Dynamic Energy Mapping Project Outline

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Contents

Abstract

This document provides an approach of creating a space-time Energy Map, or a Dynamic Energy Map. The approach is demonstrated with a conceptual urban environment 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 heating and cooling demand profile are then obtained from the EnergyPlus simulation of DOE Commercial Benchmark 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 2D and 3D map images was then extracted from CityEngine with Python script. A series of data reading, plotting, data classification and color-coding calculation utilities were implemented. An interactive interface for visualizing the images and dynamic data plot with sliders is implemented using Python. The tool is anticipated to provide decision insight for community energy management and planning, demand-side strategy design and district system sizing.

The document will also briefly discuss one of the test-bed 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. However if the indirect energy impact of the built environment as a whole was considered, 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 [44]. Community level urban design and the infrastructure layout can inevitably influence the overall energy throughput by influencing people's life pattern, energy using behavior and waste production.

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 [44]. 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 advocate 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 [63].

The core of the community energy management is to match the demand and supply as close as possible in terms of energy and exergy [6]. 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 provides great opportunity to execute the CEM strategies since it 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 is missing from the majority of current Energy Maps, leading to a simplified picture of energy impact of design choices and poor decision making such as excessively over-sized infrastructure 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 current project aims at exploring how a Dynamic Energy Map can serve as decision support tool for Community Energy Management, more specifically, to support district energy system design. The focus of the study is not on exploiting the energy using behavior of a specific site, but rather a exploration of a generic methodology of Dynamic Energy Map, thus the map setting is based on a conceptual city model with a size (68 buildings) comparable to the typical service area of a district energy system (combined heating and cooling), about 50 to 150 buildings [43]. The Dynamic Energy Map is built upon annual hourly heating (gas) and cooling energy (electricity) consumption data from DOE Commercial 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 1D energy consumption data plot of major building sectors and the whole community.

1.2 Objective and Problem Definition

The objective of the project is to provide an implementation of a dynamic energy map and experimenting with different approaches of drawing design support information and develop valuable design insights with a Dynamic Energy Map, which is best summarized by the quote: "Visualization is about exploring, not only the data, but also the method." [23].

Such experimentation is conducted with a use case scenario of supporting district energy system design, which is one of the infrastructure side strategy used in community energy management.

The question we aim to answer in this project is: to what extend and how can we use Dynamic Energy Map to optimize the design of a district system.

1.3 Outline

The document begins with a section explaining some related definitions regarding the Energy Map and its use case scenario. Then some related works are presented, including cases studies of Energy Map, Dynamic Energy Map and design issues regarding space-time visualization. Section 3 explains the methodology of the implementation of the dynamic energy map and section 3.5 explains the interface design.not finished

1.4 Related Concepts

Before diving into details about the specific project, it is necessary to clarify some key concepts including district energy system and Community Energy Planning, Energy Map and Dynamic Energy Map.

1.4.1 District Energy System

A district energy system consists of a power plant, a series of buildings as terminal energy users and a network of pipelines that transmit energy from the power plant to end-users. It can supply heating energy and service hot water to terminal buildings and can also supply cooling energy with absorption chillers. Commonly used media for energy transmission include steam, hot water or chilled water [4]. A district energy system helps reducing negative environmental impact by harvesting residual energy in the form of rejected thermal energy in the process of electricity generation (CHP based district system) or other industrial processes. It can adapt to a broader range of fuel choices including natural gas, oil, coal, waste, and renewable energy sources. This makes it more flexible and more competitive in the market and increases the energy system resilience [43]. Other non-environmental benefits include reducing the space dedicated to mechanical system and improve building design flexibility, reducing harmful gas production from stand-alone boiler combustion and reduces building cost. Comparing with a district system heat exchanger, a stand-alone chiller usually need 30% to 100% more cooling capacity, which means larger system initial cost [43].

District systems are most commonly connected to high density urban environment, university campuses, hospitals and military bases as a result of their high demand in heating energy or service hot water [43]. A district system brings the power generation near to the power end users, and reduces the energy transmission loss of both heat and electricity.

Combined Heat and Power Plant (CHP) is one of the major central plant used in a district energy system. Traditional electricity generation central plant has only about 1/3 of the energy turned into electricity and the remaining 2/3 are rejected as waste heat to the environment. CHP plant can reduce the amount of reject heat to 20% and the recovered heat is supplied to surrounding buildings for space heating or cooling [43].CHP plant can also be equipped with back-up boilers, electric boilers, and thermal storage that help shift the demand and production peak of thermal and electric energy and provide a reliable and cost-effective energy supply [46].

One famous example of CHP based district system is the Sheffield District Energy Network in UK. The Sheffield District Energy Network is a system that started to provide local buildings with heat and electricity since 1988. The system consists of an Energy Recovery Facility (ERF) located in the center of Sheffield, a pipe system transferring thermal energy with hot water, and terminal heat exchangers installed in the local buildings. Electricity generation is based on waste combustion process that produces high pressure steam and flue gas. The latter is treated and emitted to the atmosphere with 10% to 60% less pollutant below required level. The former enter the turbo generator and generates 19 MW electricity that serves 22600 local homes. After going through the electricity generator, the 400°C steam is de-pressured and dumps its heat to hot water. The hot water is then sent to the local buildings and provides these buildings with space heating [59].

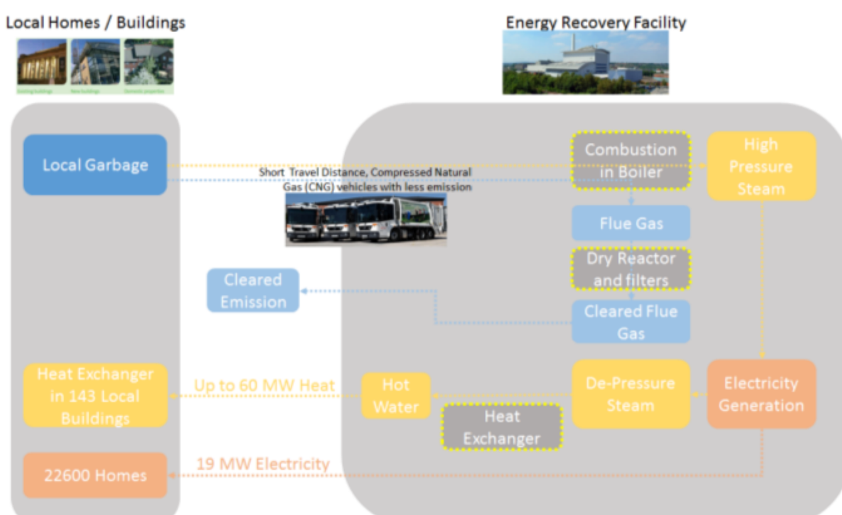

Figure 1: Sheffield District System

Energy Map helps the assessment of whether a building is suitable to be connected to the district system according to its heat demand density. A common lower bound for making a connection is $0.93kWh/ft^2$ (IEA) or 26.5 MMBtu per square mile [46].

Energy Map can be used in analyzing the network design and extension of a district system: one example of using Energy Map to analyze the potential of extension of Sheffield District System Network is illustrated in section 2.1.2.1.

1.4.2 Definition of Energy Map

1.4.2.1 Energy Thematic Map

In a restricted sense, Energy Map is an instance of a thematic map that depicts energy information. 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 [28], U.S. natural gas pipeline map [25] are under this sub-category. Other supply side topics include total energy production [18]; total energy source production [26]; sustainable energy potential map of wind, solar, biomass, geothermal [51] and hydropower [19]. Common demand side topics include: energy demand for one or more end uses [54], energy source demand [27] and energy cost [13]. The design side topics concerns building physical conditions like Calgory Heat Map [41], design policy information like climate zone map [15] and energy code adoption map [17]. 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 [3] is an instance of the former and the "Energy Sector's Vulnerabilities to Climatic Conditions" Map is an example of the latter [14].

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 [62].

The history of thematic map dates back to early 17th century, and from then on maps can present spatial patterns of features other than geographic locations [64]. 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 can performing complicated data crunching tasks including data aggregation, managing, querying and presentation. This gives Energy Map a much broader meaning.

1.4.2.2 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 a Geo-database or 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 super set of the thematic map definition, so the energy topics inherits those representable in the thematic energy map definition. Some examples of the Energy Maps under this "database" definition include: National Heat Map that records presents and supports query of heat demand density of buildings and building sectors; Renewable Energy Potential Map that uses GIS tool in renewable and residual energy potential assessment [60], a site selection model that evaluates different choices of power plant locations [66], and "Heat maps" with information of heat sources and sinks that supports district system expansion design [35].

1.4.2.3 Coupled Geo-database and Energy Simulation Platform

Development of data-driven approaches and learning methods makes the analysis of more complicated spatial-temporal data possible. With these emerging analysis tools, using data to support design is possible.

"Geo-design is a design and planning method which tightly couples the creation of design proposals with impact simulations informed by geographic contexts" [36]. 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 [39]. 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 smooth connections to urban level energy simulation tools that calculates energy performance metrics of different design alternatives on the fly. Further, they could produce knowledge by their ability to perform data-driven analysis and provide complicated design suggestions. This enhanced Energy Map may effectively automates the Geo-design work flow.

1.4.3 Definition 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. Sometimes this type of map is referred to as "space-time" map [7, 23]. 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.

1.4.3.1 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 sense to apply a universal map symbol and break points for data classification to the sequence of thematic maps in this version of Dynamic Energy Map.

1.4.3.2 Spatial-Temporal Energy-Geo-database

In a broader sense, 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 about the time field. The second task of Dynamic Energy Map is to provide more powerful reporting tools than normal Energy Maps It should account for the difficulty and complexity of spatial-temporal data visualization aiming at better conveying the dynamic spatial pattern.

1.4.3.3 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 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.

1.4.4 Definition of Local Dynamic Energy Map for Supporting District System Design

The attempt of exploring the usage of a dynamic energy map is based on a highly restricted use case of Local Dynamic Energy Map whole major intention is to support the community energy planing with a specific focus on District Energy System design. We define the Dynamic Energy Map applied in the specific case as “Local Dynamic Energy Map” that has the following properties:

- A database holding 8760-hour meta data of thermal energy demand of buildings in a typical sized community that can be served by a district system [4].
- An interactive map display interface that has multi-dimensional graphical representation of the meta data.

The data display should include 1D data plot, 2D or 3D map and 4D temporal-spatial 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. This information supports district system planning by arranging land use design to minimize total 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 scenario, we suggest the variant size symbol according to the study [22, 38]. For bivariate map scenario [61], we suggest the bivariate choropleth map representation. For detailed explanation of this design choice please refer to section 2.3.

- 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 (can be toggled) and 1D data plot.

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

1.5.1 Strong Temporal Variation of Energy Demand

Building energy demand is strongly dependent on weather condition, building type, size, building physical design, building mechanical system, appliance quality and building operation schedules. The aggregation of all parameters results in a great variation 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 schedules indicates that 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 intensity etc., indicating a dramatic variation in energy consumption data distribution among buildings in the community.

1.5.2 More Detailed Description of Energy Behavior Supports Better Design

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 complicated behavior of time-dependent energy demand, the time dimension is necessary.

We can explain this with a concrete example. Hospitals are usually constant heat consumers with very stable heat demand throughout a year (see Figure 7), while a performance center is, on the other hand, an occasional huge heat consumer with very high peak demand occuring occasionally at event time and with almost zero demand in the remaining time. It is reasonable to apply different energy planning strategy for building groups involving one of these two types of buildings. However, if time dimension is omitted, one has to choose some aggregated description of the energy consumption of the two building types, be it average, maximum, minimum or annual total. For most cases, annual total demand is used for representing a building's energy demand, especially in the case of District System design. With this approach, the different energy usage pattern of a hospital and a performance center might look the same, which results in a simplified energy plan decision.

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

Obvious mathematical concepts sometimes become obscure when it comes to real life problems. Dynamic Energy Map supports district energy system design by 1) revealing the non-coincident peak demand of heat or cool 2) providing the correct aggregation of demand and supporting better decision making.

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 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 over-sized, 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.

1.5.4 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 [24]. 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 [50].

Demand-driven energy supply is necessary to reduce energy waste and achieve better total community energy performance. Dobbelsteen et al. pointed out that the "exergetic challenge" for urban energy supply is that the building operation requires only low or medium grade energy, but the supply side energy source is usually with high energy density. In facing of this challenge, renewable energy and "residual" energy are in place to "fill the gap", providing energy supply with various energy density, facilitating the cascading strategy [6].

In order to match the supply side to the complicated behavior of the demand side in both energy quantity and quality, understanding the spatial-temporal pattern of the energy demand in the early design and planning stage is important.

1.5.4.1 District System Design

The time dimension is important to district system design 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 land use plan, demand side energy management and energy cascading design. This more accurate picture also act as the basis of further design of energy supply and infrastructure system.

With Dynamic Energy Map, one can classify energy sources and sinks into more detailed 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:

- Demonstrating the increased efficiency of district system

  Comparing with district system, a single building stand-alone equipment are sized according to its peak load, which does not occur very often for most of the cases. As a result, the stand-alone system is running on its less efficient power output for the majority of the time. On the other hand, a district system in a mixed used community has much more stable aggregated demand and can run on its optimal output power for longer time than stand-alone system, hence is more efficient. This fact can be demonstrated by dynamic energy map that compares the energy throughput of the two cases considering the system efficiency.

- 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 occasional event. Dynamic Energy Map helps identify such occasional heavy energy consumers and helps optimize landuse planing by arranging the right amount of surrounding consumers and optimize the local system design by redirect the energy capacity of the occasional heavy consumer to its surrounding buildings [46]

  A group of buildings can connect to a shared boiler or chiller, which is then connected to the district network. Buildings with different energy using profile can make the aggregated load of the group be smoother than single building. Such a building group can be served by a lead boiler and a backup boiler with the lead boiler constantly running on its optimal efficiency and the backup boiler running occasionally for meeting the peak load [46]. Dynamic Energy Map can identify such building groups that has the opportunity to create a local load balancing.

- Support the design of connections to district network

  Dynamic Energy Map can identify buildings with consistent high heat demand, i.e anchor load building [46] and buildings with occasional heat demand. By identifying 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.

- Support 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 energy surplus and deficiency over time helps design the storage capacity for single building, building group and the whole community central plant.

- Convey the energy benefit of mixed-land use.

In a mixed used urban environment, with a mixture of energy demand profile, the central plant could potentially operate at optimal output level over a longer time period than the single land use case [43]. With a Local Dynamic Energy Map, one could compare the total energy demand and the demand variation directly between the mixed land use case and the single land use case. The benefit of community level load balancing could be visible to the policy makers and planners to inform better land use design.

- Optimizing site selection of the backup central power plant

  A central power plant sometimes have backup systems to account for peak demand. With Dynamic Energy Map, one could identify the location of the cluster of occasional high heat consumers and consider placing the backup plant near the cluster of buildings with high peak demand and thus reducing the energy transmission lost

- Identify energy recovery opportunities

  The process of cooling will produce reject heat. The rejected heat could be harvested and supply the heating demand of either the building itself or its surrounding building. Dynamic Energy Map helps identify such opposite thermal energy demand and support the design of energy recovery strategies.

The cases listed above mainly explains the direct application of Local Dynamic Energy Map with aggregated information, which can still be a too simplified approach. Direct analysis of spatial-temporal data without aggregation is more preferable since it retains the valuable "dynamic" property. A more general usage of such a map is to help identify and discover patterns of energy behavior that are unknown yet. Please refer to section 2.4 for more detailed explanation.

2 Related Works

Section 2.1 and section 2.2 provide an overview of the existing instances of static and dynamic maps. The dynamic map instances are not restricted to the field of building energy analysis. Section 2.3 and 2.4 provides some supporting evidences for certain design choices. Section 2.5 provides some information on potential technologies for further development.

2.1 Static Energy Map

The following section will present some static Energy Map instances on each of the common energy topics specified in the section 1.4.2.1: energy supply, energy demand, building or infrastructure design resulted energy impact and environmental impact.

2.1.1 Supply

2.1.1.1 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 improving urban scale energy performance [53].

Some studies focus on a single type of renewable energy source:

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 land use regulations, technological potential in terms of energy production features of wind turbine and economical potential in terms of IRR.

"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, financial incentive and payback [56]

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 univariate thematic energy map.

2.1.2 Demand and Infrastructure

2.1.2.1 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) depicts heat sources and sinks, including existing ones and emerging ones 2) identify "heat zones" by the abundance of sources or sinks. The "heat zone" is then filtered with concerns of economic feasibility and environmental impact. The network extension is then designed based on the location of 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" [35]. They are mapped as point features including steelworks, CHP plants, and biomass power stations.

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" [10]. 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 a 2D raster image with a discrete 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" [54] are plotted as point features in the map. Address level heat demand data in csv format is also available for local authorities upon request [9].

The "Water Source Heat Map" is an added layer group to the existing National Heat Map with information about the the heat potential of the 4041 waterways in England. Heat potential of waterways are represented in temperature, surface area, flow rate and heat capacity (kJ/m^3 for coastal and estuary, kW for canal, river and settlement). It aims at supporting the plan of water-based thermal system as water-based heat pump [11]. The map revealed the large thermal capacity of water bodies that could serve over one million buildings in the UK [11].

2.1.2.2 Energy consumption prediction model

Kolter and Ferreira presented a modeling method to predict building energy end use in Cambridge, MA. They also developed a user application, "Energy View" with two target user groups: general public and local authorities. The model can be used by local authorities to identify energy usage outliers and by general public to compare their monthly energy consumption with predicted baseline consumption.

This case suggested how Dynamic Energy Map as a database can be combined with more complicated data analysis method that reveals more detailed spatial-temporal pattern. Their current time resolution of the energy consumption data prediction is on month. If the resolution increases to hour, the model could then be used to 1) assist better supply side control of energy generation 2) help individual users to better understand their energy usage behavior and provide more specific suggestions about energy saving behavior.

2.1.2.3 Smart Management of Urban Energy System

Energy Map also helps smart management of energy system in a large urban scale. "Smart Urban Services for Higher Energy Efficiency" (SUNSHINE) project is a European Co-Founded energy mapping project launched in 2013. The application is accessible through web page and smart phone or tablet application. It aims at developing a platform capable of 1) assessing building energy consumption behavior and create a 2D and 3D energy map, "ecomap" accordingly 2) providing automatic alerts regarding optimized usage of heating/cooling system 3) remote control of public building lighting systems [37]. The target users of the application include facility managers, policy makers, citizens and energy service companies. Function 1) is anticipated to help energy company and facility managers to identify energy consuming outliers, provide information for building pre-certification. Function 2) aims at providing more accurate baseline consumption data using weather and meter data. Function 3) allows better management of public lighting system based on illuminance requirements and weather conditions.

2.1.3 Combined Supply, Demand and Infrastructure

Dobbelsteen et al. described a framework of energy potential mapping that depicts information of energy supply, demand and infrastructure. Comparing with the previous examples, 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 [6]. 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 [6].

2.1.4 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 symbol design. For static maps, a poorly 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 3.2.3.

2.2 Dynamic Map

The majority of existing Energy Map instances or maps in general are static maps with no time information. One reason for such a lack of Dynamic Map instances, explained in [7], is the lack of proper software support, manifested as "unsupported data-format, inadequate interaction and rendering speed" [7,47]. Brownrigg claimed that the lack of software support also led to over-simplified implementations, which is justified from the instance search in result presented in the following section.

2.2.1 Energy Dynamic Map

Current Dynamic Energy Map instances are mainly 2D animated maps with very coarse spatial and temporal resolution. These instances include: State wind power capacity map that depicts the wind industry growth at state level from 2000 to 2050 [21], wind farm development map that shows the wind farm location and capacity development from 1975 to 2013 [20], solar plant development map that shows the solar plant location and capacity development from 1975 to 2013 [16], US Energy Production Map that shows state wise energy production from 1993 to 2012 [18], CO_2 emission map presenting world-wide carbon emissions from 1980 to 2014 [3]

One instance of energy demand dynamic map with high spatial resolution was found in the project "Energy Mapping to Identify Opportunities for Future Networks" [12]. The aim of the project is to "analyze the spatial and temporal distribution of energy consumption" and support decision making and design of energy network development. Energy Demand Maps of three different resolutions were created: campus level, community level and city level. Energy data was retrieved from both metered data (campus level map) and HEM simulation (community and city level map). For campus and community level maps, monthly heating demand density dynamic map and monthly electricity demand density dynamic maps are created with (kWh/m^2) as the unit. The energy demand is represented in a scale from blue to red, the same as the approach of the National Heat Map. The time dimension is added in the form of a non-interactive 2D animation . The problem for this animation is the lack of temporal and spatial legend and its non-interactive nature. Also the heating and electricity demand is represented separately, making the pairwise comparison of these two variables difficult.

However, the spatial analysis approach in representing small scale energy consumption data is questionable. With the building footprint clearly visible and centroid sparsely located on the map, it is easier and less confusing to aggregate the energy data on the centroid point or the building foot print rather than creating a density map.

2.2.2 History and Archaeology Instances of Dynamic Maps

More instances of dynamic interactive map exist in History and Archaeology practices as a result of the temporal nature of the subject. Pittsburgh Historic Map displays the urban environment layout of the City of Pittsburgh from 1835 to 2015 using a combination of historic maps and Google map as the base map. It allows users to navigate through the times with a time slider. It also contains point features of historic buildings [33]; Europe History Interactive Map that demonstrate the changes of political boundary with historic information associated to each political entity [65]. User can navigate through different historic period by forward and backward arrows and by clicking on specific entries to that period. Historic map instances focuses more on recording individual events, the temporal coherence and the space-time pattern are not as strongly emphasized as other dynamic maps that shows a dynamic process.

2.3 Works on Map Design

2.3.1 Symbol Chosen

Dong et al. assessed the effectiveness of symbol design and frame rate on the effectiveness of dynamic map display with two performance measurements: deviation and response time. They discovered the change of symbol size is more effective than color under the same frame rate. They also identified the optimal class numbers is 15 for graduated size symbol and is 10 for graduated color symbol on a 1024x768 display. The optimal frame rate identified in the study is 3 for color symbol maps and 6 for size symbol maps. They also suggest to reduce class number and frame rate if the display size is smaller than 1024x768 [22].

2.3.2 Bivariate Map Design

In order to represent heating demand and cooling demand on the same map together, a common map design problem is encountered: bivariate map design problem. Elmer presented eight possible types of representation for bivariate maps: "shaded cartographer, rectangle map, bar chart, value by alpha, choropleth with graduated symbol, bivariate choropleth, spoke glyph and shaded texture" [29]. In our current 3D representation, to incorporate the map symbol to the 3D model, the representation with dimensional changes are not suitable since they will distort the actual building geometry which makes the urban environment un-realistic. The only choices are the ones that only involves color or texture, i.e. "bivaiate choropleth, value by alpha and shaded texture". Among these three choices, bivariate choropleth representation has the highest accuracy rate, hence we choose bivariate choropleth as the representation of the current map interface design.

2.3.3 2D vs. 3D

As is mentioned in [7], the choice of 2D representation vs. 3d representation is one of the debating decisions in the world of data visualization [7]. 2D maps are easier to navigate and 2d map design has better theory support. 3D do not have sufficient map design theory, which make the design of 3D maps more difficult. 3D map is rich in geometry and can provide realistic scenes. This feature can both be an advantage or disadvantage based on the actual map usage. According to Tufte's data-ink ratio theory, the extra non-crucial richness of information should be eliminated to make the most important bits of information stand out [58]. There might be cases when the third dimension add no new information to the data display and thus should be eliminated.

2.3.4 Data Classification

The commonly used GIS software surveyed in the study include, ArcGIS [30], GRASS GIS [5], gvGIS [8], and QGIS. The data classification method adopted by the surveyed software in creating a thematic map include: 1) equal interval, 2) quantile 3) Jenks 4) Standard Deviation 5) pretty breaks 6) manual interval (use context specific break point values). The common data classification method shared by all surveyed instances are "Equal Interval", "Quantile" and "User Defined". Therefore we chose to implement the "Equal Interval" and "Quantile" method in the current project.

	Equal Interval	Quantile	Jenks	Pretty Breaks	StDev	User Defined
ArcGIS	o	o	o	x	o	o
GRASS GIS	o	o	x	x	o	o
GVSIG	o	o	o	x	x	o
QGIS	o	o	o	o	o	o

Table 1: Data Classification Method (o: yes, x: no)

2.3.5 Spacetime Map Design

Dorling and Openshaw pointed out that dynamic map provide new potential and possibilities for data analysis but also pose a great challenge as a result of the less developed theory in space-time pattern detection and measurement [23].

2.3.5.1 Time Representation

Brownrigg mentioned several methods of representing time on a map: 1) a graph or chart that represents a function over time or a time line for displaying chronological events 2) animation of snapshots 3) small-multiples of snapshots of changing states [7].

Based on this classification, the current interface design applied method 1) and 2) in time representation. The dynamic plot of temporal time series is using method 1) to anchor the quantitative information. The interactive animation approach is using method 2) for choropleth map display, as is apposed to method 3)(small-multiple method). The choice is based on the following points mentioned by Brownrigg: 1) the number of snapshots in one display is limited and the finer the detail per snapshot, the less snapshots one can contain in one display. Since the 3D representation is chosen as the major map display method, the level of details per image is high, which will result in a very small number of multiples per display 2) the subtle changes are easier to be noticed in the form of animation than with small-multiples. Both drawbacks of small-multiple method will impair the ability of conveying the rapid temporal changes of energy behavior, hence is not suitable for the current project.

2.3.5.2 Animated Maps

As is mentioned in section 2.1.4, the majority of the map design of Energy and Dynamic Energy Maps are not thoroughly considered and contain too much distraction. Hence the authors think it is helpful to conduct theory and case studies of temporal-spatial map design in the current project of Dynamic Energy Map.

In order to represent dynamic geographic processes, map animation is a natural choice. It was introduced to the world of cartography in 1930s [40]. The major application of animated maps include: 1) demonstrating the dynamic process of geographic events (weather maps in weather forecasting is such an example) 2) assisting pattern recognition and knowledge development for scientific researches. The study by Dorling and Openshaw is an example of application 2), where they discovered new leukaemia hotspots through animated maps [23].

Harrower and Fabrikant mentioned that the chanllenge of using animated maps is the overflow of information and the vulnerability to distraction. One example mentioned by Harrower and Fabrikant is the comparison of color on the map and that on the legend becomes difficult for animated maps as a result of the changing of images. This issue is considered in the current Dynamic Energy Map interface design, with a series of tick marks that pointed out the colors used on the map, for more details, please refer to section 3.6. They also proposed the audio legend approach of strengthening information convey with minimized distraction [40]. This might become one of the next extensions of the current Dynamic Energy Map interface design.

They also suggested that the difference in time should have different visual representations in data display [40]. Peuquet claimed that "The development of temporal analytical capabilities in GIS such as temporal queries requires basic topological structures in both time and space". Thus the different spatial representation seems to be a natural choice for adapting to different temporal resolution and scale.

They classify time into two types: linear and cyclic. Upon this consideration, the design of the current interface include both an overall time navigation utility and time navigation utilities that facilitate jumps with time steps corresponding to the natural period of energy data, such as month, day and hour. This design choice is anticipated to facilitate the representation of both linear changes and periodical changes of energy usage in the community.

The level of user control of playback behavior of animated maps is also debatable. Some claim providing the full freedom of adjusting this feature can enhance pattern understanding [45]. But others argue that this control will reduce time animation to still images and impair its ability in conveying temporal changes [48].

2.4 Spatial Temporal Data Analysis

In order to better utilize the power of Dynamic Maps, one has to understand the special features of spactial-temporal data and the methods of how to use spactial-temporal data. This leads to the literature study of the following section of spatial temporal data analysis.

One temptation of analyzing spatial-temporal data is to aggregate them into "time periods" and "zonal entities" and then use the static analysis method to analyze the aggregated data [23]. The problem of this approach is 1) it increases the sensitivity (i.e. minor changes in input causes dramatic changes in output) and 2) it removes the "dynamic" feature of a dynamic map [23].

One layer of the goal of a space-time map is to make "complex dynamic process" visible, in the hope of letting observers comprehend the dynamics of data presented and to gain a general insight. Baring this goal in mind, Dorling and Openshaw suggested a noise removal or data smoothing in both the time and space dimension before the actual map creation [23].

2.5 Works on Technology Regarding 4D Visualization and Interface Design

The next step for the current project is to create an on-line platform that enables easy map share and design collaboration. The following section contains some information of possible technologies for this possible extension.

Resch et al. presented a nice summary of existing web-3D and 4D visualization technologies [55]. Early approaches for web-based 3D map display are based on VRML, X3D or similar instances. Their drawbacks are the requirement of additional add-ins and their limited ability in handling large amount of data. Later approaches include some Java-based or WebGL based tools. Zipf used OpenStreetMap, Shuttle Radar Topography Mission and

Java based xNavigator to display 3D maps with a Java based plug-in [67]. WebGL based approaches include: a campus information system by Hering et al. [42], a Geo-visualization system with "browser-server" architecture by Feng et al. [34], an open source software OpenWebGlobe developed by Loesch et al. , WebGL Earth project by Klokan Technologies [57] and Cesium project by Analitical Graphics [1]. Cesium also support "time-dynamic graphical scenes" [2]

3 Methodology

This section demonstrate the Dynamic Energy Map implementation used in the project.

3.1 General Work Flow

The Dynamic Energy Map is created with a conceptual urban environment whose building density and land use pattern resembles an existing urban environment. The number of buildings in the model represents a typical sized community that can be served by a district energy system.

The inputs to the dynamic energy map are the energy consumption data and the urban environment layout. For the conceptual setting, the energy data is retrieved from the simulation of DOE Benchmark buildings, the urban environment layout is created so that it follows a typical urban environment land use pattern. The output of the dynamic energy map is a sequence of 2D or 3D energy choropleth maps . An interface is designed to provide an interactive inspection of the map sequence and create dynamic data plots (Figure 2). By replacing the simulated energy data with actual metered energy consumption data and the conceptual layout with a real urban environment layout, the same method can be directly applied to the analysis of a real project.

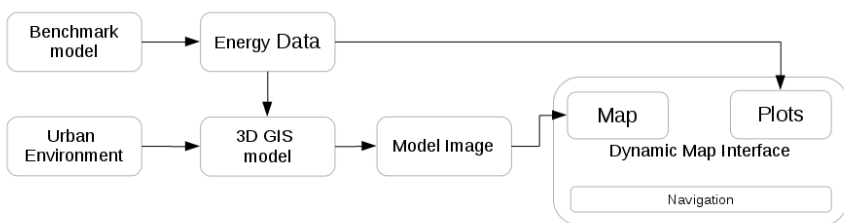

Figure 2: General Work Flow

3.2 Input

3.2.1 Energy Data

The energy profile used in the study is retrieved from simulation results of commercial building benchmark models developed by U.S. Department of Energy (DOE) [52]. The building types involved in the current project include: Large Office (LO), Medium Office (MO), Small Office (SO), Stand-alone Retail (SR), Supermarket (SU), Quick Service Restaurant (QR), Full Service Restaurant (FR), Large Hotel (LH) and Midrise Apartment (MA). The two-letter shorthand in the parenthesis after each building type is used in the building label for the dynamic map and the box plot labels in section 3.3.1. The general information for the benchmark buildings are shown in Table 2:

3.2.2 3D GIS Model

The conceptual community model is constructed in CityEngine [32]. CityEngine is a software developed by Esri. It can aggregate geographic information into buildings and is capable of

Building Type Name	Shorthand	Floor Area (ft2)	Number of Floors
Large Office	LO	498,588	12
Medium Office	MO	53,628	3
Small Office	SO	5,500	1
Warehouse	WH	52,045	1
Stand-alone Retail	SR	24,962	1
Strip Mall	SM	22,500	1
Primary School	PS	73,960	1
Secondary School	SS	210,887	2
Supermarket	SU	45,000	1
Quick Service Restaurant	QR	2,500	1
Full Service Restaurant	FR	5,500	1
Hospital	HO	241,351	5
Outpatient Health Care	OP	40,946	3
Small Hotel	SH	43,200	4
Large Hotel	LH	122,120	6
Midrise Apartment	MA	33,740	4

Table 2: DOE Benchmark Building General Information [52]

smoothly transition models to ArcGIS [31], one of the widely applied tools for Geo-referenced data presentation and analysis. Buildings in CityEngine is defined with "rules" using CGA (Computer Generated Architecture) shape grammar that is unique to CityEngine. The rule-based modeling of urban environment enables fast construction and easy adjustability of urban density, skyline and terrain control. It also enables easy aggregation of Energy profile data into 3D urban environment models.

Although the urban environment in this study is a conceptual setting, we still want it to reflect the topological and density pattern in a real urban environment. To construct the model, we first extracted the topological pattern from an existing urban design project, the Mellon Arena Project [4] (Figure 3. There are eight building types in the project: Residential (43%), Town House (2.9%), Community Center (0.4%), Commercial (3.8%), Office (19%), Hotel (4.7%), Cinema (1.4%) and Garage (24.7%). The 16 building types in DOE commercial benchmark models do not perfectly correspond to those in the Mellon Arena Site. In order to adapt the topological pattern of the Mellon Arena Project, a mapping (function) from building types of Mellon Arena Site to building types of DOE models is created as is shown in Table 3.

The four major building sectors involved in the current project are residential, commercial, office and hotel. Their topological pattern is represented in Figure 5. The conceptual model construction follows the building type topological pattern and the urban density as the Mellon Arena Project (Figure 6)

Figure 3: Mellon Arena Project Site Plan View

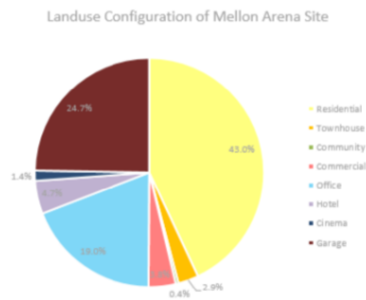

Figure 4: Mellon Arena Site Land use Configuration

Mellon Arena Type	Probability	DOE Building Type
Hotel	50%	Large Hotel
	50%	Small Hotel
Office	30%	Large Office
	30%	Medium Office
	30%	Small Office
Residential	100%	Midrise Appartment
Townhouse	100%	
Commercial + Cinema + Community Center	25%	Full Service Restaurant
	25%	Quick Service Restaurant
	25%	Super Market
	25%	Stand-alone Retail

Table 3: Mapping of Mellon Arena to Building Types of DOE benchmark model

3.3 Data Collection and Analysis

3.3.1 Simulation Data Analysis of the benchmark models

The output of EnergyPlus simulation of 16 benchmark buildings are read and processed with python script. This data loading and processing module is used in both data analysis and the dynamic plot in the interface design.

By analysing the simulation result of the Heating Energy (Gas) and the Cooling Energy (electricity), we observed a large variation between different building types.

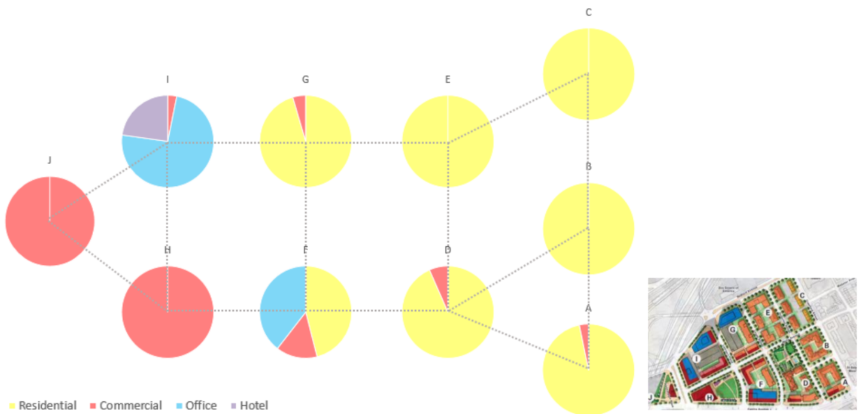

Figure 5: Building Type Topological Pattern, Mellon Arena

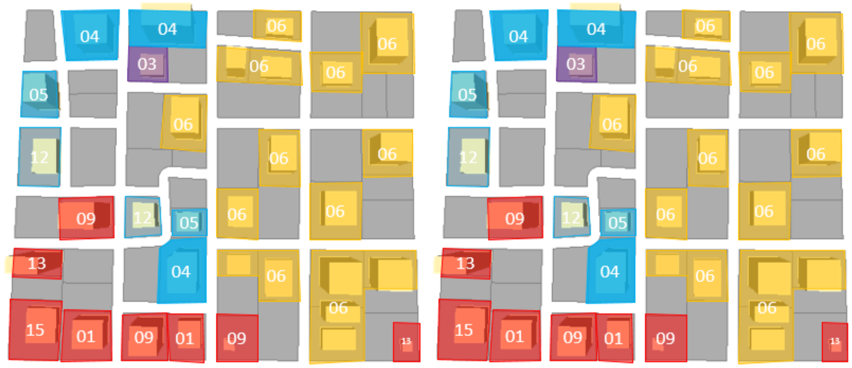

Figure 6: Site Plan of Conceptual Model
(01: Full Service Restaurant, 03: Large Hotel, 04: Large Office, 05: Medium Office,
06: Midrise Apartment, 09: Quick Service Restaurant, 12: Small Office,
13: Stand-alone Retail, 15: Super Market)

Hourly heating demand of the benchmark building types involved in the current model range from 0 to 12000 kBtu. The majority (75%) of all hourly consumption are below 2000 kBtu. All building types have a large amount of outliers on the upper side. This indicates heating demand of all building types are right skewed. The building type with highest median heating demand are Large Hotel and Super Market. These two building types could become the major "heat sink" or anchor load building to be connected to a district system. In terms of peak demand, Large Office has the highest peak heating demand (Figure 7).

Hourly cooling demand benchmark building types involved in the current model range from 0 to 2500 kBtu, which is about 20% of that of the peak heating demand. Large Hotel has no outliers on the upper side, meaning its hourly consumption are not as right skewed. Only Large Hotel has non-zero median cooling demand (about 600 kBtu), meaning it is the only building that has persistent cooling demand all year-round . The design impact is: Large Hotel can act as an anchor building for cooling if the central plant is a heating-cooling combined system that can supply cooling energy as well. The consistent high cooling load of Large Hotel also indicate a high portion of heat rejection. The reject heat could be recovered and reused if building with moderate heating demand are placed near the heavy cooling consumers (Figure 8).

The aggregated analysis above intends to provide a basic understanding of the energy profile data distribution involved in the current project. We anticipate to acquire more information than these aggregated statistics with Dynamic Energy Map.

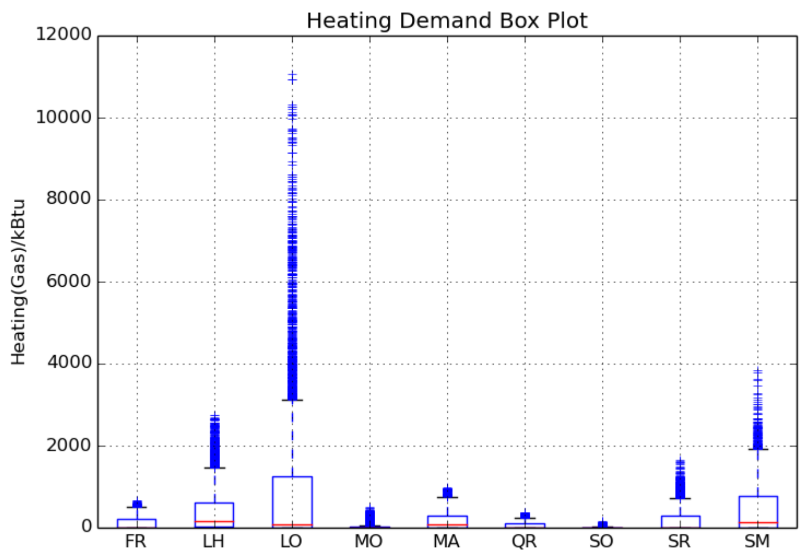

Figure 7: Heating Demand Box Plot

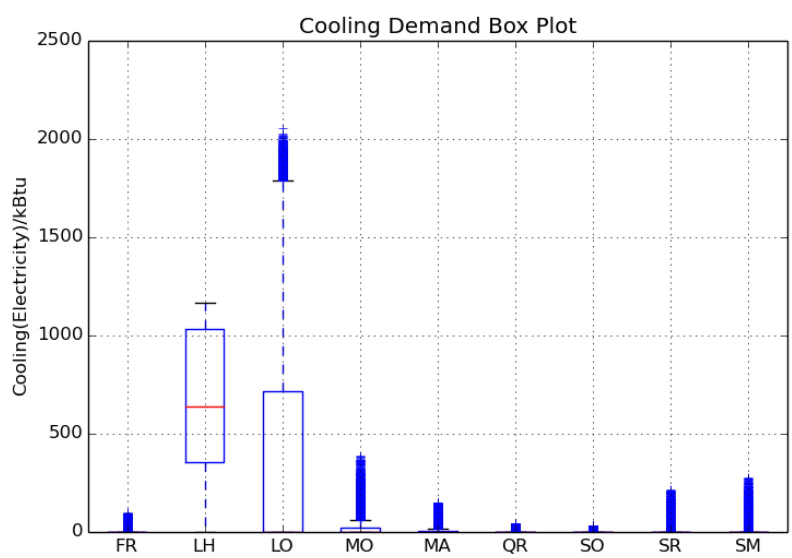

Figure 8: Cooling Demand Box Plot

3.4 Temporal Data Aggregation

The authors have experimented with two approaches to aggregate energy profile data into the conceptual model constructed in CityEngine: 1) write the energy profile data directly in the rule file for building generation in CityEngine 2) importing 3D models from CityEngine to ArcScene and aggregate the energy data into the 3D feature with "one-to-many" join.

The second approach has the advantage of 1) ready-to-use data classification method and map symbol templates that facilitates choropleth map design 2) the "time-slider" function for creating a time-wise navigation and animated map. Figure 9 shows the interface slider and the dynamic map of heating energy demand for the conceptual model using ArcGIS. There are several problems of this approach: 1) its high requirement of computational power makes it infeasible to view on a normal PC. 2) The time dimension only exist inside the map file. Although the animated map can be exported, the output animation contains neither any form of temporal label nor the control of playback. 3) For 3D GIS model, it does not contain a proper function to extract single frames of map images, making it impossible to implement exterior interface that deals with 3D maps.

The first approach, on the contrary, provides more flexibility but also requires much user-end work including: pre-processing of energy profile data, implementing data classification method and the bivariate color ramp. An interface is also needed for visualising the image sequence.

Figure 9: ArcGIS Time Slider for Temperal Data Display

Due to limited time, the experimented GIS software are only restricted to ArcGIS and CityEngine. There could be better alternatives to achieve a dynamic map with more elegance. Find a better alternative software to implement a dynamic map could be part of the work of the next stage of the project.

3.5 Interface Specification

3.5.1 User Definition

We want to specify a user profile in order to best convey the information with the Dynamic Energy Map.

The major category of user group for the Dynamic Map includes: 1) policy makers, 2) urban planners with the interest in executing community level energy strategys 3) researchers in energy related fields 4) public groups or individuals that are involved or interested in the decision making process of community energy planning.

The target user for the current interface design is restricted to researchers in energy related fields. The assumption on this user group about their skill level and background knowledge is that 1) they have the basic ability to read and understand the layout of a map environment and can associate it with the urban environment setting they are associated with 2) they have the ability to correctly understand moderately complicated map legend and data plot 3) they have the basic understanding of related concept of building energy performance attribute and the general implications of these attributes. The assumptions about their intention is that they might have different research interest and focus. These assumptions implies the interface design should: 1) provide both qualitative and quantitative information; 2) allow for some degree of user control over data classification, legend selection and full control over time navigation

3.5.2 Goal Function

The goal function of the interface is defined as: "**Revealing the spatial-temporal heating and cooling demand variation of the conceptual model with Dynamic Energy Map**."

As is mentioned in section 1.5.4.1, with the Dynamic Energy Map that depict the spatial temporal load variation, one will idealy be able to 1) idendify anchor load building, 2) conduct better design of local load balancing, 3) identify energy recovery opportunities of the following forms: an individual building with mixed heating or adjacent buildings with opposite heating and cooling demand.

1). Identify anchor load building

    To achieve this function, the map should be able to make the building with persistant high heating or cooling demand stand out. Thus the design of color scheme that assigns vibrant colors to high demand and white to low demand. The break points of "high" demand remains to be decided in further project development. For the current implementation, the break point is acquired with quantile classification method with.

2). Local load balancing

    To achieve this, the first step would be to enable users to select a subset of the existing buildings and the program will calculate the aggregated maximum load and the load variation of the selected building group within the specified time period.

    The next step is to provide a utility that finds the optimal partition of the buildings in the urban environment that has the minimum load variance ratio within the group difference. A brute force approach would be:

Step I. Generate an adjacency table (dictionary) from the collection of building lot polygons with the key being building lot centroid labels.

Step II. Create all legal partitions of the set of building centroids based on the adjacency table (i.e. a partition that includes a multi-part feature is not a legal partition)

Step III. Calculate the sum of the load variation ratio for each of the legal partition. The load variation ratio for each subset of the element in a partition (a group of building) equals

$$\frac{\text{max aggregated load} - \text{min aggregated load}}{\text{max aggregated load}}$$

Step IV. Find the partition with the minimum sum of load variation ratio

3). Identify energy recovery opportunities

To achieve this, the heating and cooling demand should be represented on the same map that better depict the correlation.

3.5.3 Specification of the Major Operation

The desired major operations for the target user include:

- Map display and data plot
- Navigation utilities that navigates through dynamic map and data plot
- Provide default settings for choropleth map display

3.5.3.1 Map display and data plot

For researchers or planners: The desired map display should be a 2D and 3D map (providing easy toggle between 2D and 3D map or align the two representations side by side) with graduated symbol or color representing the heating or cooling demand. The map display should also be coupled with corresponding data plot or data statistics that providing the quantitative insight that supports design decisions.

For general public: The desired map display should be a 3D map . Instead of using data plot, a more intuitive bar chart of the aggregated demand could be more helpful in presenting a general idea. The bivariate choropleth map legend should also be replaced with two color ramps or even with only colors of extreme value. The data classification method should also be chosen so that the peak occurrence time is emphasized rather than the absolute energy consumption value.

3.5.3.2 Navigation utilities that navigates through dynamic map and data plot

The ability to navigate through a series of map images and present dynamic data plot accordingly, is the basic function that differs the current work from a static map. Some desired behavior of the slider includes:

- Linear and cyclic time representation. According to section 2.3.5.2, the time has both linear and cyclic aspect. The time navigation utility should provide both "linear" time navigation and "cyclic" time navigation. This requires a global time navigation that accounts for the linear aspect: it can go through the whole time period with the highest time resolution. It also requires a series of default time steps settings corresponding to the natural recurring pattern of the energy usage profile

- Another desired feature is providing adjustable auto-play of the map animation. The reasoning behind this is the debatable level of user control in the study of Johnson and Nelson [45], when they argue that allowing arbitrary time control might degrade the ability of animated map on conveying temporal pattern. This feature is to be implemented in future development of the project.

3.5.4 Provide default settings for choropleth map display

Creating several default settings for choropleth map display, i.e. provide choices for data classification and color mapping. For the current implementation, the variables in display is the heating and cooling energy consumption profile. The customization choices only restrict to the two classification method: even or quantile method. The color ramp is predefined to be a bivariate color ramp from white to red and blue. For later stages, a desired behavior would be to provide the full control of color settings.

3.5.5 Guidelines from Literature Study

Here we summarizes some of the design choices made according to related literature research on dynamic map design:

- Provide both 2D and 3D map display as a result of the debating situation mentioned in section 2.3.3.

- Choose bivariate choropleth map representation which has the highest accuracy rate in map reading experiments [29].

- Providing the most commonly used data classification method: Equal Interval and Quantile Interval 2.3.4

- The number of classes for energy data classification is chosen to be 7, less than the suggested value of 10 as a result of smaller display size than 1024x768 [22]

- Provide both linear and periodical navigation based on section 2.3.5.1

- Using the principle of "dual coding" [55] to assist legend reading by section 2.3.5.2.

- Noise removal in map display of energy profile data [23]. This is done through the discrete color scheme design.

3.6 Interface Design

3.6.1 General Layout

The interface for dynamic map display includes three major sections: a series of sliders for controling images are on the left and the data plot of energy profile of building sectors and aggregated demand are on the right.

The main window on the top left is used for displaying the 2D dynamic map of the conceptual model. The lower left of the window displays the current time for the image and dynamic plot in display. The lower left section contains a series of sliders for controling interactive navigation of image and plot sequences. The right hand side of the interface contains the dynamic data plot of the four major building sectors: Hotel, Office, Residencial and Commercial buildings. The lower right are the aggregated heating / cooling demand profile for the whole site. The left column are the heating energy consumption in natural gas and the right column are the cooling energy consumption in electricity. On the lower right there are four buttons providing two default forward and backward navigation, 1h and 24h. (Figure 12). Between the aggregated heat demand and the sliders, there is a choropleth legend. According to section 2.3.5.2, the comparison of the map and the legend becomes tricky for dynamic maps. In order to assist this task, tick marks of "x" are added to the legend to indicate the color appeared in the map Figure 13.

3.6.2 Navigation Function

The navigation function is achieved with the four slider and the four buttons above the sliders on the lower left of the window. The top slider labeled with "Year round" has a range of 0 to 8760 (not inclusive). the change of 1 in the slider position corresponds to the change of 1 hour in time, which results in the display of the image of the next or previous hour in time. The slider labeled with "month" has a range of 1 to 12, which corresponds to the 12 months in year, the change of the month slider results the jump of 1 month forward or backward in time. This function is intended to provide easy comparison of montyly variation of the energy consumption behavior. Similarly, the change of the "date" and "hour" slider corresponds to the time change of one day or one hour respectively. The four buttons provides a separate control intended to provide micro level adjustment of time.

3.6.3 Dynamic Plot

The input images to the main window is generated from the CityEngine model. The graph is ploted by reading in simulation data from EnergyPlus. The starting point (left end) of the plot corresponds to the position indicated by the slider.

3.6.4 Implementation tools and strategy

The softwares or platform involved in the project include EnergyPlus for building simulation, CityEngine for 3D modeling and image generation, Python 2.7 for interface design. The interface is written in Python2.7 with standard Tkinter graphic package including the data plot section.

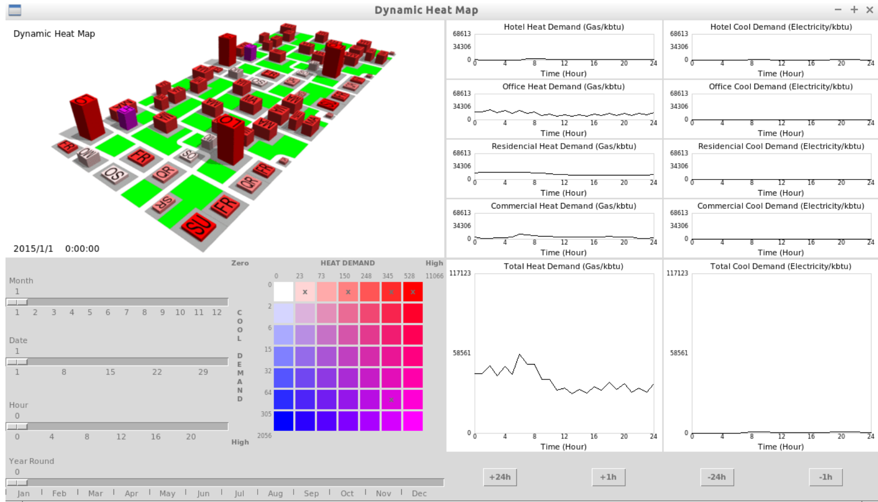

Figure 10: Dynamic Map Interface Layout (3D map)

Figure 11: Dynamic Map Interface Layout (2D map)

Figure 12: Dynamic Map Interface Layout

4 Case Analysis: Using the Current Dynamic Map to Design a District Energy System

This section uses the tool assist the design of a district energy network. The common steps in conducting such a design follows the guidance of [46]. The goal of the case study is to demonstrate how dynamic energy map can do better than static map in assist the design of a district system and in demonstrating the advantage of a district system. The major performance metric comparing the static and dynamic map is the energy throughput.

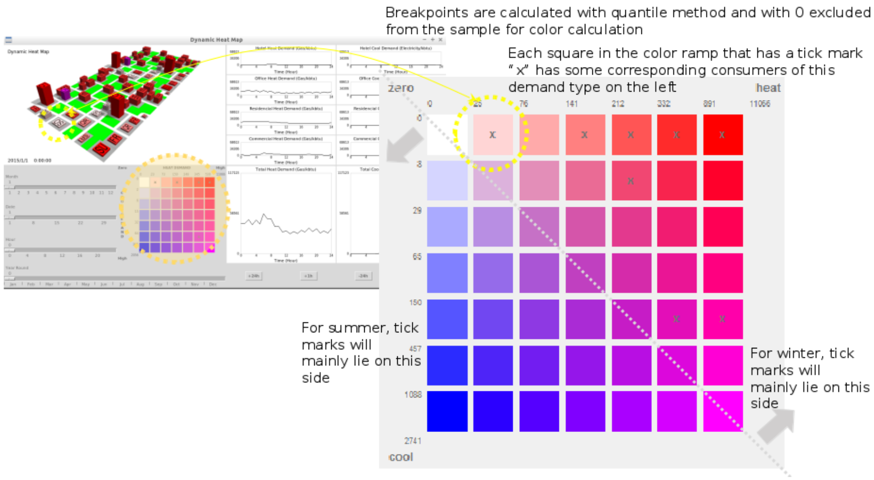

Figure 13: Bivariate Color Legend with Tick Mark Indicators

4.1 Using Static Energy Map

4.2 Using Dynamic Energy Map

5 Findings and Discussion

One of the point of having a visualization of dynamic map is, as Dorling and Openshaw suggested, to detect mistakes that could otherwise be neglected under a black box calculation routine or some false application of rule of thumbs [23].

not finished

6 Conclusion

References

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