Dynamic Energy Mapping Project Outline

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1 General Introduction

1.1 Project Overview

The burning of fossil fuels produces green house gas (GHG) and causes significant global climate changes including global sea level rise, temperature rise, ocean warming, ice sheet melting and extreme weather event [28]. Fossil fuels are finite: studies have shown that if the consuming rate of fossil fuels remain the same, the major fossil fuels including oil, gas and coal will run out by the end of the century [16,24]. Governments began to put reducing GHG as one of their major goals: the "Climate Change Act" of UK aims at reducing GHG emissions by 80% comparing to 1990 by 2050 [6], the City of Calgary aims at reducing CO_2 emission rate by 50% by 2050 [1].

Reducing GHG emission and fossil fuel consumption also took place on the community level. Community Energy Management (CEM) is a combination of community level design strategies and energy management strategies aiming at providing quality of life in an urban environment with minimized energy consumption and environmental impact [23]. It contains "land use planning", "transportation management", "site planning" and "local energy supply and delivery planning" [23]. Community level energy planning and management achieves GHG reduction by means of :1) improving energy usage efficiency, 2) conserving the use of high quality energy and 3) switching to using more renewable energy source [7].

Energy Mapping makes the community energy planning alternatives visible to planners and policy makers [2] and thus flourishes under this trend. Emerging explorations on the functionality and the power of Energy Mapping in assisting community energy planning are taking place all over the world. City of Calgary carried out an Energy Mapping Study that aims to "provide clear direction to the City and inform the private sector about the potential to reduce greenhouse gas emissions and encourage the use of alternative energy systems, through considerations such as the design of buildings and encouragement of more compact, mixed-use and high density communities." [2].

What information should an Energy Map hold and in what form should the information be conveyed or displayed is still not completely agreed between different approaches. Calgary Energy Mapping study depicts annual average energy use intensity and alternative renewable energy supply region [1]. London Heat Map contains mainly heating energy related features: high heating energy consumers, suppliers and district heating networks. Dutch Heat Map, an application of the EPM method, contains information of annual heating energy demand (or demand density), heating energy supply (or supply density), infrastructure network layout and CHP and Biomass plant location.

However, as suggested by Baird et al. existing Energy Mapping practices are mainly static, i.e. the time-dependent changes of energy demand and supply information is not included in these Energy Maps nor do they support more advanced community energy system analysis and comparison. Thus the concept of "Dynamic Energy Map" was brought about: It acts as a geo-database that holds 1) hourly energy profile data for each building and the aggregated energy profile data for the whole community; 2) hourly energy supply data of community decentralized energy sources [2].

With the Dynamic Energy Map, the temporal behavior of the demand and supply of heating, cooling and electricity are revealed and are available to be compared, analyzed and updated. For example, the Dynamic Energy Map will show the spatial and temporal changes of peak energy demand and supply and verifies whether and how well the supply meets the demand over time. A Dynamic Energy Map is also connected to simulation software [2], and can act as a key component of Geo-design that encompasses "geo-spatial modeling, impact simulations, and real-time feedback to facilitate holistic designs and smart decisions" [17]. The development of data-driven approaches and machine learning methods could also be coupled and can perform more complicated analysis of spatial-temporal behavior of energy data and provide more informative design or management support.

An initial instance of Dynamic Energy Map was created by Baird et al. in 2011-2012. The map consists of two parts: a geo-database that holds general building information (name, conditioned area) annual and monthly energy usage information (energy use intensity, annual peak demand value and monthly peak demand value); an excel screening tool that holds hourly energy usage information of each building and performs analysis and system comparison of a district energy system [2].

1.2 Objective and Problem Definition

Appealing to the definition of Dynamic Energy Map [2], its major functions could be summarized as: 1) holding, 2) visualizing and 3) analyzing community level high spatial-temporal resolution energy demand and supply data 4) connection to simulation engine for iterative performance analysis. In the initial instance of Dynamic Energy Map by Baird et al. [2], function 1) of holding spatial-temporal (although with low temporal resolution) energy data is realized. Function 4) of connecting to building simulation data is also realized by importing simulation result csv files to the geo-database (although with low temporal resolution). Function 2) visualizing and 3) analyzing high resolution energy data remains to be done.

For function 3), although the geo-database and the analysis is conducted separately, it is possible to export the analysis result and aggregate it to the geo-database. For function 2), the spatial and temporal information are visualized separately: the spatial information of 3D building geometry and location could be visually inspected in the geo-database but not the hourly energy consumption information. 2) The temporal visualization of energy demand is done separately in the excel screening tool as 3D graphs, but no spatial context is present and the spatial dimension is then lost. The authors thus identified the crucially missing function: the visualization of such a spatial-temporal changing of energy behavior as the major goal of the current project.

The objective of the project is thus defined as to 1) implement a Dynamic Energy Demand Map with the focus on creating a high-resolution spatial-temporal visualization of hourly thermal energy consumption data for each building, major building sectors and the whole community 2) testify the its use in optimizing the arrangement of land use pattern to improve the community level energy performance in terms of aggregated thermal energy demand variation and 3) support sizing of a district thermal energy supply system.

The community model is created in City Engine [19] based on the land use pattern of a mixed-use redevelopment project at Lower Hill District, Pittsburgh, PA [31]. The model contains 68 buildings, comparable to a typical service area of a district thermal energy system (combined heating and cooling), about 50 to 150 buildings [22].

The hourly heating (gas) and cooling energy (electricity) consumption profile is retrieved from DOE Commercial Benchmark Building simulation [29]. An interface was designed to combine the 8760 heating-cooling energy choropleth map images from City Engine and the 8760 hourly heating-cooling energy data from EnergyPlus to form a Dynamic Energy Map. The interface provides users with the functions of 1) navigating through the dynamic map images, 2) dynamic data plots of single buildings, building sectors and aggregated community thermal energy demand.

1.3 Related Concepts

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

1.3.1 District Energy System

A district energy system is one form of Decentralized Energy System, a "local or sub-regional supply of energy from a local source." [30]. It brings the energy generation near to the energy end users and reduces the energy transmission and distribution loss [8].

A district energy system produces thermal energy in a central plant and deliver the thermal energy to local buildings through a closed-loop pipeline network. Thermal energy are delivered in the form of steam, hot water or chilled water [2]. The central power plant can take on one of the following forms: 1) thermal power plant that only generates thermal energy, which can be either heating or cooling energy 2) co-generation system, or combined heat and power (CHP) system, that generates electricity and reuses the reject heat from electricity generation to serve space heating and service hot water to local buildings [22] 3) tri-generation system, where the central plant uses the heat generated by CHP plant to produce chilled water and supply both heating and cooling energy [5]. Corresponding to the different types of power plant, the network delivering thermal energy can be classified as 1) district heating network that only delivers steam or hot water 2) district thermal network that delivers both heating energy in the form of steam or hot water and cooling energy as chilled water.

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

- High energy generation efficiency

  Higher energy usage efficiency means with the same amount of input energy, more useful energy is produced and less are wasted. Buildings' electricity supply are mainly from centralized power plant that are far away from cities. Heat produced in power generation are normally dumped into oceans and lakes [2,25], not only causing negative environment impact [37], but also reduce the power generation efficiency to be only about 1/3 [25]. District Energy System has high energy generation efficiency as a result of 1) it can utilize high efficiency large-scale energy generation equipment [22] and 2) it is closer to the energy end user which reduces the energy loss due to transmission and distribution [25].

- Better Exergy Performance

  The quality of energy is usually described with exergy. It is defined as "maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir" [34]. It represents the energy one can get out of the system. One example of a District Energy system helps improving exergy performance and better match the thermal energy supply and the low and medium-quality building energy demand [4] is the low-temperature (or low-energy) district heating system [38] which has a supply temperature of around 50 ^{o}C and return temperature of around 25^{o} C [38].

- Multiple fuel choices including renewable energy sources

> The central plant of a district energy system can use a broad range of fuel choices including natural gas, oil, coal, waste, and renewable energy sources including geothermal, solar thermal and biomass, in the generation of thermal energy. This makes the switch to large scale renewable energy source possible. It also makes the district thermal energy system more flexible and more competitive in the market and increases the energy system resilience [22, 25].

It also reduces the space and cost dedicated to installation and maintenance of HVAC systems in single buildings. It also reduces harmful gas emission of NO_x, SO_x by using non-combustion energy sources as lake body and by filtering [25] the flue gas [33].

1.3.2 Heat Map

Although "heat map" is generally accepted as "graphical representation of data where the individual values contained in a matrix are represented as colors" [35], with respect to buildings, a "heat map" may be defined as "a spatial plan of existing and planned building heat demand, and decentralized energy networks and generation equipment" [8]. It is also a GIS "live database" that allows new development information to be incorporated. It is a key component to the decentralized energy master plan [8]. One of the well-known instances of a heat map is the "London Heat Map" [26]

1.3.3 Energy Map

International District Energy Association (IDEA) define Energy Map as: "a tool that can be used to organize/present data as the basis for defining energy character areas as part of energy planning" [25]. It is a "GIS based system" that can be used to develop energy strategies, prioritize project, identify potential growth opportunities and impose planning restrictions [25]. Dobbelsteen et al. adopted the term "Energy Potential Mapping" that assist the development and plan of a sustainable built environment. It is a method that "visualizes local energy potentials and demand in order to support spatial planning towards more energy-efficient urban or rural environment" [4]. UK used the "Decentralized Energy Masterplanning" as a method that helps local authorities identify low carbon strategies that "maximises the opportunity for large-scale schemes to capture and use waste heat from major energy sources" [8].

With respects to the various definitions above, an Energy Map could be understood as a generalization of a heat map that includes energy supply, demand and infrastructure information of various energy forms and technologies. Some existing use cases of suggest an Energy Map could be used to visualize the community or city level energy demand reduction with high performance building design [1] or adoption of alternative energy supply technologies [1]. It can be used in supporting district heating system design [8, 21] by visualizing the heat sources and sinks.

1.3.4 Dynamic Energy Map

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

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

1.4.1 Strong Temporal Variation of Energy Demand

Different building types often indicates different energy demand profile. For example, the residential building heat demand profile has two major peaks, morning and evening, and is relatively low for the rest of the day. For office buildings, there is a peak heat demand in the morning and a relatively high heat demand through the day time but drops in the evening. Hospitals usually have a more flattened demand throughout the day. Within a mixed-used urban environment, the arrival of peak demand for different buildings are usually not simultaneous [8].

In the design of a district energy system, mixing building types with different time-of-use energy profile can be helpful in creating a less variate aggregated energy demand. This allows the central CHP plant in a district energy system to a have higher utilization rate and reduces the need for backup plant that accounts for high peak demand [8].

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

One common mistake for sizing a district thermal energy system is to add up the peak demand of each terminal users. Since the peak demand of individual buildings do not occur at the same time, the end result of summing up the peak demand at each end point exceeds the actual total demand peak of the community, hence with this approach, the whole district system becomes excessively over-sized, which reduces the whole system efficiency. A Dynamic

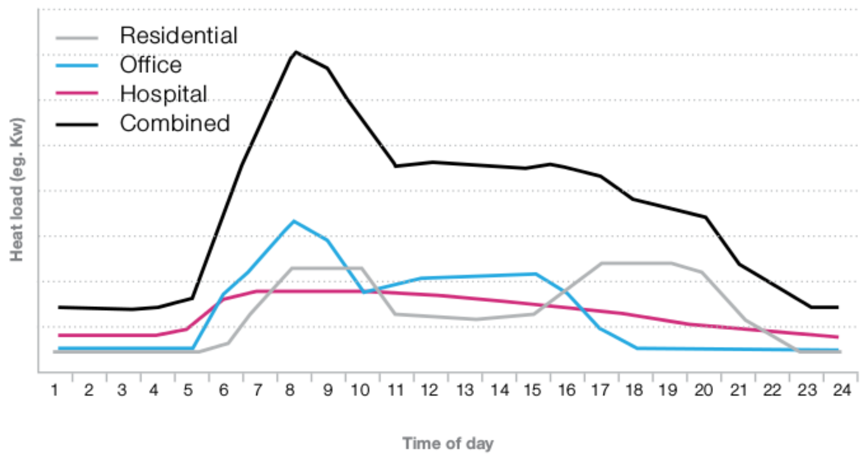

Figure 1: Mixing Load of Different Building Type [8]

Energy Map can reveal the problem of such approaches by directly providing the aggregated thermal energy demand for the community and for single buildings or building sectors. It allows a side by side comparison of single building demand and aggregated demand and eliminates the misunderstanding of the demand aggregation. With the direct information of aggregated thermal energy demand, it also assists actually sizing a district thermal energy system.

2 Related Works

Section 2.1 and section 2.2 provide an overview of the existing instances of static energy maps and dynamic energy maps. A list of summary of techniques used in the production of Static and Dynamic Energy Map instances are as in Table 1:

Project Name	Type	Software
Calgary Map	Static, Stand-alone	?
London Heat Map	Static, web, interactive	?
National Heat Map	Static, web, interactive	Google Map API
Water Source Heat Map	Static, web, interactive	Google Map API
Dutch Heat Map	Static, Stand-alone	?
Lowe Hill District Map	Dynamic, web, interactive	ArcScene, ArcMap, GIS Cloud, excel
Energy Mapping to Identify Opportunities for Future Network	Dynamic, Stand-alone	QGIS

Table 1: Map Technology Summary Table

2.1 Static Energy Map

2.1.1 Calgary Energy Map

One of the early instances of Static Energy Mapping practices is the Energy Mapping Study of City of Calgary in 2008, carried out by Canadian Urban Institute. It aims at providing insights to achieve the goal of reducing 50% of Green House Gas (GHG) emissions by 2050 [1]. It depicts 1) how building design strategies and land use planning can influence the city level energy use intensity 2) the availability of alternative energy sources and the opportunities to combine building level sustainable design technology with the community level energy system design.

Calgary energy map first compares energy use intensity (the annual total demand for thermal energy of space heating cooling, hot water and electricity per unit area [1]) in GJ/ha between two development cases: “business as usual” case and “ultra-high efficiency” case (Figure 2). The comparison demonstrated a 34% reduction in energy use intensity from the former to the latter [1].

It also shows alternative energy sources of district energy, solar hot water, solar air, energy sharing and PV installation on the map (Figure 3). By overlaying the alternative

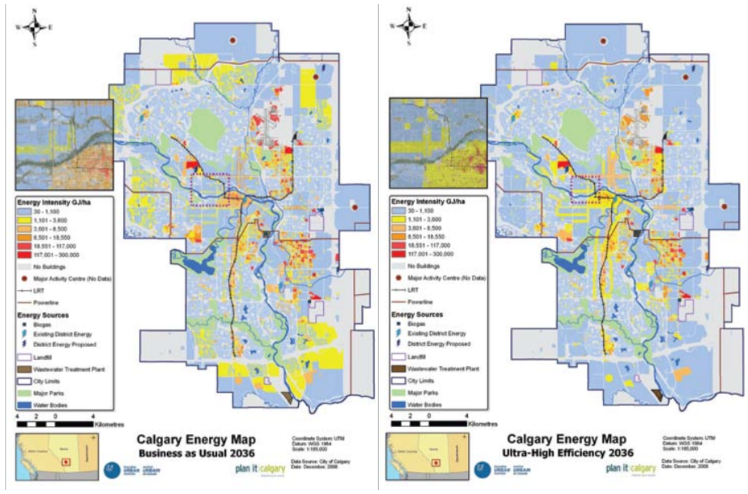

Figure 2: Calgary Energy Map (Business as Usual, Ultra-High Efficiency) [1]

technology map and the "ultra-high efficiency" map, it highlights the opportunities of using alternative renewable energy sources and district energy system to further improve the energy performance of high energy demand areas after high performance building design was applied [1].

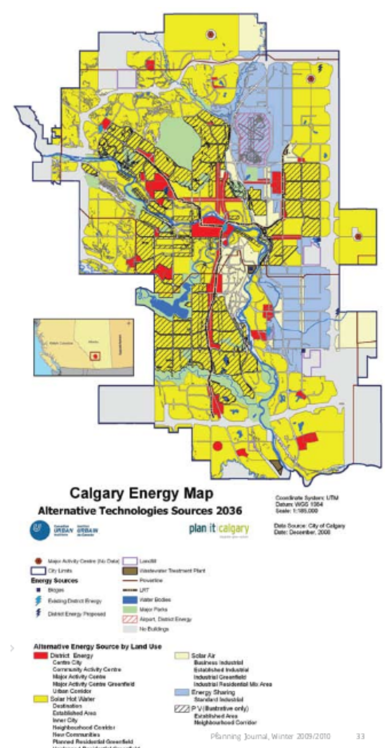

Figure 3: Calgary Energy Map Alternative Energy Source [1]

2.1.2 UK Heat Map

Under the goal of supplying 25% of the total energy with decentralized energy (DE) by the year 2025, the Decentralised Energy Master Planning Program (DEMaP) was conducted between 2008 to 2010 to "identify opportunities for district heating networks through heat mapping and energy masterplanning" [26]. In this study, the term DE only refers to "combined heat and power systems connected to district heating networks" [8].

London Heat Map is a publicly accessible interactive map developed as part of the DEMaP project. It is completed for the London Boroughs in 2012. It can act as a starting point of Energy Master Plan for local authorities, and can assist developers to make connections to existing DE networks to meet policy requirements (London Plan DE policy) [8, 26]. Point features of high heating energy consumers and suppliers, existing and emerging energy networks are depicted on the interactive map. High DE potential regions ("focus area" [8]) are identified and depicted on the map to highlight the opportunities of utilizing the heat supply in the community planning and development (Figure 4). The "live-database" property of London Heat Map allows new data of energy consumption be uploaded by users.

The criteria applied for identifying focus area include: 1) near to existing or emerging DE network, 2) high heat demand density 3) anchor load building, 4) diverse heating demand profile 5) has public ownership with policy concerns to make connections to the DE network [8]. The physical constraint are also considered in finalizing the high DE potential regions.

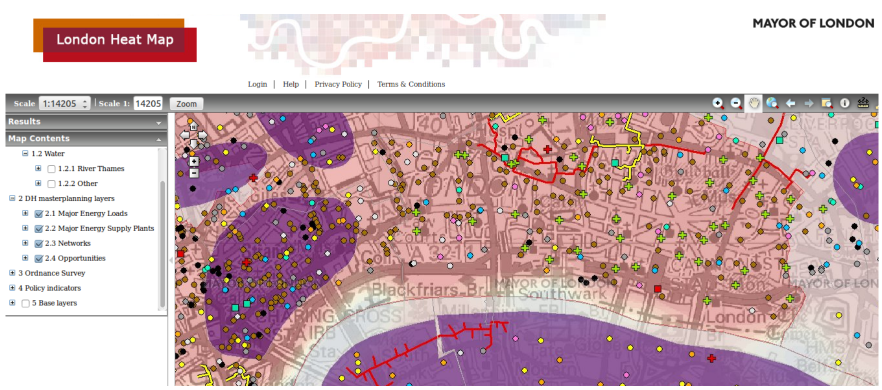

Figure 4: London Heat Map [27]

National Heat Map (Figure 5) is another UK energy mapping project that focuses more on the industry side [8]. It is a "high resolution web-based" heating energy interactive map, developed by the Department of Energy and Climate Change (DECC). It aims at "support planning and deployment of local low-carbon energy projects in England" [10]. Power plant developers can use this map to consider the feasibility for a CHP plant under policy requirements [8]. 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 representing low to high heating demand. Heat source of CHP stations and thermal power stations 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].

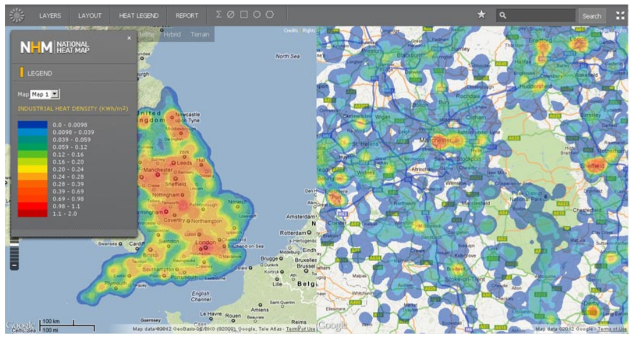

Figure 5: National Heat Map [32]

The "Water Source Heat Map" (Figure 6) 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].

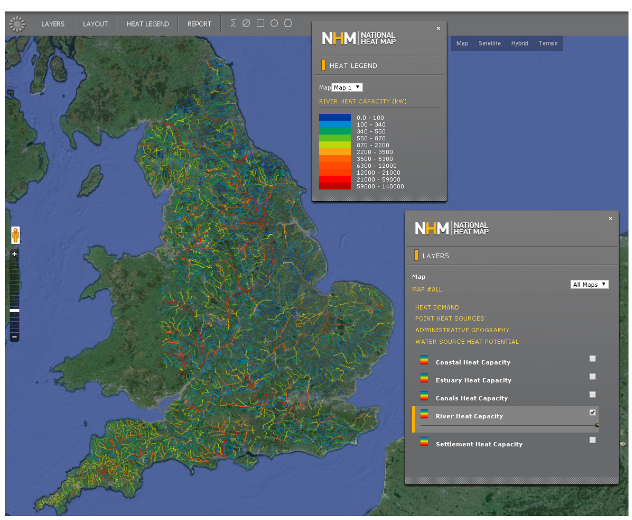

Figure 6: Water Heat Map [11]

2.1.3 Energy Potential Mapping

Dobbelsteen et al. described a framework of Energy Potential Mapping (EPM) that aggregates information of energy supply, demand and infrastructure on the same map with demand and supply represented in the same unit of GJ or GJ/ha [4].

In 2010, a "Heat Mapping" study under the framework of EPM was launched by TU Delft aiming at visualizing heat demand and supply and infrastructure with the same unit that facilitates easy comparison and facilitates the matching of supply and demand [4]. The map is presented with aggregated supply and demand in a 3D Heat Map. The absolute quantity of each type of demand and supply is represented with extruded height in the 3D map. Demand is represented with a transparent 3D feature, and each supply source is represented with solid 3D feature in a different color [4].

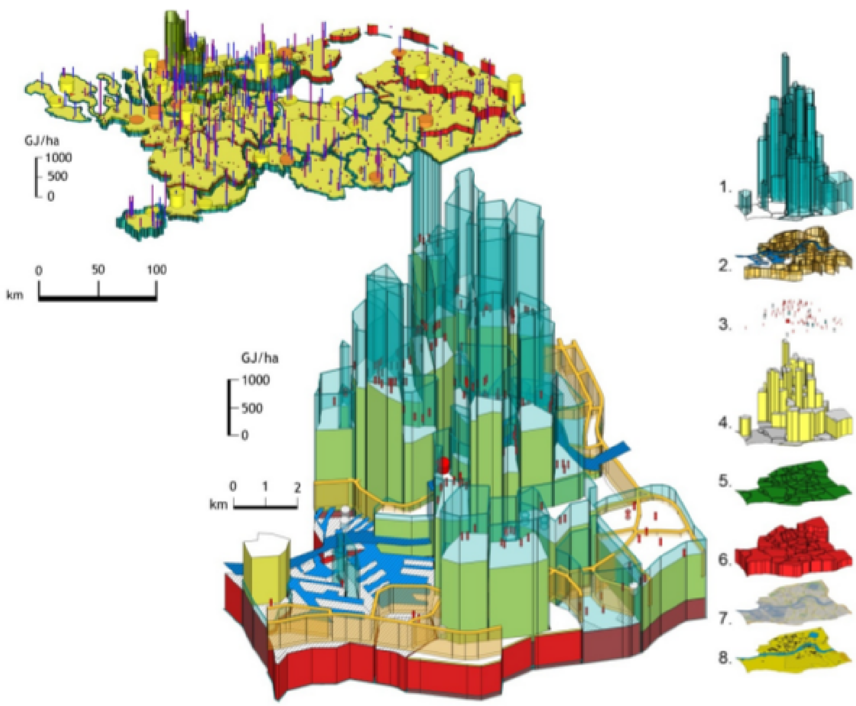

Figure 7: Heat Mapping of Netherlands and Rotterdam [4]

2.2 Dynamic Energy Map

As is discussed before, dynamic map includes time information in a map. Several existing approaches occur.

2.2.1 Lower Hill District Dynamic Mapping Project

In 2011 to 2012, the Dynamic Energy Map of the Lower Hill District, Pittsburgh, PA was created. It is designed to conduct feasibility analysis and comparison of alternative energy supply techniques of a district energy system [2, 31]. A geo-data base was created with ArcMap, ArcScene and Sketchup. In the database, each building, represented as a 3D feature, contains attributes of its building name, annual energy consumption, energy use intensity (EUI), and annual and monthly peak demand. The map is online accessible via GIS Cloud (Figure 8).

Figure 8: Online Accessible GIS-database with GIS Cloud [2, 31]

The feasibility analysis and temporal data display are separated from the geo-database and is performed in a excel screening tool. The tool takes input of energy cost rate, building type and size, development phase and central plant types and feature and produces a feasibility analysis and related temporal graphs (Figure 9) of annual hourly energy consumption for each building type and the aggregated demand of natural gas, cooling use electricity and total electricity.

2.2.2 Energy Mapping to Identify Opportunities for Future Networks Project

Another instance of energy demand dynamic map with high spatial resolution was found in the project “Energy Mapping to Identify Opportunities for Future Networks” [15]. The aim of the project is to “analyze the spatial and temporal distribution of energy consumption”

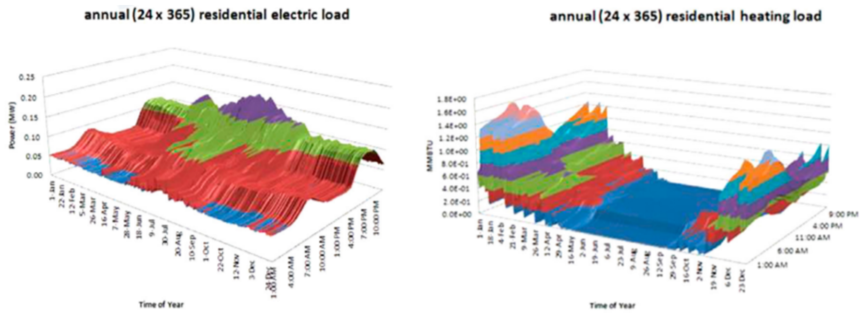

Figure 9: Heating Load and Electricity Load for Residencial Building [2]

and support decision making and design of energy network: more specifically, to identifiy opportunities of District Heating, CHP plant development and Building Design Improvement [15].

Energy Demand Maps of three different resolutions were created using QGIS: campus level, community level and city level. Energy data was retrieved from both metered data (used in campus level map) and HEM simulation (used in community and city level map). HEM is a tool for "mapping the possiblemapping the possible carbon and energy performance of a dwelling. It has pre-simulated results embedded as a data table in the tool and applies the appropriate system and context calculations to provide instant energy, carbon and cost results" [20].

For the campus level map, the heat demand density (heat demand over conditioned area) were depicted to identify "outliers": the buildings with high heat demand [12]. These outliers were potential buildings need to be improved in building insulation level or HVAC system efficiency. They claim a spatial map is sufficient for this outlier identification process (Figure 10). They also created a temporal spatial map of monthly heat consumption that is in the form of both small multiples (Figure 11) and non-interactive animated map (Figure 12). With the dynamic map, they identified two campus buildings with high heat demand through the whole year (anchor load building) and concluded that the two buildings could connect to a district heating system. They also created two animated maps with electricity and natural gas. By comparing these two animated maps, consistent high consumers for electricity and gas were identified as potential candidate building for a micro-CHP system [36].

The community level spatial and temporal GIS analysis undertook a similar process as the campus level except for the energy data is retrieved from HEM simulation. By comparing the four different building types: "Traditional Build, New Build, Council Estate, High Rise Flat", they identified the consistent high gas and electricity demand of High Rise Flat buildings. They also discovered that the improvement of building design could adjust the

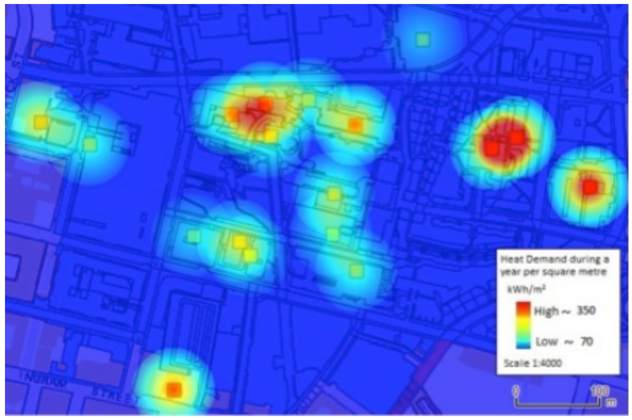

Figure 10: Campus Level Heat Demand Density Map [12]

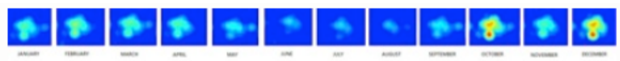

Figure 11: Campus Level Monthly Heat Demand Map in Small Multiples [12]

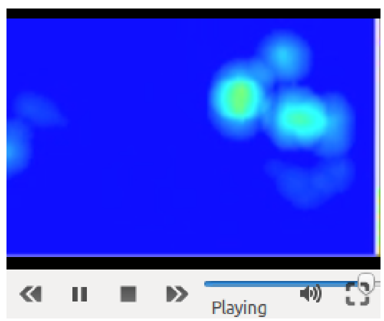

Figure 12: Campus Level Monthly Heat Demand Map in Animation [12]

heat to power ratio (HTP) and could make applying CHP option feasible [14].

City level map does not contain temporal mapping analysis and is left out from the case study [13].

3 Building From Previous Work

As is mentioned in the introduction, a dynamic energy map has four major functions: 1) holding, 2) visualizing and 3) analyzing community level high spatial-temporal resolution energy demand and supply data 4) connection to simulation engine for iterative performance analysis.

In the initial instance of Dynamic Energy Map by Baird et al. [2], function 1) of holding spatial-temporal (although with low temporal resolution) energy data is realized by processing the energy simulation data with Microsoft excel and importing the csv file including "building name, total conditioned area annual, energy use intensity, annual and monthly peak demand". The further improvement of the current project is to make the geo-database hold more high resolution energy data, meaning the 8760 hourly energy data should be contained in the dynamic energy map.

Function 4) of connecting to building simulation data is also realized by importing simulation result csv files to the geo-database (although with low temporal resolution).

For function 3), the feasibility analysis of a district energy system is performed in a stand-alone excel tool [2] but it is possible that the analysis result could be linked in to the geo-database as the energy simulation result.

For function 2), the spatial and temporal information are visualized separately in the Lower District Hill Project: the spatial information of 3D building geometry and location could be visually inspected in the geo-database but not the hourly energy consumption information. 2) The temporal visualization of energy demand is done separately in the excel screening tool as 3D graphs, but no spatial context is present and the spatial dimension is then lost. The authors thus identified the crucially missing function: the visualization of such a spatial-temporal changing of energy behavior as the major goal of the current project.

Figure 13: Unified Dynamic Energy Map Display System

4 Methodology

4.1 Overview

The Dynamic Energy Map is created with a conceptual urban environment whose building density and land use pattern resembles a redevelopment project at Lower Hill District, Pittsburgh, PA [31]. The number of buildings in the model represents a typical sized community that can be served by a district energy system [25].

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 of new construction which comply with ASHRAE 90.1-2004 Standard [29].

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 images.

An interface is designed to provide an interactive inspection of the map sequence and create dynamic data plots (Figure 14). 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.

The major functions of the current program include:

i. comparing heating and cooling demand to identify energy recovery opportunities

ii. comparing heating and electricity demand to size co-generation system

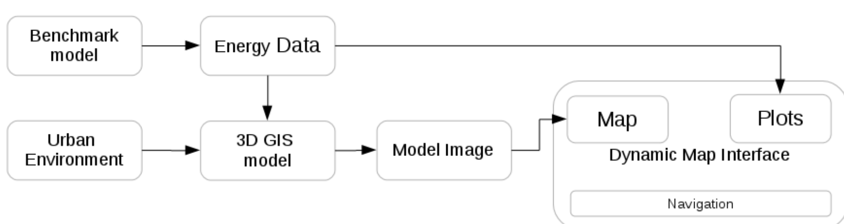

Figure 14: General Work Flow

4.2 Input

4.2.1 Benchmark Models and Energy Data

In the Lower Hill District project preliminary district system feasibility analysis session, DOE benchmark buildings were substituted for buildings in the community model. This approach allows for a fast initial system assessment [2].

Following the same approach, the energy profile used in the current study is retrieved from simulation results of commercial building benchmark buildings developed by U.S. Department of Energy (DOE) [29]. There are 16 building types in the benchmark models (Figure 2). 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 display. The general information for the benchmark buildings are shown in Table 2:

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 [29]

The benchmark buildings comply with the ASHRAE Standard 90.1-2004. The HVAC system types are shown in Table 3. The major heating systems of the benchmark buildings are furnace and boilers, except that the small hotel and the warehouse has individual space heaters other than furnace. The cooling systems are chillers for Large Hotel (air-based) and Large Office (water-based) and PACU (packed air-conditioning unit) for other building types.

Table 3: Benchmark Building HVAC System

	Heating	Cooling	Air
Small Office	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Medium Office	Furnace	PACU (packed air-conditioning unit)	MZ VAV (multizone variable air volume)
Large Office	Boiler	Chiller (2) water cooled	MZ VAV (multizone variable air volume)
Primary School	Boiler	PACU (packed air-conditioning unit)	CAV (constant air volume)
Secondary School	Boiler	Chiller (2) air cooled	MZ VAV (multizone variable air volume)
Stand-Alone Retail	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Strip Mall	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Suprmarket	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Quick Service Restaurant	Furnace	PACU (packed air-conditioning unit)	CAV (constant air volume)
Full Service Restaurant	Furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Small Hotel	ISH (individual space heater), furnace	IRAC (individual room air conditioner), PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Large Hotel	Boiler	Chiller (2) air cooled	FCU (Fan Coil Unit) and VAV (variable air volume)
Hospital	Boiler	Chiller (2) water cooled	CAV (constant air volume) and VAV (variable air volume)
OutPatient Healthcare	Furnace	PACU (packed air-conditioning unit)	CAV (constant air volume) and VAV (variable air volume)
Warehouse	ISH (individual space heater), furnace	PACU (packed air-conditioning unit)	SZ CAV (single-zone constant air volume)
Midrise Apartment	Furnace	PACU-SS	SZ CAV (single-zone constant air volume)

4.2.1.1 Input for Identifing Energy Recovery Opportunities

The major heat rejection sources include heating mode heat rejection and cooling mode heat rejection. The heat rejection in heating mode happens during the process of the mixing of conditioned and outside air. The heat rejection in cooling mode happens at the condensing process when the high temperature refrigerant gas condenses with one of the following heat rejection forms [3]:

- Air cooled unit: ambient air is blown through condensing coils and removes heat from the gas refrigerant.
- Cooling tower: cooled water flow past the condensing unit and takes away the heat from the gas refrigerant. The water is then cooled through evaporation.
- Fluid cooler: water is sprayed on the condensing coil with fan forced air flowing in the opposite direction as the water. It causes evaporation cooling effect that takes away the heat from the gas refrigerant.

The heat "condenser total heat of rejection" [3] (THR) in the condensing process equals to the "net refrigeration effect" [3](RE), which is the hourly cooling demand, plus the compressor input, it can be represented as the following equation:

$$THR = RE * f$$

f is the "Heat Rejection Factor" and it is typically between 1.15 and 1.25 [3]. The water-based system has heat rejection factor closer to 1.15 and air-based system closer to 1.25 [3].

To help users identify energy recovery opportunities, the energy information needed to retrieve include: space heating energy demand and space cooling energy demand, which is an indicator for heat rejection that could be recovered and shared within a single building or a building group.

From Table 5, Large Hotel, Medium Office, Midrise Apartment, OutPatient Healthcare, Small Hotel and Stand-alone Retail use both electricity and natural gas for space heating, the rest of the building types uses only natural gas for space heating. We thus use the EnergyPlus simulation output parameters "heating:electricity" and "heating:gas" to represent the space heating demand of reference buildings.

Electricity is the only fuel used for space cooling, thus the EnergyPlus output parameter "cooling:electricity" is used to represent space cooling demand. According to the suggested

Table 5: Annual Total Heating Demand by Fuel Type

	Electricity [kBtu]	Gas [kBtu]
FullServiceRestaurant	0.0	856637.1
Hospital	0.0	14045664.0
LargeHotel	843.6	2960506.8
LargeOffice	0.0	4741180.3
MediumOffice	450791.3	192226.8
MidriseApartment	56.9	494959.6
OutPatient	199581.9	2881638.9
PrimarySchool	0.0	1579186.5
QuickServiceRestaurant	0.0	383297.2
SecondarySchool	0.0	7746443.0
SmallHotel	52129.9	450393.2
SmallOffice	0.0	66631.5
Stand-aloneRetail	6966.5	976583.4
StripMall	0.0	1013188.1
SuperMarket	0.0	3043905.2
Warehouse	0.0	1039850.2

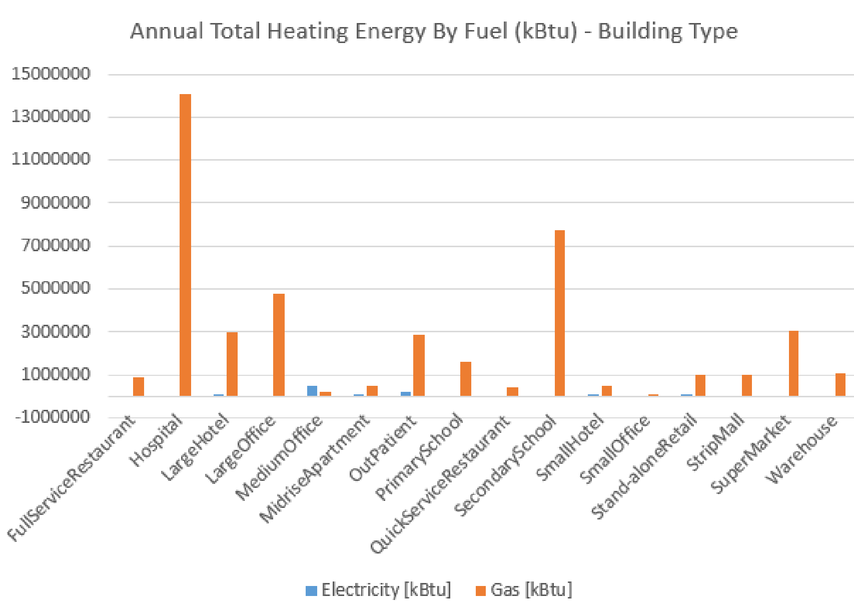

Figure 15: Heating Fuel

heat rejection factor [3], the heat recovery potential will be calculated with $f = 1.15$ for

Large Office and Hospital, and $f = 1.25$ for the remaining building types:

$$\text{Heat Recovery Potential} = \text{cooling:electricity} \times f$$

In summary, to facilitate identification of energy recovery opportunities for single buildings and within building groups, the hourly “heating:electricity”, “heating:gas” and “cooling:electricity” output will be extracted from energyPlus simulation of DOE Commercial benchmark buildings.

4.2.1.2 Input for Sizing District Co-generation System

For the sizing of a district co-generation system, the relevant information needed are the total heating demand, and the total electricity demand. The general principle used in Lower Hill District project [2] is to use the minimum total heat demand (space heating and service hot water) over time to assess the minimum capacity of electricity generation (E_{heat}) such that its heat bi-product from electricity generation will always be consumed. The maximum total electricity demand (E_{elec}) is used for assessing the capacity of a backup system or a second phase system development by $C_{backup} = E_{elec} - E_{heat}$ where C_{backup} is the capacity of electricity generation for the backup system or second-phase development.

Heating demand assessed in the sizing of co-generation system is different from the energy recovery use case. It contains the space heating demand and the service hot water demand. From the summary files of benchmark models, the fuel used for providing service hot water is natural gas for all building types (Table 6)

The output parameter “electricity:facility” was extracted to represent the total electricity demand.

Table 6: Service Hot Water by Fuel Type

	Electricity [kBtu]	Gas [kBtu]
FullServiceRestaurant	0	253664.3
Hospital	0	719402.7
LargeHotel	0	6793934.2
LargeOffice	0	231381.1
MediumOffice	0	34178.3
MidriseApartment	0	289719.3
OutPatient	0	44054.5
PrimarySchool	0	174768.0
QuickServiceRestaurant	0	82071.5
SecondarySchool	0	441512.2
SmallHotel	0	394017.1
SmallOffice	0	10928.3
Stand-aloneRetail	0	0.0
StripMall	0	0.0
SuperMarket	0	23799.7
Warehouse	0	0.0

4.2.2 3D GIS Model Geometry

The conceptual community model is constructed in CityEngine [19]. CityEngine is a software developed by Esri. It can aggregate geographic information into buildings and is capable of smoothly transition models to ArcGIS [18], 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 [2] (Figure 16. 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

Figure 16: Mellon Arena Project Site Plan View

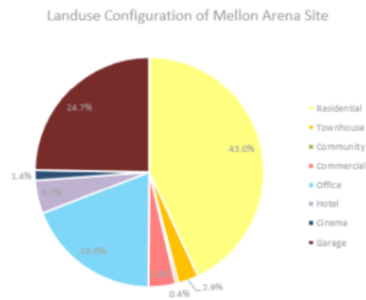

Figure 17: Mellon Arena Site Land use Configuration

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 7.

The four major building sectors involved in the current project are residential, commercial, office and hotel. Their topological pattern is represented in Figure 18. The conceptual model construction follows the building type topological pattern and the urban density as the Mellon Arena Project (Figure 19)

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 7: Mapping of Mellon Arena to Building Types of DOE benchmark model

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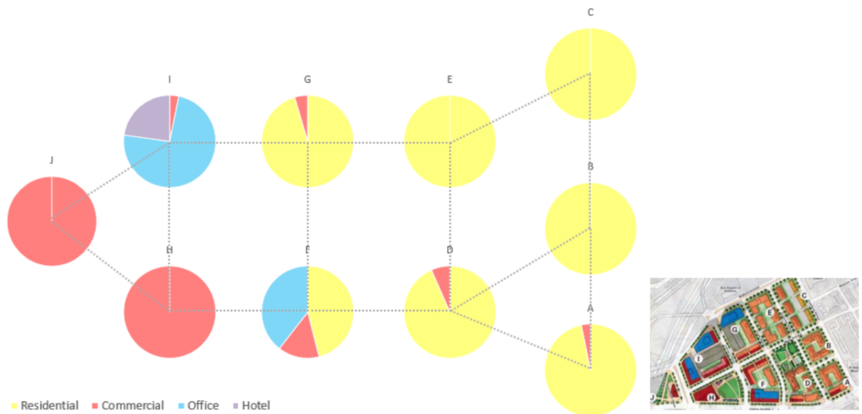

Figure 18: Building Type Topological Pattern, Mellon Arena

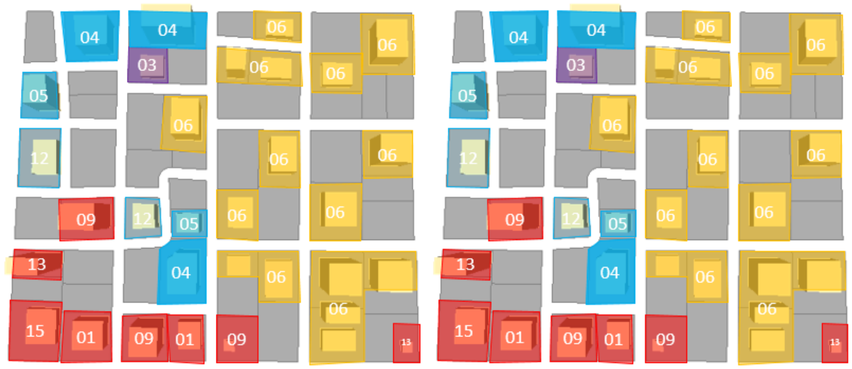

Figure 19: Site Plan of Conceptual Model
(01: Full Service Restaurant, 03: Large Hotel, 04: Large Office, 05: Medium Office, 06: Midrise Apartment, 09: Quick Service Restaurant, 12: Small Office, 13: Stand-alone Retail, 15: Super Market)

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