Carnegie Mellon University

Master Thesis

Dynamic Energy Mapping

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Abbreviations

CMU	**C**arnegie **M**ellon **U**niversity

Symbols

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

Chapter 1

Methodology

1.1 Overview

The Dynamic Energy Map is created with a conceptual urban environment with the following properties:

i. Building density and land use pattern are realistic.

   To achieve this, the project used a redevelopment project at Lower Hill District, Pittsburgh, PA [12] as a prototype and is created based on extracted topological patterns from this redevelopment projec.

ii. The number of buildings in the model represents a typical sized community that can be served by a district energy system [17].

   To achieve this, the original model created under crateria i. is duplicated and thus there are 68 buildings in total, within the range of a typical district energy system service capacity of 50 to 150 [17].

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 [2].

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 1.1). 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.

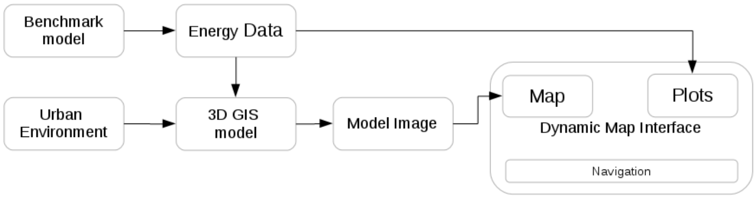


FIGURE 1.1: General Work Flow

The major functions of the current dynamic energy map interface include:

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

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

Details in input output data and the interface design process will be explained in more details in the following sections.

1.2 Input

1.2.1 Benchmark Models and Energy Data

In the Lower Hill District project, the DOE benchmark buildings were substituted for buildings in the community model in the district system feasibility analysis. This approach allows for a fast initial assessment of the district system [9].

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) [2]. There are 16 building types in the benchmark models (Figure 1.1). 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 1.1:

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 1.1: DOE Benchmark Building General Information [2]

The benchmark buildings comply with the ASHRAE Standard 90.1-2004. The HVAC system types are shown in Table 1.2. 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 furnaces. 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 1.2: 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)

1.2.1.1 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. This source of heat rejection is more difficult to capture and is thus left out from the energy recovery potential calculation in this study. The current study will only focus on the cooling induced heat reject.

The heat rejection in cooling mode happens during the condensing process when the high temperature refrigerant gas condenses with one of the following heat rejection forms [37]:

- 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. It causes evaporative cooling effect that takes away the heat from the gas refrigerant.

The "condenser total heat of rejection" [37] (THR) in the condensing process equals to the "net refrigeration effect" [37](RE, the hourly cooling demand), plus the compressor input, it can be represented with the following equation:

$$THR = RE * f \ [37] \tag{1.1}$$

f is the "Heat Rejection Factor" and it is typically between 1.15 and 1.25 [37]. The water-based system has heat rejection factor closer to 1.15 and the air-based system closer to 1.25 [37].

To help users identify energy recovery opportunities, the energy information needed to retrieve include: space heating energy demand and space cooling energy demand. The space cooling demand (RE in Equation 1.1) is an indicator for heat rejection that could be recovered and shared within a single building or a building group.

From Table 1.4, 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.

TABLE 1.4: Annual Total Heating Demand by Fuel Type [2]

	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

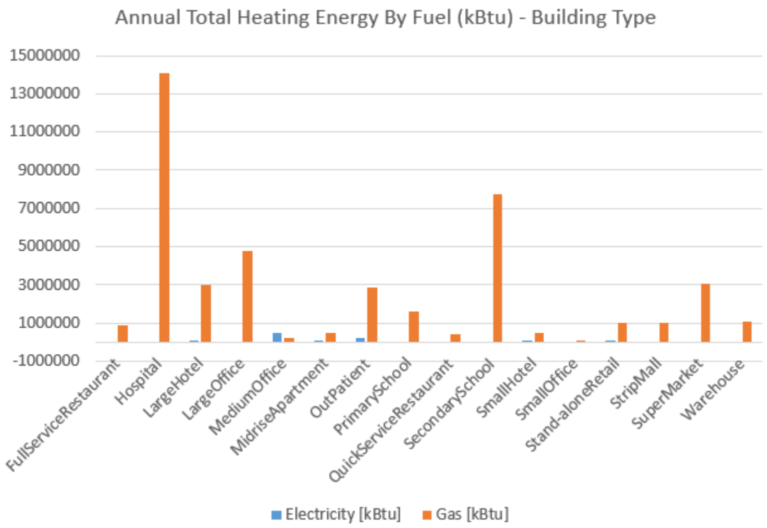


FIGURE 1.2: Heating Fuel

Electricity is the only fuel used for space cooling [2], thus the EnergyPlus output parameter "cooling:electricity" is used to represent space cooling demand. According to the suggested heat rejection factor [37], 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:

$$\text{Heat Recovery Potential} = \text{cooling:electricity} \times f \tag{1.2}$$

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.

1.2.1.2 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 [9] 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 in Section 1.2.1.1 . 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 1.5)

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

TABLE 1.5: Service Hot Water by Fuel Type

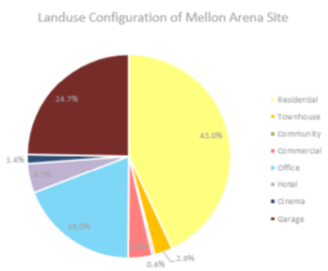
	Electricity [kBtu]	Gas [kBtu]
FullServiceRestaurant	0	253664.3
Hospital	0	719402.7
LargeHotel	0	6793934.2
LargeOffice	0	231381.1
MediumOffice	0	34178.3
MidriseApartment	0	289719.3
OutPatient	0	44054.5
PrimarySchool	0	174768.0
QuickServiceRestaurant	0	82071.5
SecondarySchool	0	441512.2
SmallHotel	0	394017.1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

1.2.2 3D GIS Model Geometry

The conceptual community model is constructed in CityEngine [11]. CityEngine is a software developed by Esri [38]. It can aggregate geographic information into buildings and is capable of smoothly transition models to ArcGIS[39], 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, which is difficult to do in the current ArcGIS, the technical details will be explained in Appendix A.

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 [9] (Figure 1.3a. 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%).

(A) Mellon Arena Project Site Plan View



(B) Mellon Arena Site Land use Configuration

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 1.6.

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

The four major building sectors involved in the current project are residential, commercial, office and hotel. Their topological pattern is represented in Figure 1.4. The conceptual model construction follows the building type topological pattern and the urban density as the Mellon Arena Project (Figure 1.5)

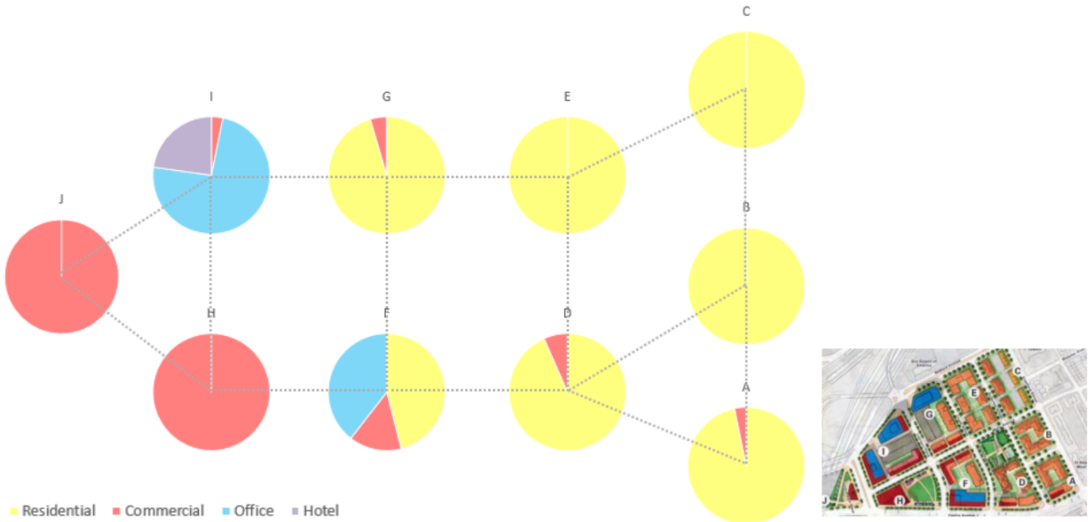


FIGURE 1.4: Building Type Topological Pattern, Mellon Arena

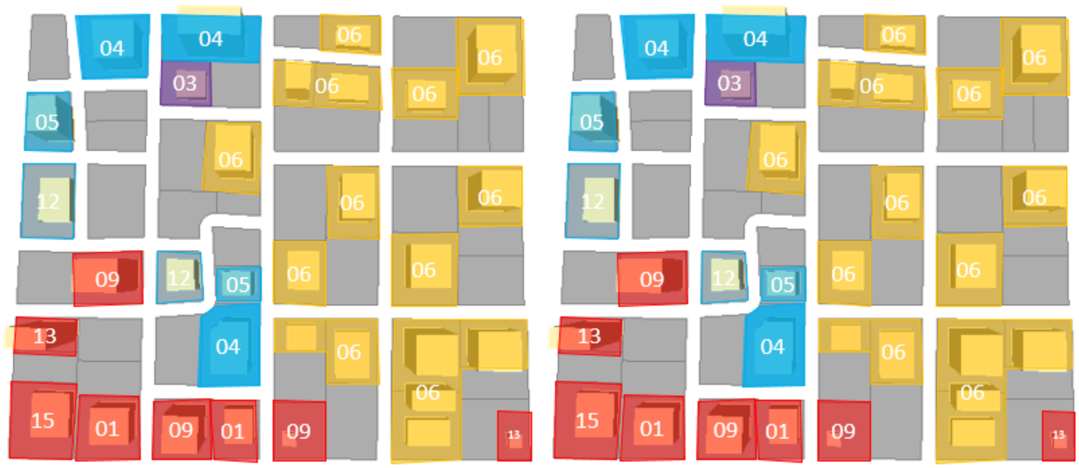


FIGURE 1.5: Site Plan of Conceptual Model
(01: Full Service Restaurant, 03: Large Hotel, 04: Large Office, 05: Medium Office, 06: Midrise Apartment, 09: Quick Service Restaurant, 12: Small Office, 13: Stand-alone Retail, 15: Super Market)

Appendix A

Implementing Dynamic Energy Map in CityEngine

A.1 General Introduction

The following document records the method of using CityEngine to visualize the dynamic energy (heating energy in kwh for this document) changes with a slider bar embeded in the CityEngine software. To be more specific, users will be able to navigate through the 8760 hour of a year with a time slider and see the color-coded energy consumption data for all buildings in the community model for the hour the slider cursor rest at. The detailed rule file is included in Appendix **??**.

The general process is to find a base map if it is a real site or generate a random urban environment layout if it is a conceptual setting. Add attributes of “landuse” and “time” to the building lot. Then write a rule file with energy consumption data (or the color representation of each energy consumption data) for each building type held in string lists in the rule file and then apply the rule files to the building lot. Finally set the attribute of “landuse” and “time” in the rule file to be driven by the value of the object attribute “landuse” and “time”. The “time” attribute is to index into the string list of energy profile (in rule files) for each building type. For example, when the “time” attribute of all building blocks are set to 10, all the buildings in the community model will change its color to the color representing its heating energy consumption in the 10th hour (zero-indexing) of the year.

Each step will be explained in more details in the following session.

A.2 Explaining Each Steps

A.2.1 Create a Urban Environment Layout

If one is working with a real project, an OSM Map [40] will be a good choice for a base map. The OSM file contains many useful attribute such as street center line, building name, elevation etc. It is of xml format and is easy to manipulate as text files, which makes it easier to work with and less bulky comparing to ArcGIS gdb files. Figure A.1 is an example of the CMU Campus OSM Map.

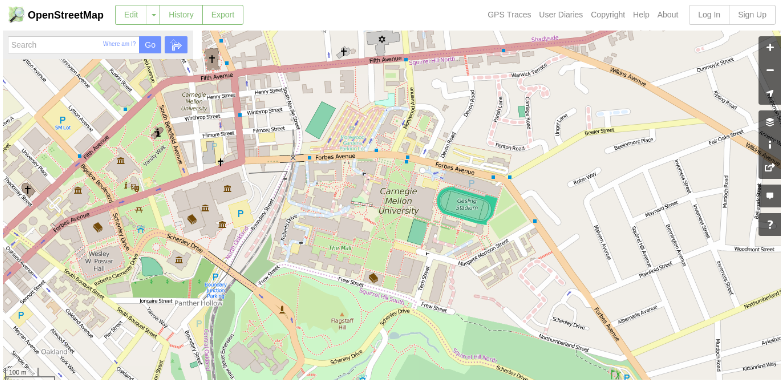


FIGURE A.1: CMU OSM Map [40]

If it is a conceptual setting, then create a random city of proper size using “grow street” function with some clean-ups (Figure A.2).

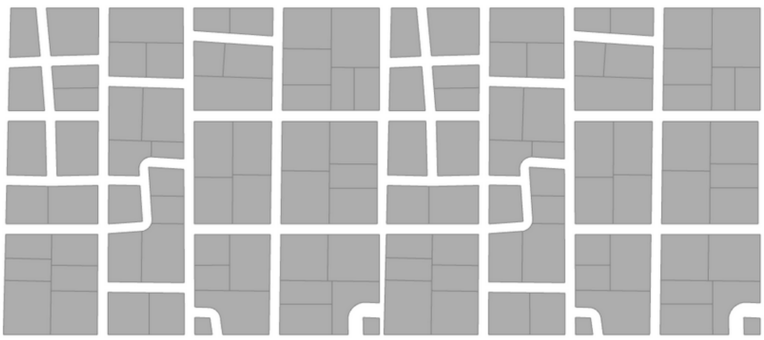


FIGURE A.2: Conceptual City Generated with CityEngine

A.2.2 Add Attributes to Building Lots

To implement the function of a time slider-bar that navigates and shows energy consumption for each building in each hour of the year, two additional attributes are needed: 1) "time" attribute of type float (ideally we would like it to be integer but there is no integer types in object attribute) ranges from 0 to 8760 (not inclusive) that represents the hour of a year and 2) "landuse" attribute of type float (since no integer type is available) that represents the land use type of the lot.

Adding these two attribute could be done either inside an OSM base map or inside CityEngine.

The typical way to add a building attribute can be done by selecting all building lots and right click one of the Object attributes and select "Add Object Attribute" to add new attributes.

If an OSM base map is available with building footprint information, adding attributes can be achieved within OSM maps by one searching for `"<tag k="building" v="yes"/>"` and add two new tags after this line:

`"<tag k="time" v="0">"`

`"<tag k="landuse" v="0">"`

A.2.3 Importing Base Map (Optional)

If one is working on a real project, one can add an geo-referenced terrain image to make the model more realistic. In the following example, the terrain geo-tiff was retieved from PASDA website [41] according to the "Allegheny County Imagery 2013 - Tile Index". The image showing the area of interest is clipped in ArcMap and imported as a geo-referenced image (.tif) to CityEngine (Figure A.3).

After importing geo-referenced image, OSM map could be imported and a working base was formed (Figure A.4).

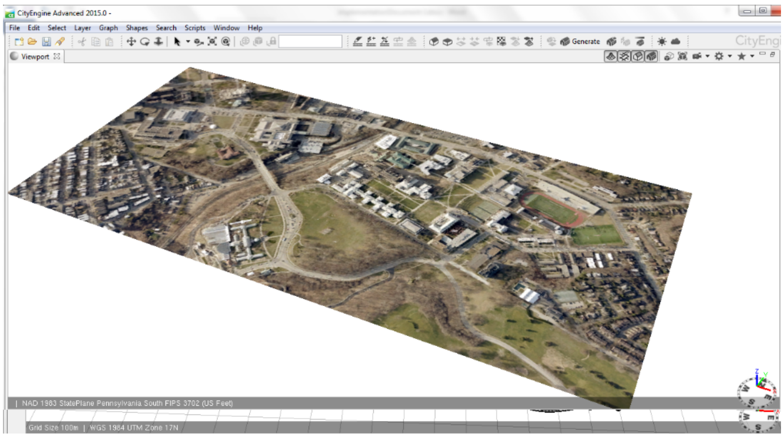


Figure A.3: Example of Geo-referenced Image in CityEngine

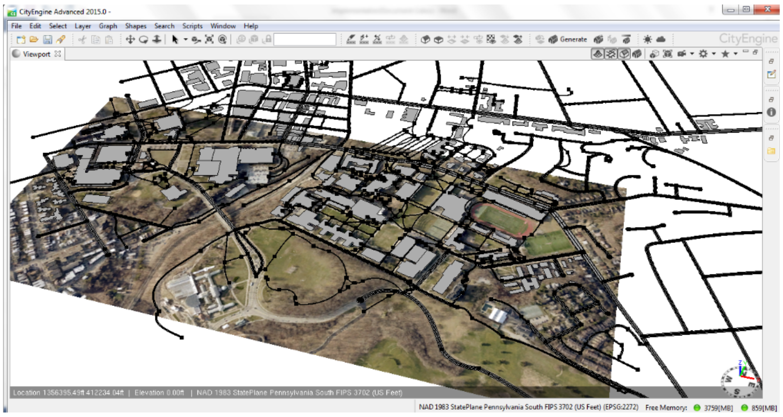


Figure A.4: Geo-tif with OSM Map

A.2.4 Writing Rule File for Building Generation

We used "time" as the index into the string array that holds the hourly heating energy consumption data. By setting the rule attribute "time" to some t, we will be able to retrieve the energy consumption information at hour "t" from the energy string list.

When implementing the dynamic energy map inside CityEngine, one should decide a proper color scheme for encoding the energy consumption data. No building-science specific breakpoints were specified at the current stage of the project. We used the continues red-to-blue color ramp in the stand-alone CityEngine based Dynamic Energy Map implementation.

A.2.5 Deciding Data Encoding

The first approach for representing energy information with color is to encode it with a graduated color symbol from red to blue, with red indicating low heating demand and blue indicating high heating demand. Each color within this red-to-blue color scheme is represented as a real number between 0 and 1 with 0 representing pure red and 1 representing pure blue. The first approach to calculate the corresponding color for each heating energy value is to calculate the normalized distance between the current value and the maximum value (Equation A.1).

$$\frac{E_{current} - E_{max}}{E_{max}} \tag{A.1}$$

$E_{current}$ is the energy consumption for the current time spot, E_{max} is the maximum energy consumption over the year. The problem for this approach is that the color changing is not visible enough as a result of a extremely right skewed energy data (with each data point representing the hourly energy consumption of a certain building in the community at a certain hour of a year) distribution (Figure A.5).

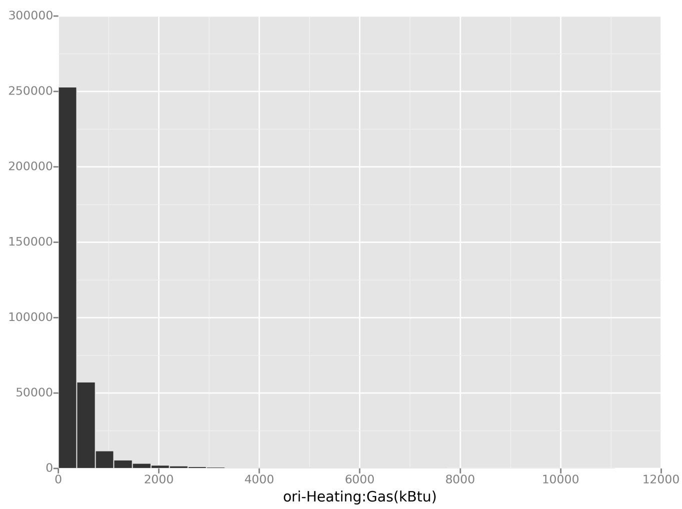


FIGURE A.5: A histogram of hourly energy consumption per building, for the 68 buildings in the community

By directly applying this normalized color scheme, the color distribution on a map will be very un-even, with most of the buildings colored with the red color for most of the time.

Kolter and Ferreira has used discovered that the annual total energy consumption of the 6500 buildings in Cambridge MA area follows a "log-normal" distribution [42]. By applying similar log scaling for the hourly heating energy data of the community, we found that the hourly heating energy distribution also roughly follows a normal distribution (Figure A.6). We apply log scaling to make the distribution less skewed and calculate the color from energy ($E_{current}$) as follows:

$$\frac{\ln(E_{current}) - \ln(E_{max})}{\ln(E_{max})} \tag{A.2}$$

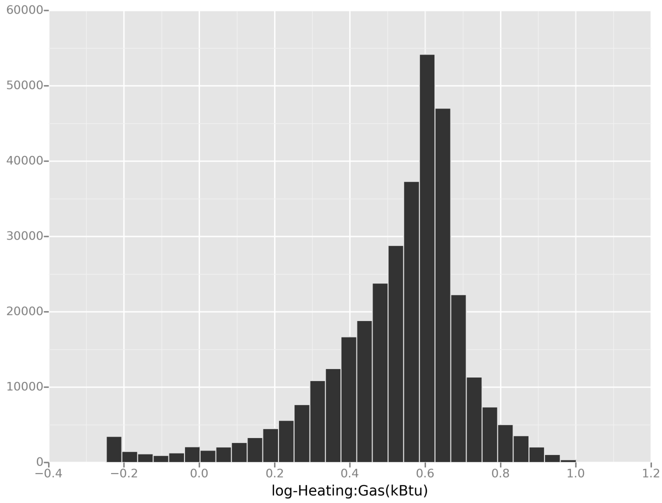


Figure A.6: Heating Demand of Conceptual City

Figure A.7 is one snapshot of the conceptual urban environment model under the log scaled calculation method in Equation A.2.

A.2.6 Associating Rule Attribute with Object Attribute

How to globally set all "time" attribute for each rule file is a key problem to solve to implement the time-navigation. Writing a python code for processing all the rule files as pure text files and apply rule files to its corresponding lot at each given "time" could be one solution, but there are two drawbacks 1) it is time and space consuming because as many as each 8760 rule files need to be generated 2) the "slider-bar" feature associated with the object attribute will not be available if implemented this way.

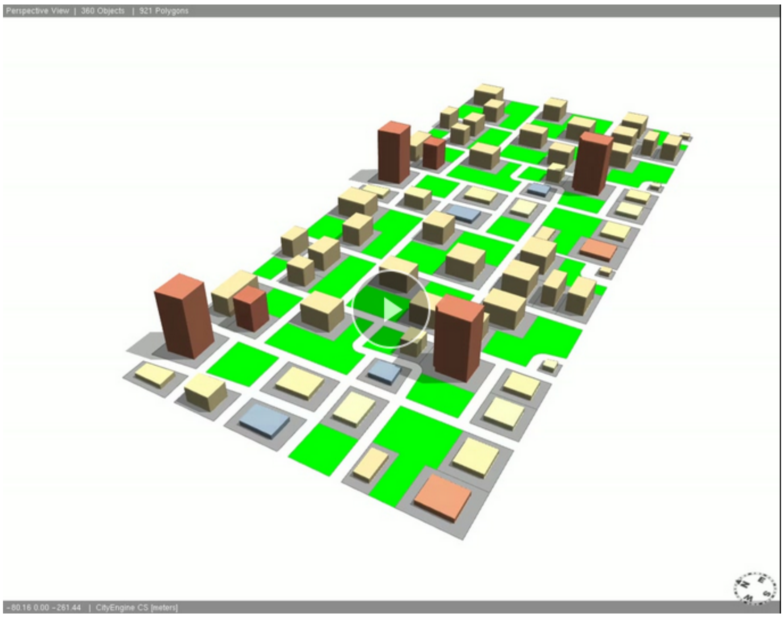


FIGURE A.7: Animated demonstration of the log-scaled dynamic energy heating demand map
Click here to go to the animation link.

We want to use object attribute (building lot) to drive the change of "time" for rule files for each building. The way to create the connection between object attribute "time" and the building attribute defined in rule files is by setting the source of "time" attribute (in rule file) by the building lot "time" attribute using "Connection Editor".

After the connection is established, one will select all buildings of interest in the community model and change the object attribute "time" of all selected building lots to visually inspect the color-coded energy consumption of all selected buildings. The Campus example is depicted in Figure A.8 and the community example is depicted in (Add figure here !!!)

Figure A.8: Slider in Campus Example

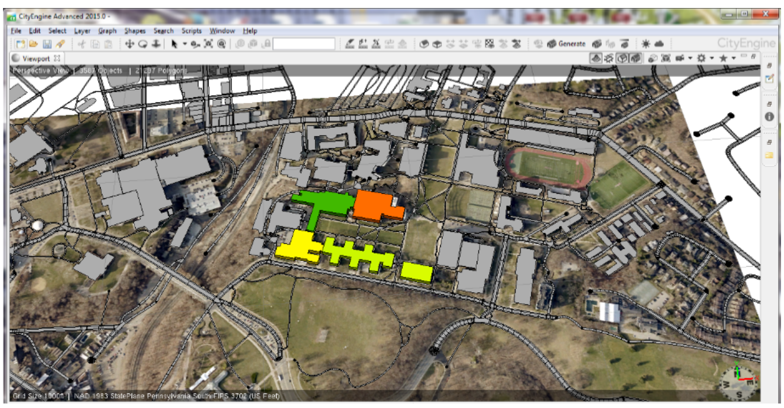


Figure A.9: Finished Campus Example

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