Dynamic Energy Mapping Project Outline

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Contents

Abstract

This document provides an approach of adding the "time" dimension to an Energy Map. The approach is demonstrated with a model of a conceptual urban setting created in CityEngine based on the extracted topological and density pattern from an existing urban design project. The buildings in the conceptual model is then assigned an energy profile of certain DOE Commercial Benchmark Building Reference model based on its building type. Hourly energy demand profile of heating and cooling end use is then obtained from the EnergyPlus Reference models. The energy consumption data is classified into groups with consideration of building energy design context and the data distribution properties. A corresponding color coded energy profile is then generated and imported to CityEngine. 8760 color coded 3D map images was then extracted from CityEngine with Python script. A data reading, ploting, color-coding calculation and a user interface for visualizing the images and dynamic data plot with sliders is implemented using Python and related packages. The tool is anticipated to provide decision support for community energy management and planning, demand-side strategy design and district system sizing.

The document will also briefly discuss one of the testbed for data classification and visualization.

1 General Introduction

1.1 Project Overview

Buildings alone account for 40% of the total energy usage in the United States. Although, if one was to consider the indirect energy impact of the built environment as a whole, the community design induced energy and environmental impact could exceed this already high ratio. The focus of reducing energy usage in the building sector has once been focused only on the scale of individual buildings and equipment [23]. However the community level urban design and the infrustructure layout can substentially influence the overall environmental impact by influencing people's life pattern, energy using behavior and waste production.

Community Energy Planning is a combination of community level design and energy management strategies aiming at providing quality of life in an urban environment with minimized energy consumption and environmental impact [23]. The awareness of the importance of the environmental design on energy performance and quality of life is reflected in design concepts such as New Urbanism, Smart Growth and Transit-Oriented Growth. These concepts advocates a compact and pedestrian and bicycle friendly urban growth that minimizes car usage by creating mixed-used communities, well-functioned road, complete public transportation system and diverse housing choices [33].

The core of the community energy management is to match the demand and supply as close as possible in terms of energy and exergy [3]. CEM reduces energy use impact by 1) distributed energy generation with sustainable energy source that close in exergy to the demand side, 2) application of district energy system that reuses waste heat 3) energy cascading that arranges the demand side as a chain of decreasing exergy demand so that the entropy generation is minimized 4) smart grid system that makes electricity demand and supply match

Energy Map accords with the concept of "geo-design", a performance-based design method, and makes the energy performance metrics of community design and management alternatives visible to planners and policy makers. It facilitates quantitive comparison of design alternatives and informs better decision making. However the temporal variation of energy performance metrics are missing from the current Energy Maps, leading to a simplified picture of energy impact of design choices and poor decision making such as excessively oversized infrustructure systems and loss of energy recovery and reuse opportunities.

Dynamic Energy Map reveals the temporal variation and better serves "geo-design" approach by revealing the problem of such simplified pictures of energy supply and demand and support better time-of-use energy system design, community energy management and policy making.

The project implemented a Dynamic Energy Map on a conceptual city model with a use senario of supporting district energy system sizing. The Dynamic Energy Map is built upon hourly heating and cooling energy consumption data from DOE Commertial Benchmark Building simulation. City Engine is used in 3D urban environment image generation with each building color-coded according to its hourly energy demand. An interface is then designed to achieve the "dynamic" function with sliders to navigation through the 8760 hours through a year and present the energy consumption data in the form of 3D color-coded map and data plot.

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1.2 Definition of Energy Map

1.2.1 Energy Thematic Map

In a restricted sense, Energy Map is an instance of a thematic map that depicts energy information. It is an abstract representation of some energy feature in an urban environment. It is useful in providing energy related qualitative or quantitative insight.

The energy topics depicted in an Energy Map can be classified into four major categories: energy supply, energy demand, energy related building design / urban planning, and energy related environmental impact. One common sub-category of the supply side topics concerns the locations and evolving process of energy infrastructures such as power plants, energy transmission pipelines, energy refining facilities and market hubs. EIA state energy profile map [16], U.S. natural gas pipeline map [13] are under this sub-category. Other supply side topics include total energy production [10]; total energy source production like global coal production map [14]; sustainable energy potential map of wind, solar, biomass, geothermal energy potential [26] and hidropower potential [11]. Common demand side topics include: energy demand for one or more enduses [28], energy source demand like coal demand [15] and energy cost [6]. The design side topics concerns building physical conditions like Calgory Heat Map [21], design policy information like climate zone map [8] and energy code adoption map [9]. The energy behavior environmental impact map include both the impact of building or energy infrastructure to environment and the environment change to buildings or infrastructures. The carbon emission map as [1] is an instance of the former and the "Energy Sector's Vulnerabilities to Climatic Conditions" Map is an example of the latter [7].

It is necessary to mention some unfortunate terminology overloading involved in the topic of Energy Map. The term "Heat Map" used in this discussion refers to the Energy Map with building heating energy as its theme, not to be mis-interpreted as the color-coded representation of matrix values as in this definition [32].

The history of thematic map dates back to early 17th century, and from then on maps can present spatial patterns of some feature in addition to merely recording locations of geographic features [34]. Over a century later, spatial analysis emerges and map starts to assisting geo-data analysis. Finally after the born of modern computer and the development of database, map becomes a more powerful information system that undertakes more complecated tasks including data aggregation, managing, query and presentation. This gives Energy Map a much broader meaning.

1.2.2 Geo-database of Building Energy

In a broader sense, Energy Map is a hibernation of two types of databases: building energy database, a subset of the BIM (Building Information Model), and Geographical Information System (GIS). The basic functions of an Energy Map includes 1) storing energy data in an organized fashion, that facilitate easy analysis and query of energy data and 2) provide reports in the form of graphs, tables, animations etc that conveys numerical information in a way that best support pattern recognition and decision making.

This definition can be considered as a superset of the thematic map definition, so the energy topics inherits those representable in the thematic energy map. Some examples of the Energy Maps under this "database" definition include: National Heat Map that records and presents heat demand density of buildings and building sectors, Renewable Energy Potential

Map that uses GIS tool in renewable and residual energy potential assessment [30], a site selection model that evaluates different choices of power plant location [35], and "Heat maps" with information of heat sources and sinks that supports district system expanssion design [17].

1.2.3 Coupled Geo-database and Energy Simulation Platform

"Geodesign is a design and planning method which tightly couples the creation of design proposals with impact simulations informed by geographic contexts" [18]. It is a performance based approach in urban and environmental planning. Traditionally, each performance metric is represented with a choropleth map layer. By stacking these layers together, the performance metrics are aggregated for each location on the map and a judgement of design alternatives are formed based on the aggregated performance metrics [20]. However, some of the performance metrics require complicated calculation or simulation, especially those with temporal variations. Hence the new development of Energy Map will not only record data but also "produces data" by providing stooth connections to urban level energy simulation tools that calculates energy performance metrics of different design alternatives on the fly. This enhanced Energy Map may effectively automates the geo-design work flow.

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

1.3.1 Strong Temporal Variation of Energy Demand

Building energy demand is strongly dependent on weather condition, building type, size, building physical design, building mechanical system and appliance quality and building operation schedules. The aggregation of all parameters results in a great variance in the range and extreme value of energy consumption. Weather condition have strong seasonal pattern and day-night pattern. This type of variation takes the form of a global influence on building heating or cooling load. Building operation schedules vary greatly from building to building as a result of difference in building type and occupant behavior. Different operation scheduces indicates the arrival of peak demand within a mixed-use urban environment are not simultaneous. Difference in building type also suggest difference in indoor environment requirement such as ventilation rate, lighting intencity etc., indicating a dramatic variation in energy consumption data distribution among buildings in the community. Upon these considerations, a simple annual or monthly average cannot effectly represent the real energy consumption behavior of an individual building and the whole urban environment. In order to present this complecated behavior of time-dependent energy demand, the time dimension is necessary.

1.3.2 Close Match of Supply Side to Demand Side Improves Community Scale Energy Performance

As a result of the finiteness of fossil fuels, the using of renewable energy begins to come into play. In 2013, renewable energy account for 9% of the primary energy source of residential and commercial buildings [12]. Electricity generated from sustainable sources normally do not have much storage capacity, hence in order to meet the energy demand with renewable electricity, a better understanding of the spatial-temporal pattern of energy demand is important [25].

Demand-driven energy supply is necessary to reduce energy waste and achieve better total community energy performance, and in order to match the supply side to the complicated behavior of the demand side, understanding the spatial-temporal pattern of the energy demand in the early design and planning stage is important.

1.3.2.1 District Energy System Sizing

A district energy system consists of a power plant, a series of buildings as ternimal energy users and a network of pipelines that transmit energy from the power plant to end-users. Commonly used media for energy transmission include steam, hot water or chilled water [2]. A district energy system helps reducing negative environmental impact by harvesting residual energy in the form of rejected heat or coolth in the process of electricity generation or other industrial processes. It can adapt to a broader range of fuel choices including natural gas, oil, coal, biomass and garbage. This makes it more flexible and more competitive in the market [22]. Other non-environmental benifits include reducing the space dedicated to mechanical system and improve design building design flexibility, reducing harmful gas production from stand-alone boiler conbustion.

Dynamic Energy Map supports district energy system design by 1) revealing the non-coincident peak demand of heat or coolth 2) providing the aggregated demand supporting better decision making.

Obvious mathematical concepts sometimes become more obscure when it comes to real life problems. It is well understood that linearity holds for expectation not max, i.e. the sum of max values of each distribution does not equal to the maximum of the sum of values in each distribution. However this mistake is not rare in the sizing of a district system. One common approach of sizing a district system is to add up the capacities of each terminal devices. However, each individual device is sized to meet its peak demand. Since the peak demand of individual buildings do not occur at the same time, the end result of summing up the max demand at each end point exceeds the actual total demand peak of the community, hence with this approach, the whole district system becomes excessively oversized, which reduces the whole system efficiency. Dynamic Energy Map can reveal the problem of such approaches by directly providing the aggregated demand and the demand for single buildings or building sectors side by side, eliminating the misunderstanding of the aggregated demand and providing the actual data for system sizing.

1.3.2.2 Community Energy Planing

As is mentioned in the project overview, the community energy planning involves landuse design and infrustructure design. The time dimension is important to community energy planning because it reveals the temporal complexity of the community energy supply and demand. The ability to describe the energy using behavior with more details then a mere max, min and average and to classify building energy demand into more detailed behavior prototypes is the first step to energy oriented landuse plan, demand side energy management and energy cascading design. This more accurate picture also act as the basis of further design of energy supply.

With Dynamic Energy Map, one can classify energy sources and sinks into more specified categories and design for more specific combinations of sources and sinks. One can also identify energy sources and sinks that dynamically changes over time. The temporal-spatial energy supply and demand information can be helpful in the following cases:

- Enable the design of local load balancing

  Large public facilities like stadiums or performance centers normally have mechanical systems with large capacity to meet its peak demand but the large capacity might only be used under occassional event. Dynamic Energy Map helps identify such occassional heavy energy consumers and helps optimize landuse planing by arranging the right amount of surrounding consumers around and optimize the local system design by redirect the energy capacity of the ocational heavy consumer to surrounding buildings [24]

- Support the design of connections to district network

  Dynamic Energy Map can identify buildings with constant high heat demand and buildings with occassional low heat demand. By identify these two types of buildings, urban planners could connect the former to the district system and the latter could be connected to the former with ambient water loop so that the latter could "borrow" heat from the former and reduces the community energy throughput.

- Help design of local energy storage devices

  Energy storage devices can shift the peak supply to meet peak demand, and it also made the community energy flow more complicated. Accurate information of the surplus and deficiency over time helps design the storage capacity for single building, building group and the whole community.

- Convey the energy benifit of mixed-landuse.

  With a Local Dynamic Energy Map, one could compare the total energy demand and the demand variation directly between the mixed landuse case and the single landuse case. The benefit of community level load balancing could be visible to the policy makers and planners to inform better landuse design.

1.4 General Description of Dynamic Energy Map

Within the current context, "dynamic" refers to changing over time, hence Dynamic Energy Map is an Energy Map equipped with temporal information. As a result of the "dynamic" property, one assumption about Dynamic Energy Map is that at least one of the energy related variables depicted in the map should change over time. Due to the fact that there are three versions of definitions for Energy Map, there are also three versions of corresponding Dynamic Energy Map.

1.4.1 Thematic Map Time Series

In a restricted sense, where an Energy Map is defined as a thematic map focusing on energy topics, Dynamic Energy Map is just a series of maps, each of which is a thematic Energy Map representing the status of energy information happened at a certain time spot. Also with the convention that thematic maps are ordered in increasing time order. The purpose of such a Dynamic Energy Map is to facilitate the comparison of thematic maps at different time steps. Baring this in mind, it makes more sence to apply a universal map symbol and breakpoints to the sequence of thematic maps in this version of Dynamic Energy Map.

1.4.2 Spatial-Temporal Energy-geo-database

In a broader sence, where Energy Map is defined as energy-geo-database, Dynamic Energy Map is an energy-geo-database with "time" being one of its data entries. One major purpose of Dynamic Energy Map under this definition is to enable search, filter and query of the energy data by "time" field, thus presumably, time should act as one of the indexes in the database that facilitates faster search and query of the time data. The second task of Dynamic Energy Map is to provide more powerful reporting tools than normal Energy Maps that accounts for the difficulty and complexity of spatial-temporal data visualization aiming at better conveying the dynamic spatial pattern.

1.4.3 Performance Based Geo-design Support Platform

When Dynamic Energy Map becomes a platform coupled with Energy Simulation tools, design alternatives would be evaluated and compared at each given time spot or time window according to the design context. This enables more detailed energy analysis.

2 Objective and Problem Definition

2.1 Exploring potential use cases of Dynamic Energy Map

The major objective of this study is to explore the power of Dynamic Energy Map with a use case senario of supporting district energy system design, which is one of the infrastructure side strategy used in community energy management. Aligned with this major goal, there are two sub-goals of the project: evaluating some possible approaches to implement dynamic energy map and presenting one major implementation approach

2.1.1 Definition of Dynamic Energy Map for Supporting District System Design

District system supply thermal energy to the surrounding community, thus the community heating or cooling demand decide the size of a district system. Therefore heating demand and cooling demand are selected as the major variables in the study. We define “Local” Dynamic Energy Map for Community level design support as:

- A database holding 8760-hour meta data of energy demand of buildings in a moderate sized community served by a district system [2].
- An interface that has multi-dimensional graphical display of the meta data.

The data display would include 1D data plot, 2D or 3D map and 4D temperal-statial navigation:

- 1D: data plot for providing quantitative information of energy demand or supply

  The Local Dynamic Energy Map displays the aggregated hourly energy demand of the whole community and major building sectors throughout the year. It enables comparison of different urban design alternatives in terms of total demand and demand variation. These information supports district system planning by arranging landuse design to minimize load variation.

- 2D or 3D: graphical display of spatial relationship of energy data

  The Local Dynamic Energy Map applies a graduated symbol or color to buildings in the community to provide the intuition of the building energy demand changing within a community. It helps identify the rank of energy demand in a community and provides a guidance in energy cascading design.

  For univariant map senario, we suggest the variant size symbol according to the study of Garlandini et al. [19]. For bivariate map senario [31], which is the case for the current study, when heating demand and cooling demand are depicted on the map together, we suggest a two dimentional color ramp representation.

- 1D + 2D or 3D: interactive graphical display of spatial-temporal pattern of energy data.

  The Local Dynamic Energy Map compares energy demand of different time of year by providing a easy navigation with a time slider. Energy demand of each time spot is expressed with 2D or 3D map and 1D data plot.

3 Related Works

add logic!!!!!!

3.1 Static Energy Map

The majority of existing Energy Map instances are static maps with no time information. As is mentioned in the thematic map definition, the major application of Energy Maps include energy supply, energy demand, building or infrastructure design resulted energy impact and environmental impact. The sub-section will present some more detailed examples in each use cases.

3.1.1 Supply

3.1.1.1 Assessing Renewable Energy Potential

In order to reduce environmental impact, increase resilience of local energy supply and match energy intensity of supply and demand in urban environment, renewable energy source of wind, solar, geothermal, biomass and hydropower becomes an increasingly important energy source. Comparing with fossil fuel, the energy production with renewable energy has strong correlations to geo-locations, thus the energy map of renewable energy availability and demand can support energy planning that aims at improve urban scale energy performance [27].

Some study focuses only on one type of renewable energy source.

- Wind:

  Voivontas et al. developed a decision support tool using GIS for accessing the wind energy potential in four aspects:the theoretical potential in terms of wind speed, availability potential in terms of landuse regulations and technological potential in terms of energy production features of wind turbine and economical potential in terms of IRR.

- Solar

  "NYC City Solar Map" presents solar energy potential for buildings across the New York city. The map presents solar energy generation curve, estimated solar system installation area, finantial incentive and payback [29]

Other efforts tackles multiple renewable energy sources:

Ramachandra and Shruthi produced a series of district level renewable energy theoretical potential maps of solar, wind, hydroenergy and biomass in Karnataka State, India. The potential is estimated based on data of global solar radiation, wind speed, hydropower plant capacity, and plantation and livestock information. GIS is used in aggregating energy potential data to each district. Each type of renewable energy source is presented as a single variable thematic energy map.

3.1.2 Demand and Infrastructure

3.1.2.1 Analysis or design support of existing energy infrastructures

Finney et al. studied the potential expansion opportunities for the Sheffield district energy network by producing a heat mapping that 1) depictes heat sources and sinks, including existing ones and emerging ones 2) identify "heat zones" by connecting sources and sinks. The "heat zone" is then filtered with concerns of economic feasibility and environmental impact. The network extenssion is then designed based on the remaining "heat zones". Heat demand is assessed with population density for residential buildings and is represented on the map as polygon features with graduated color. Heat demand for non-residential buildings are assessed with gas consumption and is mapped as point features with graduated size. Heat sources are identified with the criteria "producing recoverable, low-grade 'waste' heat" [17]. They are mapped as point features including steelworks, combined heat and power (CHP) plants, and biomass power stations. The "heat zone" is identified based on abundance of sources or sinks.

National Heat Map is a "publicly accessible high resolution web-based" heating energy interactive map, developed by the Department of Energy and Climate Change (DECC) in UK. It aimed at "support planning and deployment of local low-carbon energy projects in England" [5]. Heating demand density (kwh/m^2) of four major building sectors: public buildings, commercial buildings, industry buildings and residential buildings, together with the total demand is plotted on the map as 2D raster feature with a color scheme from blue to red, with blue for low heating demand and red for high heating demand. Heat source of CHP stations and "Thermal Power Stations" [28] are plotted as point features in the map. Address level heat demand data in csv format is also available for local authorities [4]. National Heat map helps identify the potential connections between heat sources and sinks.

3.1.2.2 Energy consumption prediction model

1. "A large-scale study on predicting and contextualizing building energy usage", Kolter, J. Zico; Ferreira Jr, Joseph.

3.1.2.3 Smart Management of Urban Energy System

1. "Smart Urban Services for Higher Energy Efficiency"(SUNSHINE) project (2013): energy consumption map, automatic alerts, remote control of public building lighting system.

3.1.3 Combined Supply, Demand and Infrustructure

Comparing with the previous examples, Dobbelsteen et al. described a framework of energy potential mapping that 1) in addition to renewable energy source, it also considered residual energy as energy sources and 2) aggregated multiple types of energy potentials in a single map with the unit of GJ or GJ/ha [3]. The energy potential of sources are estimated by theoretical potential multiplied by a serious of "limiting factors". The energy demand includes buildings and transportation. The authors also suggest to map energy storage on the map. A case study of "HEAT Mapping" is presented with aggregated supply and demand presented in a single 3D Heat Map. The absolute quantity of each type of demand and supply of a certain region is represented with extruded height in the 3D map. Demand is represented with a transparent 3D feature, each supply source is represented with solid 3D feature in a different color. The aggregation of information is valuable in answering the question of whether the supply meets the demand, the representation becomes too complicated [3].

3.1.4 Reflections

The existing mapping approaches had their main effort in the data calculation and aggregation, however the resulted visual representation is questionable for most instances. One common issue is too much distraction from unthoughtful map symbology design. For static maps, a poor designed visual representation might still be tolerable, but for Dynamic Energy Map with an additional time dimension, each additional bit of distraction will prevent the necessary information from getting through. Hence the authors think it is necessary to discuss the map design aspect, and look for examples of best practices. This is done in section x.x.!!!!!!

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