E**nergy**P**otential**M**apping

Symbols

THR	condenser total heat of rejection	Btuh
RE	net refrigeration effect	Btuh
f	Heat Rejection Factor	1

Chapter 1

General Introduction

1.1 Project Overview

The burning of fossil fuels produces green house gas (GHG) and causes significant global climate changes including global sea level rise, temperature rise, ocean warming, ice sheet melting and extreme weather event [2]. Fossil fuels are finite: studies have shown that if the consuming rate of fossil fuels remain the same, the major fossil fuels including oil, gas and coal will run out by the end of this century [3, 4]. Governments began to put reducing GHG as one of their major development goals: UK launched the "Climate Change Act" that aims at reducing GHG emissions by 80% comparing to 1990 by 2050 [5]; the City of Calgary aims at reducing CO_2 emission rate by 50% by 2050 [6].

Reducing the GHG emission and the fossil fuel consumption also takes place at the community level. Community Energy Management (CEM) is a combination of community level design strategies and energy management strategies aiming at providing quality of life in an urban environment with minimized energy consumption and environmental impact [7]. It contains "land use planning", "transportation management", "site planning" and "local energy supply and delivery planning" [7]. Community level energy planning and management achieves GHG reduction by means of :1) improving energy usage efficiency, 2) conserving the use of high quality energy and 3) switching to using more renewable energy source [8].

Energy Mapping makes the community energy planning alternatives visible to planners and policy makers [9] and thus flourishes with the increasing attention to community planing. Emerging explorations on the role and power of Energy Mapping in assisting community energy planning are taking place all over the world. The City of Calgary carried out an Energy Mapping Study that aims to "encourage the use of alternative energy systems, through considerations such as the design of buildings and encouragement of more compact, mixed-use and high density communities." [9]. The "London Heat Map" project that helps developers and planners to "identify opportunities for decentralised energy projects" [24].

What information should an Energy Map hold and in what form should the information be conveyed or displayed is still not completely agreed between different approaches. Calgary Energy Mapping study depicts annual average energy use intensity and alternative renewable energy supply region [6]. London Heat Map contains mainly heating energy related features: high heating energy consumers, suppliers and district heating networks. Dutch Heat Map, an application of the Energy Potential Method (EPM) method developed by Dobbelsteen et al. [20], contains information of annual heating energy demand (or demand density), heating energy supply (or supply density), infrastructure network layout and CHP and Biomass plant location.

However, as suggested by Baird et al. existing Energy Mapping practices are mainly static, i.e. the time-dependent changes of energy demand and supply information is not included in these Energy Maps nor do they support more advanced community energy system analysis and comparison. Thus the concept of "Dynamic Energy Mapping" [9] was brought about:

i. It acts as a geo-database that efficiently holds
   - hourly energy profile data for each building and the aggregated energy profile data for the whole community [9];
   - hourly energy supply data of community [9].

ii. It visualizes the dynamic energy demand and supply changes with high spatial and temporal resoltion [9].

iii. It performs data analysis and supports district system sizing [9].

iv. It can be connected to simulation tools that can supports instant performance analysis [9].

With a Dynamic Energy Map, the temporal behavior of the demand and supply of heating, cooling and electricity are revealed and are available to be compared (function ii), analyzed (function iii) and updated (function i and iv). One can see how well the supply meets the demand over time. One can also use it as a key component of Geo-design that encompasses "geo-spatial modeling, impact simulations, and real-time feedback to facilitate holistic designs and smart decisions" [10]. The development of data-driven approaches and machine learning methods could also be coupled and can perform more complicated analysis of spatial-temporal behavior of energy data and provide more informative design or management support.

1.2 Objective and Problem Definition

An initial instance of Dynamic Energy Map was created by Baird et al. in 2011-2012. The map consists of two parts: a geo-database that holds general building information (name, conditioned area) annual and monthly energy usage information (energy use intensity, annual peak demand value and monthly peak demand value); an excel screening tool that holds hourly energy usage information of each building and performs analysis and system comparison of a district energy system [9].

In the initial instance [9], function i) of holding spatial-temporal (although with low temporal resolution) energy data is realized by processing the energy simulation data with Microsoft excel and importing the csv file including "building name, total conditioned area annual, energy use intensity, annual and monthly peak demand". One goal of the current project is to make the geo-database hold higher resolution energy data, i.e. the 8760 hourly energy data of each building and the whole community will be contained in the dynamic energy map.

Function iv) of connecting to building simulation data is also realized by importing simulation result csv files to the geo-database (although with low temporal resolution).

For function iii), the feasibility analysis of a district energy system is performed in a stand-alone excel tool [9] but it is possible that the analysis result could be linked in to the geo-database as the energy simulation result.

For function ii), the spatial and temporal information are visualized separately in the initial instance [9]: the spatial information of 3D building geometry and location could be visually inspected in the geo-database but not the hourly energy consumption information. The temporal visualization of energy demand is done separately in the excel screening tool as 3D graphs, but no spatial context is present and the spatial dimension is then lost.

The authors thus identified the crucially missing function: the visualization of such a spatial-temporal changing of energy behavior as the major goal of the current project.

The objective of the project is thus defined as to

1. Implement a Dynamic Energy Demand Map with the focus on creating a high-resolution spatial-temporal visualization of hourly thermal energy consumption data for each building, major building sectors and the whole community
2. Demonstrate how such a Dynamic Energy Demand Map can support
   (a) Identification of energy recovery opportunities of single buildings or building groups
   (b) Support the sizing of a district energy system CHP plant

The community model is created in City Engine [11] based on the land use pattern of a mixed-use redevelopment project at Lower Hill District, Pittsburgh, PA [12]. The model contains 68 buildings, comparable to a typical service area of a district thermal energy system (combined heating and cooling), about 50 to 150 buildings [13].

The hourly heating cooling and electricity energy consumption profile is retrieved from DOE Commercial Benchmark Building simulation [1].

An interface was designed to combine the 8760 heating-cooling energy choropleth map images from City Engine and the 8760 hourly heating-cooling energy data from EnergyPlus to form a Dynamic Energy Map. The interface provides users with the functions of 1) navigating through the dynamic map images, 2) dynamic data plots of single buildings, building sectors and aggregated community thermal energy demand.

1.3 Related Concepts

Some related key concepts will be discussed in this section: the district energy system, the Energy Map and the Dynamic Energy Map.

1.3.1 District Energy System

A district energy system is one form of Decentralized Energy System, a "local or sub-regional supply of energy from a local source." [14]. It brings the energy generation near to the energy end users and reduces the energy transmission and distribution loss [15].

A district energy system produces thermal energy in a central plant and delivers the thermal energy to local buildings through a closed-loop pipeline network. Thermal energy are delivered in the form of steam, hot water or chilled water [9]. The central power plant can take on one of the following forms: 1) thermal power plant that only generates thermal energy, which can be either heating or cooling energy 2) co-generation system, or combined heat and power (CHP) system, that generates electricity and reuses the reject heat from electricity generation to serve space heating and service hot water to local buildings [13] 3) tri-generation system, where the central plant uses the heat generated by CHP plant to produce chilled water and supply both heating and cooling energy [16]. Corresponding to the different types of power plant, the network delivering thermal energy can be classified as 1) district heating network that only delivers steam or hot water 2) district thermal network that delivers both heating energy in the form of steam or hot water and cooling energy as chilled water.

A district thermal energy system corresponds to the three means of community level GHG reduction as follows:

- It has high energy generation efficiency

  Higher energy usage efficiency means with the same amount of input energy, more useful energy is produced and less are wasted. Buildings' electricity supply are mainly from centralized power plant that are far away from cities. Heat produced in power generation are normally dumped into oceans and lakes [9, 17], not only causing negative environmental impact [18], but also reduce the energy generation efficiency to be only about 1/3 [17]. District Energy System has high energy generation efficiency as a result of 1) it can utilize high efficiency large-scale energy generation equipment [13] and 2) it is closer to the energy end user which reduces the energy loss due to transmission and distribution [17].

- Better Exergy Performance

  The quality of energy is usually described with exergy. It is defined as "maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir" [19]. It represents the energy one can get out of the system. One example of a District Energy system helps improving exergy performance and better match the thermal energy supply and the low and medium-quality building energy demand [20] is the low-temperature (or low-energy) district heating system [21] which has a supply temperature of around 50 ^{o}C and return temperature of around 25^{o} C [21].

- Multiple fuel choices including renewable energy sources

  The central plant of a district energy system can use a broad range of fuel choices including natural gas, oil, coal, waste, and renewable energy sources including geothermal, solar thermal and biomass, in the generation of thermal energy. This makes the switch to large scale renewable energy source possible. It also makes the district thermal energy system more flexible and more competitive in the market and increases the energy system resilience [13, 17].

Apart from the environmental benefit, a district energy system also reduces the space and cost dedicated to installation and maintenance of HVAC systems in single buildings. It also reduces harmful gas emission of NO_x, SO_x by using non-combustion energy sources as lake body and by filtering [17] the flue gas [22].

1.3.2 Heat Map

Although "heat map" is generally accepted as "graphical representation of data where the individual values contained in a matrix are represented as colors" [23], with respect to buildings, a "heat map" may be defined as "a spatial plan of existing and planned building heat demand, and decentralized energy networks and generation equipment" [15]. It is also a GIS "live database" that allows new development information to be incorporated. It is a key component to the decentralized energy master plan [15]. One of the well-known instances of a heat map is the "London Heat Map" [24]

1.3.3 Energy Map

International District Energy Association (IDEA) define Energy Map as: "a tool that can be used to organize/present data as the basis for defining energy character areas as part of energy planning" [17]. It is a "GIS based system" that can be used to develop energy strategies, prioritize project, identify potential growth opportunities and impose planning restrictions [17]. Dobbelsteen et al. adopted the term "Energy Potential Mapping" that assist the development and plan of a sustainable built environment. It is a method that "visualizes local energy potentials and demand in order to support spatial planning towards more energy-efficient urban or rural environment" [20]. UK used the "Decentralized Energy Masterplanning" as a method that helps local authorities identify low carbon strategies that "maximises the opportunity for large-scale schemes to capture and use waste heat from major energy sources" [15].

With respects to the various definitions above, an Energy Map could be understood as a generalization of a heat map that includes energy supply, demand and infrastructure information of various energy forms and technologies. Some existing use cases of suggest an Energy Map could be used to visualize the community or city level energy demand reduction with high performance building design [6] or adoption of alternative energy supply technologies [6]. It can be used in supporting district heating system design [15, 25] by visualizing the heat sources and sinks.

1.3.4 Dynamic Energy Map

According to the study of Baird et al. , a Dynamic Energy Map is a Energy Map equipped with temporal information of energy supply and demand. It enables spatial-temporal comparison, aggregation and query of energy demand and supply. It is coupled with Energy simulation tools, and design alternatives would be evaluated and compared at each given time spot or time period. By performing advanced data analysis method, the dynamic map makes patterns that are omitted in static maps visible and analyzable. Both aspects enable more detailed energy analysis and design support.

1.4 Why "time" dimension is important for an Energy Map

1.4.1 Strong Temporal Variation of Energy Demand

Different building types often indicates different energy demand profile. For example, the residential building heat demand profile has two major peaks, morning and evening, and is relatively low for the rest of the day. For office buildings, there is a peak heat demand in the morning and a relatively high heat demand through the day time but drops in the evening. Hospitals usually have a more flattened demand throughout the day. Within a mixed-used urban environment, the arrival of peak demand for different buildings are usually not simultaneous [15].

In the design of a district energy system, mixing building types with different time-of-use energy profile can be helpful in creating a less variate aggregated energy demand. This allows the central CHP plant in a district energy system to a have higher utilization rate and reduces the need for backup plant that accounts for high peak demand [15].

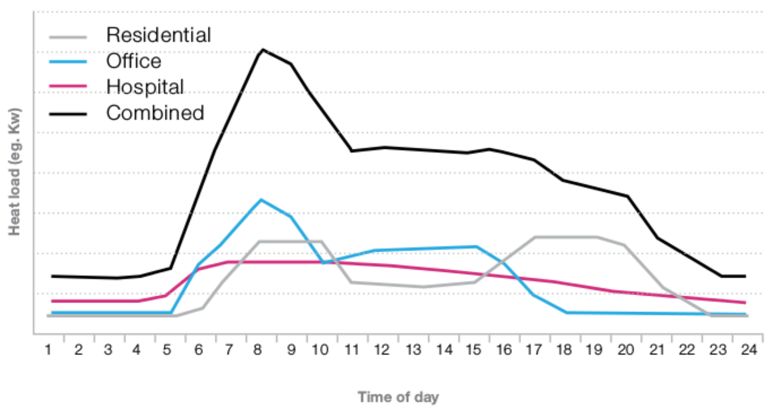

Figure 1.1: Mixing Load of Different Building Type [15]

1.4.2 Aggregation of Peak Value Becomes Tricky for Data with Time Variation

One common mistake for sizing a district thermal energy system is to add up the peak demand of each terminal users. Since the peak demand of individual buildings do not occur at the same time, the end result of summing up the peak demand at each end point exceeds the actual total demand peak of the community, hence with this approach, the whole district system becomes excessively over-sized, which reduces the whole system efficiency. A Dynamic Energy Map can reveal the problem of such approaches by directly providing the aggregated thermal energy demand for the community and for single buildings or building sectors. It allows a side by side comparison of single building demand and aggregated demand and eliminates the misunderstanding of the demand aggregation. With the direct information of aggregated thermal energy demand, it also assists actually sizing a district thermal energy system.

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