Load Composition Analysis in Support of the NERC Load Modeling Task Force 2019-2020 Field Test of the Composite Load Model

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Synopsis

In 2015, NERC's reliability standards were revised to require the use of dynamic load models in transmission planning studies.[1] To comply with the standards, planners must use load models that explicitly represent the dynamic behavior of the different constituents of load at each load bus within their transmission planning models. The most important of these constituents are motor-driven and power electronics-based loads. Collectively, these representations are known as composite load models.[2]

In anticipation of the compliance date for the new standards, NERC's Load Modeling Task Force (LMTF), in 2019, initiated a field test of composite load models involving the regional reliability planning entities. In support of the field test, DOE and BPA researchers developed region-specific composite load models that could be assigned to each non-industrial load bus in the planning models for each of the North American interconnections.[3] Separate models were developed for each hour of a summer peak day, a winter peak day, and a spring light-load day.

This report is the technical documentation for the load composition analysis that was conducted to develop these non-industrial composite load models.

[1] https://www.nerc.com/_layouts/15/PrintStandard.aspx?standardnumber=TPL-001-4&title=Transmission%20System%20Planning%20Performance%20Requirements&jurisdiction=United%20States

[2] https://www.nerc.com/comm/PC/LoadModelingTaskForceDL/Dynamic%20Load%20Modeling%20Tech%20Ref%202016-11-14%20-%20FINAL.PDF

[3] The industrial load bus models that were used in the field test were based on ones that had been previously developed for planners in the Western interconnection.

1. Introduction

Transmission planning studies are conducted routinely to ensure that the bulk electric power system can be operated reliably under anticipated conditions. A special emphasis of these studies is to ensure continued operation following unexpected events, such as the unplanned loss of a large generator or transmission line.

Following the 1996 blackouts on the west coast, transmission planners found, among other things, that the models they had used to represent the behavior of loads in their studies were not accurate [Kosterev, et al. 1999]. They found, specifically, that their models did not fully capture the dynamic behavior of loads under stressed system conditions. This finding led transmission planners in the Western Interconnection to begin developing new load models that focused on the dynamic behavior of motors.

The need for improvements in load modeling, again, became an issue for transmission planners in the 2000's when it was observed that, contrary to expectations, system voltages sometimes did not recover instantaneously following normally cleared faults on the transmission system. Upon investigation, they determined that some faults were causing large numbers of single-phase induction motors used in residential central air conditioners to stall and continue to depress system voltages locally until they shut-down. Although the phenomena had been documented in the past (see, for Willams, et al. 1992), in the 2000's, there was increased concern that "fault induced delayed voltage recovery" or FIDVR might lead to a cascading voltage collapse.

Industry's concern over this possibility led the US Department of Energy (DOE) to support a national initiative on the study of FIDVR. DOE and NERC held several workshops at which technical findings were presented and discussed.[4]

In conjunction with these workshops and based on studies that DOE had sponsored, the transmission planners in the Western Interconnection developed a new approach for modeling the dynamic behavior loads in their studies, called the composite load model. The distinguishing feature of the composite load model is the explicit representation of the dynamic behavior of the different constituents of load at each load bus within their transmission planning models. The most important of these constituents are motor-driven and power electronics-based loads [NERC 2016].

The Western Electric Coordinating Corporation (WECC), which is the regional reliability planning entity, began phased adoption of the composite load model in 2011. The use of the composite load model is now an established practice for planners in the Western interconnection. WECC currently maintains libraries of composite load models that have been developed for each load bus within the

[4] https://certs.lbl.gov/initiatives/fidvr/

interconnection. These libraries are drawn upon routinely by transmission planners in the Western interconnection to conduct transmission planning studies.

In 2015, NERC's reliability standards were revised to require the use of the dynamic load models (i.e., the composite load model) in transmission planning studies.[5] The use of the composite load models is a comparatively new practice for the majority of planners in the Eastern and Texas interconnections. Currently, there are no interconnection-wide libraries of composite load models currently available for these planners to use.

In anticipation of the compliance date for the new standards, NERC's Load Modeling Task Force (LMTF), in 2019, initiated a field test of composite load models involving the regional reliability planning entities in the Eastern and Texas interconnections. In support of the field test, DOE and BPA researchers developed region-specific composite load models that could be assigned to each non-industrial load bus in the planning models for the two interconnections.[6] Separate models were developed for each hour of a summer peak day, a winter peak day, and a spring light-load day.

This report is the technical documentation for the load composition analysis that was conducted to develop these non-industrial composite load models. It is an application of methods that have been outlined previously by NERC [NERC 2017].

The report is organized in three sections following this introduction. In section 2, we provide additional background on the composite load models and the analysis issues that must be addressed in developing these models for Eastern and Texas interconnections. In section 3, we describe and provide documentation on each of the four main steps involved in the load composition analysis process that was used to develop composite load models for the field test. In section 4, we briefly review examples of the output from the load composition analysis. An appendix is also provided that documents the mapping of information used in the analysis across the various data sources.

[5] https://www.nerc.com/_layouts/15/PrintStandard.aspx?standardnumber=TPL-001-4&title=Transmission%20System%20Planning%20Performance%20Requirements&jurisdiction=United%20States

[6] The industrial load bus models that were used in the field test were based on ones that had been previously developed for planners in the Western interconnection. These models were reviewed and updated as appropriate for use in the Eastern and Texas interconnections through a separate analysis.

2. The Role of Load Composition Analysis in Supporting the Development of Composite Load Models

Transmission planning studies are conducted using positive-sequence models that simulate the dynamic behavior of the electric power system under stressed conditions. The positive-sequence models are, in turn, supported by (or comprised of) a large number of individual models that represent the dynamic behaviors of both each generator and each load. Each load is represented through use of a composite load model.

A composite load model is a portfolio comprised of seven distinct types of load behaviors.[7] A separate composite load model is specified for each load bus (or feeder) within the transmission system at which load is withdrawn (or served). Developing composite load models, therefore, involves specifying the relative proportions of each the seven different types of load behaviors, so that collectively they are reflective of all loads served at each feeder.

For feeders at which a single (or group of similar) industrial customer(s) is served, there is already a large library of industry-specific composite load models, which was developed for planners in the Western interconnection. These can be readily transferred and used to represent industrial feeders in the Eastern and Texas interconnections.

However, the vast majority of feeders in all interconnections serve non-industrial loads. Developing composite load models for them requires new methods because these loads can differ considerably from those in the Western interconnection. One important difference is climate, which affects the magnitude of weather-sensitive loads, such as air conditioning (or space cooling) and space heating. Another important difference is electrification, which affects the magnitude of space heating, water heating, and cooking loads.

Despite these differences, there are also important similarities among non-industrial loads in all of the interconnections that facilitate the development of composite load models. First, they are comprised mainly of either residential or commercial buildings. Second, for any given type of residential or commercial building, there are many similarities in the systems each relies on to provide space cooling, space heating, water heating, cooking, lighting, refrigeration, etc.

Both these differences and similarities in residential and commercial buildings' uses of electricity have been studied systematically. In particular, forty years of demand-side management planning by utilities has led to the availability of a great deal of information on the uses of electricity in residential- and commercial-sectors. Much is now known about the variability (or sensitivity) of end-use loads, such as space cooling and space heating, on an hourly basis under different climatic conditions. Similarly, much

[7] See https://www.nerc.com/comm/PC/LoadModelingTaskForceDL/Dynamic%20Load%20Modeling%20Tech%20Ref%202016-11-14%20-%20FINAL.PDF for descriptions of the seven types of load behaviors.

is also known about the degree or extent of electrification of certain end uses (space heating, water heating, and cooking) in different regions of North America.

We draw from this base of information in order to develop composite load models for non-industrial feeders across North America through a process we term “load composition analysis.”

3. Overview of the DOE/BPA Load Composition Analysis Process

The objective of DOE/BPA load composition analysis is to develop composite load models that are reflective of composition of loads in each of the regions of the Eastern and Texas interconnections. Separate models are developed for each hour of a summer peak day, a winter peak day, and a spring light load day. In the end, these models are developed for four types of feeders for each of 96 weather cities across North America.

The load composition analysis process consists of four steps. See Figure 1.

Step 1 involves the compilation and analysis of publicly available information on the uses of (or end uses for) electricity in the residential and commercial sector.

Step 2 involves compilation and application of region-specific information on weather as well as on the discretionary uses of electricity (i.e., for space heating, water heating, and cooking) to develop region-specific hourly loads for each building and end use.

Step 3 involves mapping the region-specific hourly loads, by building type and end use, to the seven composite load model load types.

Step 4 involves the preparation of representative feeder models for each target region.

The basic unit of analysis is a building type and the electric end uses within that building type. For the residential sector, a single representative building type comprised of 13 end uses was used. For the commercial sector, 11 representative building types each comprised of 12 end uses were used. See Table 1.

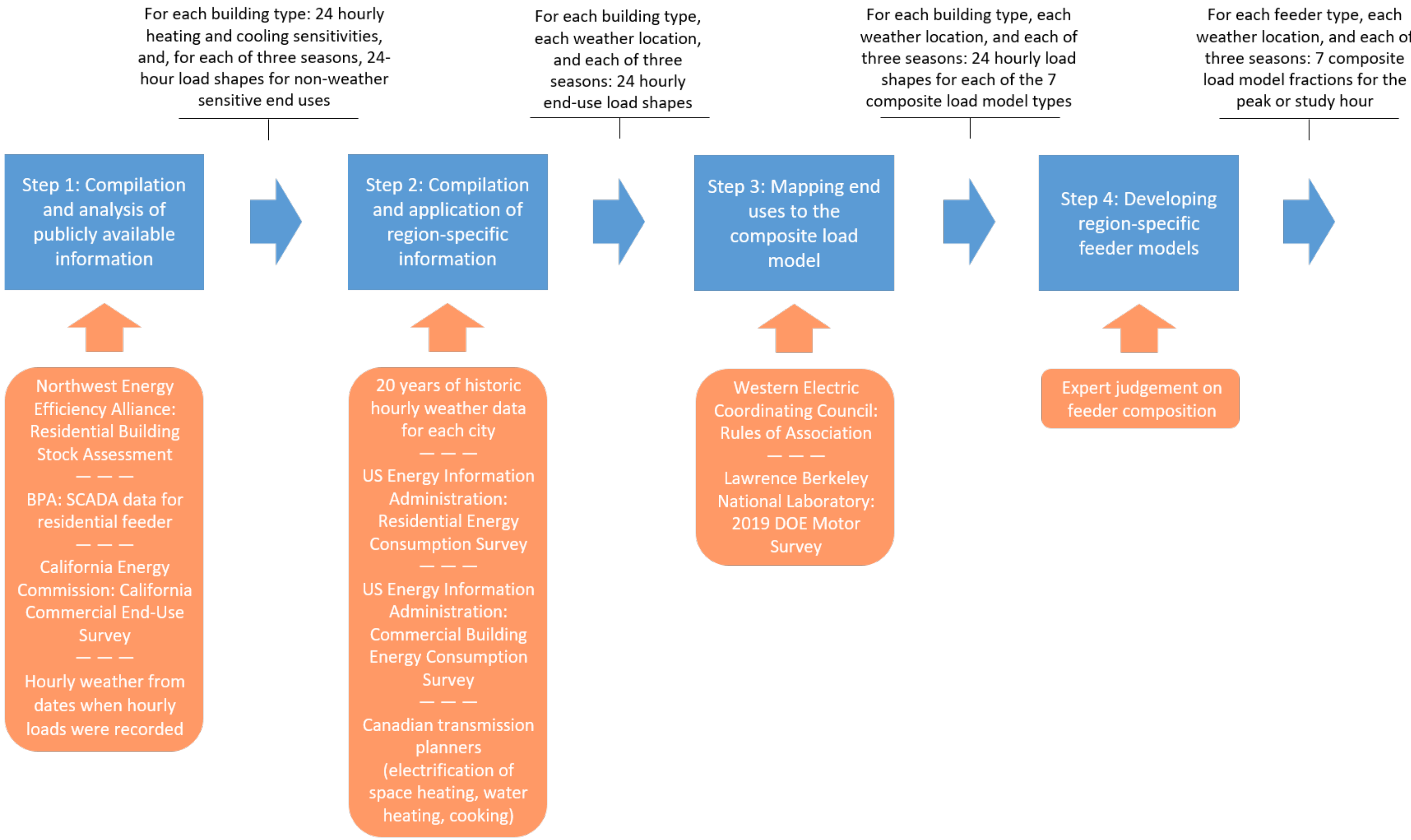

Figure 1. Load Composition Analysis Process

Table 1. Building Types and End Uses

	Building Types	End Uses
Residential	Single Family	Heating – resistance Heating – heat pump Cooling Hot Water Oven Refrigeration Freezer Lighting Entertainment Computer Washer Dryer Plugs Other
Commercial	Large Office Small Office Retail Grocery Restaurant Lodging Health School Warehouse Refrigerated Warehouse Miscellaneous	Heating Cooling Ventilation Water Heating Cooking Refrigeration Exterior Lighting Interior Lighting Office Equipment Miscellaneous Process Motors Air Compressor

3.1 Step 1. Compilation and analysis of publicly available data

The objective of step 1 is to process and transform hourly metered information collected in one region of North America into a form that can be re-expressed or extrapolated to be representative of conditions in other regions of North America.

The methods we employ make several assumptions: First, we assume that size differences among buildings of a given type can be accounted for by first normalizing end use load information collected from a group of building in one region by floor area and then later by multiplying the normalized values by the floor area of a different group of like buildings in another region (Step 1a, below). Second, we assume that non-weather sensitive loads are common to all buildings of a given type across all regions (Step 1b, below). Third, we assume that weather sensitive loads recorded in one region can be used to project weather sensitive loads in another region through the use of statistical correlations, which we call hourly weather sensitivity factors, that express hourly loads as a function of hourly measures of weather (Steps 1c, below).

The outputs from step 1 are, for each building type, normalized, hourly non-weather sensitive loads and hourly weather sensitivity factors for both heating and cooling.

The load composition analysis process is based on end-use load information that has been collected for samples of hourly metered residential and commercial buildings. The information for residential buildings was collected by the North Energy Efficiency Alliance through the Residential Building Stock Assessment (RBSA) project in 2013-4 [Ecotope 2014]. The RBSA project characterized the existing residential building stock in the Northwest region based on data from a representative sample of homes. Within the RBSA project, the RBSA Metering Study was a whole-house metering study covering most energy end uses in 101 homes in the Pacific Northwest. The information from the RBSA project was augmented by historic SCADA information collected by BPA for a predominantly residential feeder near Vancouver, WA from 2015-7.

The information for commercial buildings was developed by the California Energy Commission through the California Commercial End-Use Survey (CEUS) project in 2002 [Itron 2006]. CEUS was a comprehensive study of commercial sector energy use, primarily designed to support the state's energy demand forecasting activities. A stratified random sample of 2,800 commercial facilities was targeted from the service areas of Pacific Gas & Electric, San Diego Gas and Electric, Southern California Edison, Southern California Gas Company and the Sacramento Municipal Utility District. Simulated energy use for each survey participant was calibrated to actual historical energy consumption from utility billing records. The software created end-use load profiles and electricity and natural gas consumption estimates by end-use for user-defined commercial market segments.

Table 2 and Table 3 show, for each end use, the number and total floor area of residential homes and the total floor area of the commercial buildings whose metered or calibrated load shape information was used in the load composition analysis, respectively.

Table 2. Residential End-Use Metered Data from the Residential Stock Building Assessment

End Use	Homes Metered	Total Square Footage Metered
Computer	73	158,351
Dryer	85	180,009
Entertainment	83	178,212
Freezer	39	801,38
Hot Water	47	917,12
Lighting	86	188,275
Other	33	77,155
Oven	56	111,877
Plugs	90	195,081
Refrigerator	89	193,885
Washer	83	184,895

Table 3. Total Floor Area of Commercial Buildings in the California Commercial End-Use Survey That Were Used to Develop End-Use Load Shapes

End Use	College	Grocery	Health	Large Office	Lodging	Misc.	Refrig. Warehouse	Restaurant	Retail	School	Small Office	Warehouse	Total
Heating	4,871	1,511	9,038	9,374	36,341	14,093	335	1,148	15,169	16,641	6,408	1,703	**116,632**
Cooling	11,185	4,307	10,065	9,392	40,383	31,561	336	5,375	35,346	19,174	15,105	1,891	**184,120**
Ventilation	11,732	4,585	10,069	9,392	40,573	33,871	339	5,375	36,247	19,678	15,105	1,891	**188,857**
Water Heating	3,277	2,205	367	1,907	16,638	19,437	2,722	484	34,102	13,269	13,322	9,514	**117,244**
Cooking	11,497	5,313	11,169	9,691	42,848	35,657	2,722	6,132	33,446	20,005	15,611	4,136	**198,227**
Refrigeration	11,968	5,582	11,169	9,691	42,848	37,968	2,722	6,132	39,535	20,005	18,175	7,941	**213,736**
Exterior Lighting	11,968	4,032	10,468	9,691	41,652	37,175	2,722	2,455	39,718	20,005	15,810	7,941	**203,637**
Interior Lighting	11,968	5,582	11,169	9,691	42,848	39,342	2,722	6,132	44,597	20,005	18,469	15,307	**227,832**
Office Equipment	11,968	5,582	11,169	8,648	42,848	38,989	2,722	6,132	44,066	20,005	18,449	14,432	**225,010**
Miscellaneous	10,402	5,582	10,468	9,691	40,017	39,114	2,635	5,877	38,962	19,649	16,904	14,848	**214,149**
Process	0	0	731	0	375	2,288	0	0	3,373	0	516	0	**7,283**
Motors	9,786	3,604	6,350	5,991	37,604	24,461	2,722	1,950	15,442	10,327	4,951	2,588	**125,776**
Air Compressors	10,908	0	7,086	3,232	14,832	13,282	416	0	10,597	3,274	2,586	4,058	**70,271**
Segment Total	**11,968**	**5,582**	**11,169**	**9,691**	**42,848**	**39,342**	**2,722**	**6,132**	**44,597**	**20,005**	**18,469**	**15,307**	**227,832**

Step 1a. Normalization of load information using building floor area

For each building type, all hourly load information was first normalized by the floor area of the buildings from which the loads were collected. This was accomplished by summing the loads from all of the buildings of a given type, separately for each end use and for each hour, and then dividing each by the total floor area of the buildings from which loads had been metered.

Step 1b. Development of non-weather sensitive hourly loads by season

Non-weather sensitive load shapes were developed by averaging the normalized loads for each hour across all weekdays in each season (also excluding holidays) separately for each non-weather sensitive end use.

For the residential building analysis, summer hourly load shapes were developed from loads metered during the months of June through September. Winter hourly loads were developed from loads metered during the months of December through February. Spring hourly loads were developed from loads metered during the months of April and May.

For the commercial building analysis, summer hourly load shapes were developed from loads metered during the months of July through September. Winter hourly loads were developed from loads metered during the months of December through February. Spring hourly loads were developed from loads metered during the months of March through May.[8]

Step 1c. Development of hourly weather sensitivity factors

Hourly weather sensitivity factors were developed by correlating statistically hourly weather sensitive loads to hourly measures of weather. A separate sensitivity factor was developed for each hour of the day. Hourly cooling and heating sensitivity factors were developed using hourly load and weather information from weekdays (excluding holidays) during the same summer and winter months used to develop non-weather sensitive loads.

The hourly measure of weather is based on a well-established metric called the heat index [National Weather Service 2020]. It is a non-linear combination of both dry bulb temperature and relative humidity.

[8] The months from which spring hourly loads were developed differ between residential and commercial buildings because of the climates in which the original load shapes were developed or monitored. Spring in the pacific northwest, which was the source of load information for residential buildings, is generally concentrated in the months of April and May. Spring in California, the source of load information for commercial buildings, is generally concentrated in the months of March, April, and May.

[Equation 1]

$$HI = -42.379 + 2.04901523*T + 10.14333127*RH - .22475541*T*RH - .00683783*T*T - .05481717*RH*RH + .00122874*T*T*RH + .00085282*T*RH*RH - .00000199*T*T*RH*RH$$ [9]

HI – heat index; T – temperature (F)[10]; RH – relative humidity (%)

To account for the effects of thermal lag, which is a form of heat storage in the physical mass of buildings, a weighted version of heat index is used in the past two hourly values of index are combined with the current hourly value.

[Equation 2]

$$HI_{adj} = (0.6 * HI_t) + (0.3 * HI_{t-1}) + (0.1 * HI_{t-2})$$

The correlation between the hourly weighted heat index and hourly cooling or heating load is estimated using a simple linear regression. The regression yields both a constant (or intercept term) and coefficient that depends on the hourly weighted heat index value. The constant and coefficient, taken together, are the hourly weather sensitivity factor.

Hourly weather sensitivity factors for residential cooling and heating were developed using SCADA data collected by BPA from a predominantly residential feeder in Vancouver, WA in a four-step process. First, hourly SCADA data from a time of the year when little or no cooling or heating was expected were used to develop an hourly non-weather sensitive feeder load (a "mild day" load). Second, this load was subtracted from hourly feeder loads on selected days during the summer and winter months when cooling and heating, respectively, were expected. See Figure 2 for an illustration of the steps involved in applying this process to estimate summer cooling loads. Third, the resultant hourly summer cooling and winter heating feeder loads were normalized by an estimate of the total floor area of residences in the feeder.[11] Fourth, the hourly weighted heat index on these summer and winter days were regressed against the normalized summer cooling and winter heating loads, respectively.

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[9] Note that this version of the equation applies only when the temperature is greater than 80 degrees F, and also when both the temperature is greater than 112 degrees F and the relative humidity is greater than 13%. For the equations that apply to other ranges of temperatures and relative humidity, see https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml.

[10] Note that hourly Canadian weather, which is recorded in Centigrade, is first converted to Fahrenheit before applying this equation.

[11] The total floor area of the residences in the feeder was estimated by dividing the mild day load by the normalized non-weather sensitive loads estimated in step 1b.

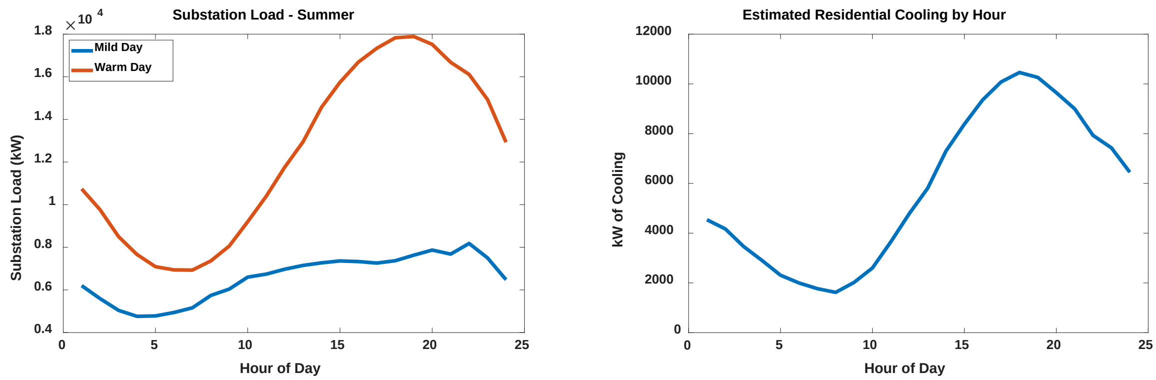

Figure 2. Substation Loads Used to Estimate Residential Cooling Loads (left); Estimated Residential Cooling Load (right)

The hourly weather sensitivity factors for commercial building cooling and heating were developed by applying the same regression-based approach to the aggregated and normalized CEUS commercial buildings by type. The regressions relied on the hourly weighted heat indices and the hourly weekday loads drawn from the same months used to develop the non-weather sensitive loads for these building types (again excluding holidays).

Figure 3 present examples of this analysis process for cooling loads in grocery stores for two different hours (4 AM and 4 PM). Each figure displays the hourly normalized cooling loads that were measured along with the regression line that best correlates these loads with the weighted hourly heat index values.

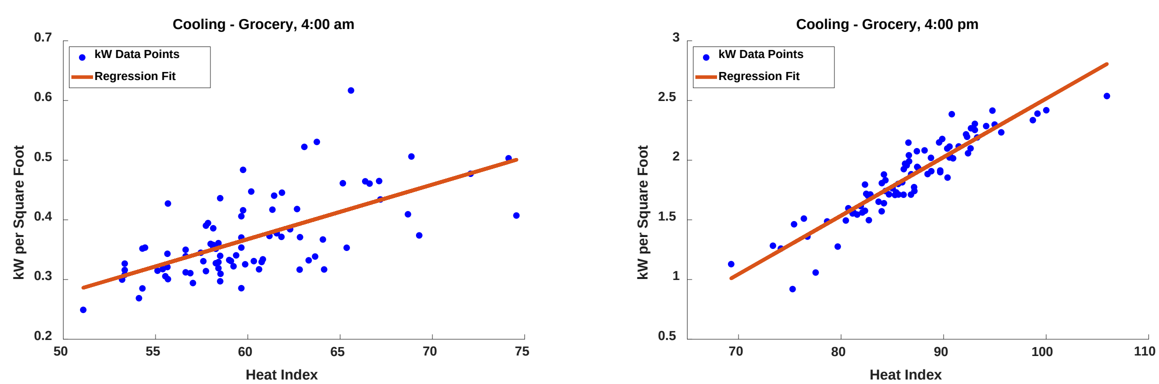

Figure 3. Cooling Load Versus Heat Index for Grocery at 4 AM (left); Cooling Load Versus Heat Index for Grocery at 4 PM (right)

3.2 Step 2. Compilation and application of region-specific information

The outputs from step 1 are, for each building type, hourly weather sensitivity factors for both cooling and heating, and seasonal, normalized, hourly non-weather sensitive loads. Step 2 applies region-specific information on hourly weather and on the discretionary use of electricity for space cooling, space heating, water heating, and cooking to adjust these outputs to develop region-specific hourly loads for all buildings and end uses.

Step 2 involves identifying weather stations and developing representative hourly weather information for them for each region, and then applying this information to the weather sensitivity factors to estimate hourly weather-sensitive loads (step 2a). It then involves developing information on the extent to which electricity is used for space cooling, space heating, water heating, and cooking in each region, and then using this information to adjust the hourly load shapes for each of these end uses (step 2b).

The outputs from step 2 are, for each building type and for these end uses, alone, a region-specific, normalized, set of hourly loads for a summer peak day, winter peak day, and spring light load day. Step 2 does not involve adjustments to any of the remaining end uses (i.e., those other than space cooling, space heating, water heating, and cooking). These remaining hourly normalized load shapes are simply passed directly from step 1 on to step 3.

Step 2a. Estimation of region-specific hourly weather-sensitive loads

The estimation of region-specific hourly weather-sensitive loads involves three intermediate steps. First, representative weather cities were identified by transmission planners in each of the regions. Second, 20 years of historic weather information was reviewed and 24-hour heat index profiles were developed to be representative of summer peak day, winter peak day, and spring light load day conditions separately for each of weather cities. Third the hourly profiles for each weather city were applied to the weather sensitivity factors to produce unique hourly weather-sensitive loads for both cooling and heating that were also specific to each weather city.

Leadership of the NERC LMTF met with representatives of each of the NERC regional reliability planning entities to identify cities (airports) whose weather would be best reflective of conditions across each region. A total of 96 weather cities were identified through this process. See Figure 4 and Appendix A.

For each weather city, 20 years of historic hourly weather information (from 1999 through 2018) was assembled from the National Centers for Environmental Information and Government of Canada Historical Climate Data [NCEI 2020, Government of Canada 2020] and the heat index was calculated for each hour. The identification of hourly weather for a representative summary peak, winter peak, and spring light load day is based on selecting the day from this historical record based on the following criteria.

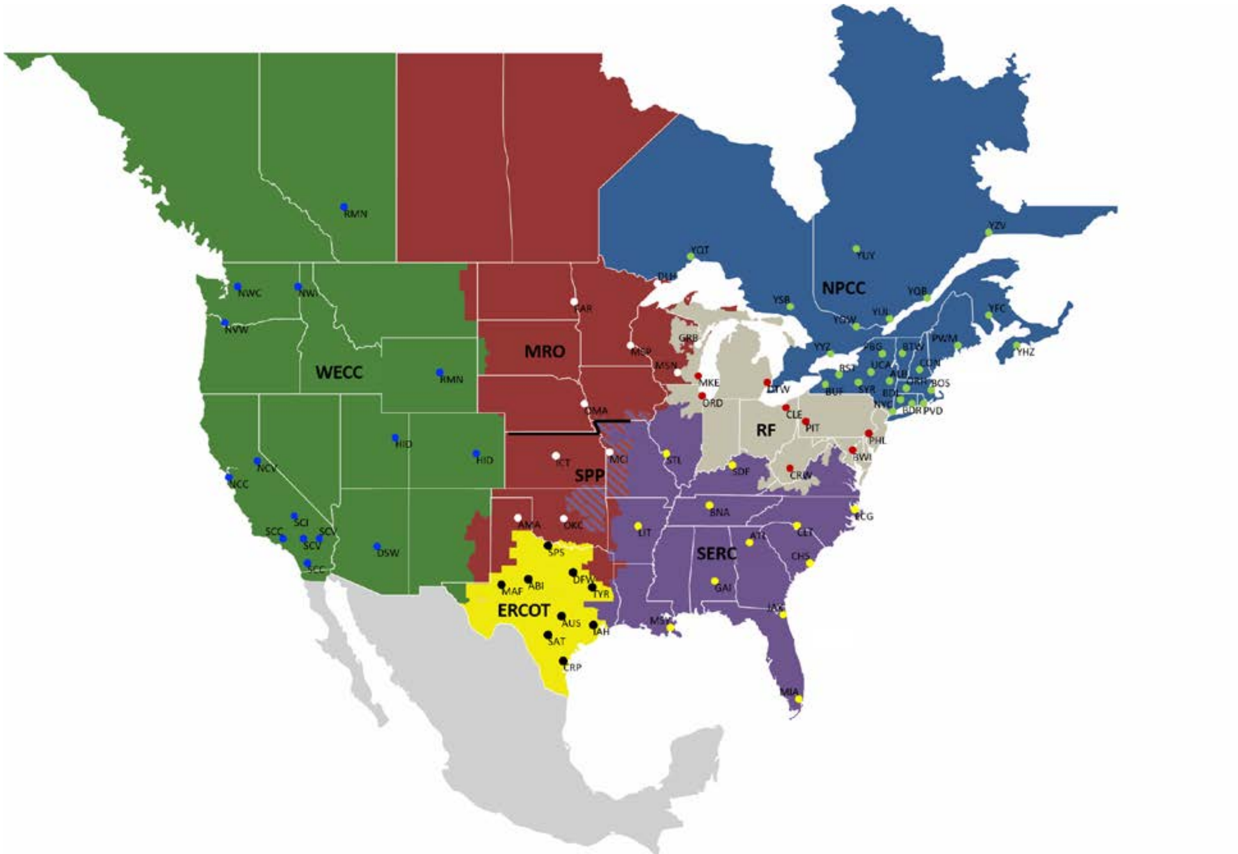

Figure 4. North American Weather Cities Used in Load Composition Analysis

For the summer peak day, the criteria were that the day had to be drawn from the months of July and August and that the highest daily hourly heat index value had to correspond to the 90th percentile across all highest daily hourly heat index values recorded over the 20-year record. For the winter peak day, the criteria were that the day had to be drawn from the period between December 15th and February 15th and that the lowest daily hourly heat index value had to correspond to the 90th percentile across all lowest daily hourly heat index values recorded over the 20-year record. See Figure 5.

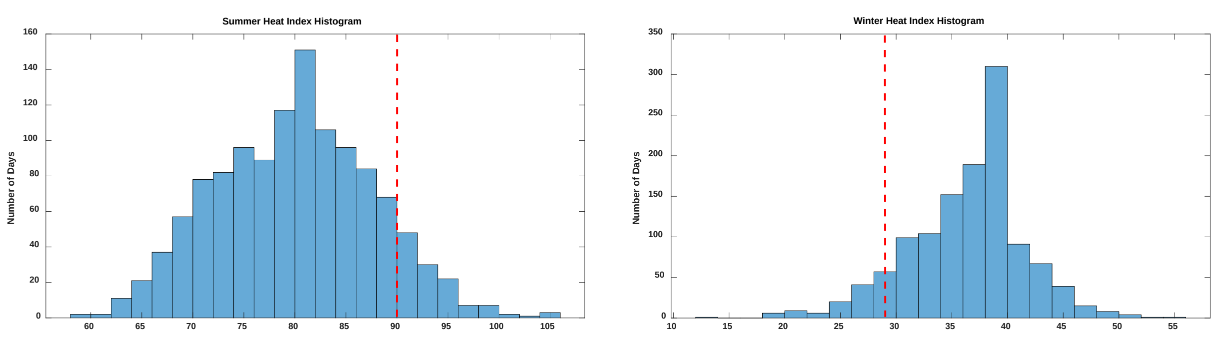

Figure 5. Identification of Summer Peak Day – example (left); Identification of Winter Peak Day – example (right)

For the spring light load day, the criteria were that the day had to be drawn from the months of April and May and that the highest daily hourly heat index value had to be between 68 and 72 degrees F.

The 24-hour heat index values for the summer peak, winter peak, and spring light load day are then lagged (see Equation 2) and then combined with the weather sensitivity factors to yield 24 normalized hourly cooling and heating loads for each building type.

Step 2b. Estimation of region-specific hourly loads for discretionary electricity end uses

The estimation of region-specific hourly loads for space cooling, space heating, water heating, and cooking involves scaling the normalized hourly loads for these end uses by electrification factors that reflect the extent to which electricity is used for these end uses in each region.

The electrification factors for the weather cities in the United States were taken from survey research conducted by the US Energy Information Administration (EIA). The surveys relied on a statistically-based sampling procedure that produces electrification factors that are representative of each building type for each of nine census regions in the US. See Figure 6.

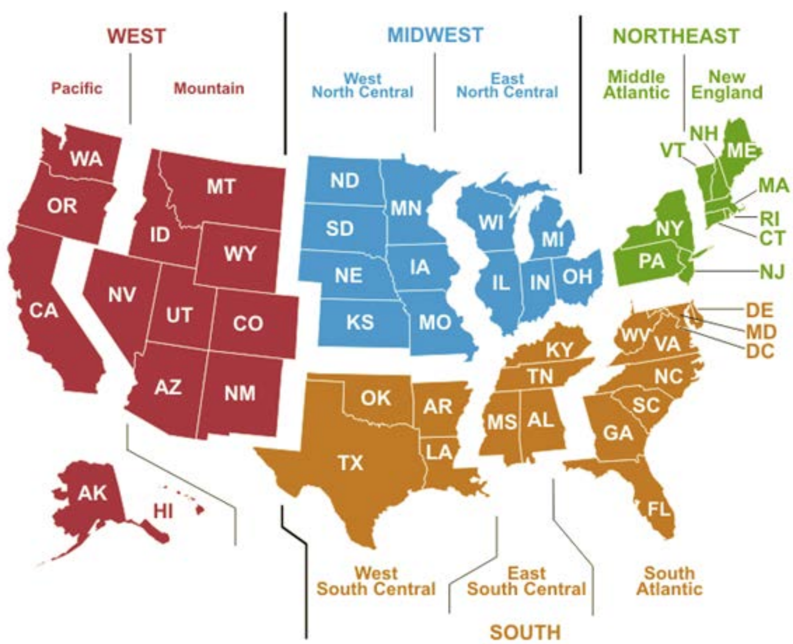

Figure 6. U.S. Census Regions

The residential electrification factors were taken from the EIA Residential Energy Consumption Survey (RECS) [US EIA 2015]. RECS is a periodic study that provides detailed information about energy usage in U.S. homes. For the 2015 survey, which is the basis for the residential electrification factors, approximately 5700 surveys were conducted. See Table 4. Note that the electrification factor for cooking is applied to the residential non-weather sensitive load shape for oven.

Table 4. Electrification Factors – U.S. Residential

Region	Heat Pump	Other Electric Heat	Cooling	Water Heating	Cooking
New England	3%	10%	75%	36%	59%
Middle Atlantic	3%	11%	88%	31%	43%
East North Central	3%	17%	92%	34%	57%
West North Central	4%	18%	92%	40%	75%
South Atlantic	24%	32%	95%	72%	78%
East South Central	24%	39%	93%	76%	75%
West South Central	8%	45%	95%	58%	71%
Mountain	8%	19%	78%	31%	67%
Pacific	7%	25%	66%	32%	53%

The commercial electrification factors were taken from the Commercial Building Energy Consumption Survey (CBECS) [US EIA 2012] CBECS is a national sample survey that collects information on the stock of U.S. commercial buildings, including their energy-related building characteristics and energy usage data (consumption and expenditures). For the 2012 survey, which is the basis for the commercial electrification factors, approximately 6700 surveys were conducted. See Table 5.

Table 5. Electrification Factors – U.S. Commercial

Region	Heat Pump	Other Electric Heat	Cooling	Water Heating	Cooking
New England	9%	2%	77%	45%	27%
Middle Atlantic	9%	6%	89%	41%	31%
East North Central	5%	8%	90%	39%	33%
West North Central	7%	14%	87%	49%	32%
South Atlantic	27%	20%	91%	62%	30%
East South Central	17%	23%	88%	59%	31%
West South Central	10%	30%	81%	47%	25%
Mountain	10%	13%	84%	40%	31%
Pacific	15%	21%	88%	51%	22%

The electrification factors for the weather cities in Canada were provided by Canadian members of the Northeast Power Coordinating Council. See Table 6 and Table 7.

Table 6. Electrification Factors – Canadian Residential

City	Heating	Cooling	Water Heating	Cooking
Fredericton	67%	58%	93%	97%
Halifax	56%	48%	50%	95%
Ottawa	28%	88%	23%	86%
Quebec City	77%	42%	88%	92%
Thunder Bay	26%	88%	51%	81%
Sudbury	15%	88%	21%	85%
Montreal	77%	42%	88%	92%
Rouyn Noranda	77%	42%	88%	92%
Toronto	15%	88%	21%	85%
SeptIles	77%	42%	88%	92%
Calgary	8%	77%	13%	96%

Table 7. Electrification Factors – Canadian Commercial

City	Heating	Cooling	Water Heating	Cooking
Fredericton	78%	56%	71%	0%
Halifax	51%	63%	57%	19%
Ottawa	17%	89%	89%	52%
Quebec City	62%	84%	82%	63%
Thunder Bay	19%	90%	25%	47%
Sudbury	12%	89%	23%	50%
Montreal	62%	84%	82%	63%
Rouyn Noranda	62%	84%	82%	63%
Toronto	12%	89%	23%	50%
SeptIles	62%	84%	82%	63%
Calgary	8%	77%	13%	96%

3.3 Step 3. Mapping end uses to the composite load model

Step 3 involves mapping, by building type, the seasonal, normalized, hourly end-use loads to the seven composite load model load types used in transmission planning modeling studies.

The outputs from Step 3 are, for each building type, a region-specific, normalized, set of hourly loads each of the seven composite load model load types for a summer peak day, winter peak day, and spring light load day.

The mapping is embodied in a series of "look-up" tables—one for each building type—that are known collectively as the Rules of Association. The original Rules of Association were developed by transmission planners and industry experts in the Western Interconnection. In 2019, aspects of the Rules of Association were updated by information from a recently completed DOE assessment of motor systems in the commercial and industrial sectors [Rao, et al 2019].

The DOE Motor System Market Assessment project was a field assessment of the current stock, electricity consumption, and cost-effective energy savings opportunity for motor systems in U.S. commercial building and industrial facilities. The assessment involved field surveys of over 300 industrial and 150 commercial facilities across the United States. The assessment documents the increased reliance on variable speed drives for many fan and pumping motors in the commercial sector (compared to what was indicated in the original Rules of Association).

Table 8 through Table 11 present the updated Rules of Association used in the load composition analysis for all commercial, large office, lodging, and residential buildings, respectively.

Table 8. Rules of Association for All Commercial Buildings Except Large Office and Lodging

	Heating	Cooling	Vent	WaterHeat	Cooking	Refrig	ExtLight	IntLight	OfficeEquip	Misc	Process	Motors	AirComp
MOTOR A	0	0.65	0	0	0	0.8	0	0	0	0	0	0	1
MOTOR B	0	0.05	0.7	0	0	0.1	0	0	0	0	0.3	1	0
MOTOR C	0	0.1	0	0	0	0.1	0	0	0	0	0	0	0
MOTOR D	0	0	0	0	0	0	0	0	0	0	0	0	0
PWREL	0	0.2	0.3	0	0	0	0	0	1	0	0.3	0	0
CONST-R	1	0	0	1	1	0	0	0	0	1	0.4	0	0
COST-I	0	0	0	0	0	0	1	1	0	0	0	0	0

Table 9. Rules of Association for Large Office

	Heating	Cooling	Vent	WaterHeat	Cooking	Refrig	ExtLight	IntLight	OfficeEquip	Misc	Process	Motors	AirComp
MOTOR A	0	0	0	0	0	0.8	0	0	0	0	0	0	1
MOTOR B	0	0.6	0.5	0	0	0.1	0	0	0	0	0	1	0
MOTOR C	0	0.15	0	0	0	0.1	0	0	0	0	0	0	0
MOTOR D	0	0	0	0	0	0	0	0	0	0	0	0	0
PWREL	0	0.25	0.5	0	0	0	0	0	1	0	1	0	0
CONST-R	1	0	0	1	1	0	0	0	0	1	0	0	0
COST-I	0	0	0	0	0	0	1	1	0	0	0	0	0

Table 10. Rules of Association for Lodging

	Heating	Cooling	Vent	WaterHeat	Cooking	Refrig	ExtLight	IntLight	OfficeEquip	Misc	Process	Motors	AirComp
MOTOR A	0	0.35	0	0	0	0	0	0	0	0	0	0	1
MOTOR B	0	0.15	0.9	0	0	0	0	0	0	0	0.3	1	0
MOTOR C	0	0.1	0	0	0	0	0	0	0	0	0	0	0
MOTOR D	0	0.35	0	0	0	1	0	0	0	0	0	0	0
PWREL	0	0.05	0.1	0	0	0	0	0	1	0	0.3	0	0
CONST-R	1	0	0	1	1	0	0	0	0	1	0.4	0	0
COST-I	0	0	0	0	0	0	1	1	0	0	0	0	0

Table 11. Rules of Association for Residential Buildings

	Heating	Cooling	Computer	Dryer	Entertainment	Freezer	HotWater	Light	Other	Oven	Plugs	Refrig	Washer
MOTOR A	0	0	0	0	0	0	0	0	0	0	0	0	0
MOTOR B	0	0.1	0	0	0	0	0	0	0	0	0	0	0
MOTOR C	0	0.1	0	0.4	0	0	0	0	0	0	0.1	0	1
MOTOR D	0.1	0.8	0	0	0	1	0	0	0	0	0	1	0
PWREL	0	0	1	0	1	0	0	0	0.5	0	0.1	0	0
CONST-R	0.9	0	0	0.6	0	0	1	1	0.5	1	0.8	0	0
COST-I	0	0	0	0	0	0	0	0	0	0	0	0	0

3.4 Step 4. Developing region-specific feeder models

Step 4 involves developing region-specific feeder models that are representative of different "economic" activities, which are used to distinguish non-industrial feeders from among one another.

The outputs from step 4 are composite load models for feeders for 96 region-specific sets of hourly loads for a summer peak day, a winter peak day, and a spring light load day.

Four distinct feeder models were developed. Each feeder model is comprised of a floor-area weighted combination of the normalized hourly loads for different combinations of building types.

The first feeder model, RES, is representative of a feeder serving loads in a suburban area. This model is comprised largely of residential buildings. However, it also contains a variety of low-rise non-residential buildings, such as small office, retail, grocery, restaurants, schools, hospitals, etc. See Table 12.

Table 12. Composition of Suburban or RES Feeder

Building Type	Number	Avg. SqFt/Building	Total SqFt	
Res. Home	4000	1500	6000000	81.2%
College	0	500000	0	0.0%
Grocery	2	45000	90000	1.2%
Health	4	10000	40000	0.5%
Large Office	0	700000	0	0.0%
Lodging	0	50000	0	0.0%
Miscellaneous	1	10000	10000	0.1%
Refrigerated Warehouse	0	50000	0	0.0%
Restaurant	20	5000	100000	1.4%
Retail	30	20000	600000	8.1%
School	4	100000	400000	5.4%
Small Office	0	50000	0	0.0%
Warehouse	3	50000	150000	2.0%

The second feeder model, COM, is representative of a feeder serving loads in a downtown, urban area. This model features, uniquely among the four feeder models, large high-rise offices, which feature central HVAC plants. In contrast to low-rise buildings which rely on composite load motor type A for cooling, high-rise buildings rely on composite motor type B for cooling. See Table 13.

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Table 13. Composition of Downtown Urban or COM Feeder

Building Type	Number	SqFt/Building	Total SqFt	
Res. Home	0	1500	0	0.0%
College	0	500000	0	0.0%
Grocery	2	45000	90000	1.5%
Health	4	10000	40000	0.6%
Large Office	6	700000	4200000	68.1%
Lodging	20	50000	1000000	16.2%
Miscellaneous	1	10000	10000	0.2%
Refrigerated Warehouse	0	50000	0	0.0%
Restaurant	25	5000	125000	2.0%
Retail	30	20000	600000	9.7%
School	0	100000	0	0.0%
Small Office	2	50000	100000	1.6%
Warehouse	0	50000	0	0.0%

The third feeder model, MIX, is a hybrid that combines as aspects of both the RES and COM feeder models. It is representative of feeders serving transition zones between largely residential suburban areas and dense high-rise urban areas. It contains fewer residential buildings than RES, but also does not contain large offices, which are prominent in COM. See Table 14.

Table 14. Composition of Hybrid or MIX Feeder

Building Type	Number	SqFt/Building	Total SqFt	
Res. Home	2000	1500	3000000	49.9%
College	0	500000	0	0.0%
Grocery	3	45000	135000	2.2%
Health	6	10000	60000	1.0%
Large Office	0	700000	0	0.0%
Lodging	6	50000	300000	5.0%
Miscellaneous	2	10000	20000	0.3%
Refrigerated Warehouse	2	50000	100000	1.7%
Restaurant	40	5000	200000	3.3%
Retail	40	20000	800000	13.3%
School	4	100000	400000	6.7%
Small Office	12	50000	600000	10.0%
Warehouse	8	50000	400000	6.7%

The fourth feeder model, RUR, is representative of feeders serving rural areas. Like RES, it contains a significant amount of residential buildings. But, it differs from RES in the variety and proportions of non-residential buildings. See Table 15.

Table 15. Composition of Rural or RUR Feeder

Building Type	Number	SqFt/Building	Total SqFt	
Res. Home	400	1500	600000	43.5%
College	0	500000	0	0.0%
Grocery	1	45000	45000	3.3%
Health	0	10000	0	0.0%
Large Office	0	700000	0	0.0%
Lodging	1	50000	50000	3.6%
Miscellaneous	0	10000	0	0.0%
Refrigerated Warehouse	0	50000	0	0.0%
Restaurant	5	5000	25000	1.8%
Retail	3	20000	60000	4.3%
School	1	100000	100000	7.2%
Small Office	0	2000	0	0.0%
Warehouse	10	50000	500000	36.2%

4. Representative Outcomes from the Load Composition Analysis

The outputs from the load composition analysis are composite load models for four sets of feeders for 96 region-specific sets of hourly loads for a summer peak day, a winter peak day, and a spring light load day. Figure 7 shows, for a single region/weather-city (Atlanta) how the hourly loads vary over the hours of the summer peak day for the RES and MIX feeder models. Figure 8 shows how the composite load model proportions vary at the time of summer peak demand for these same four feeders.

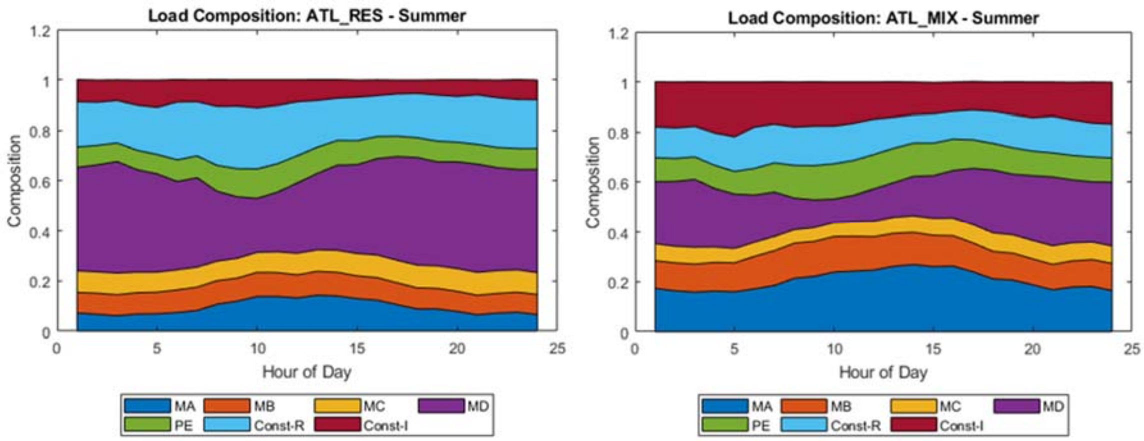

Figure 7. Summer Peak Day, Atlanta – RES Feeder (left); Summer Peak Day, Atlanta – MIX Feeder (right)

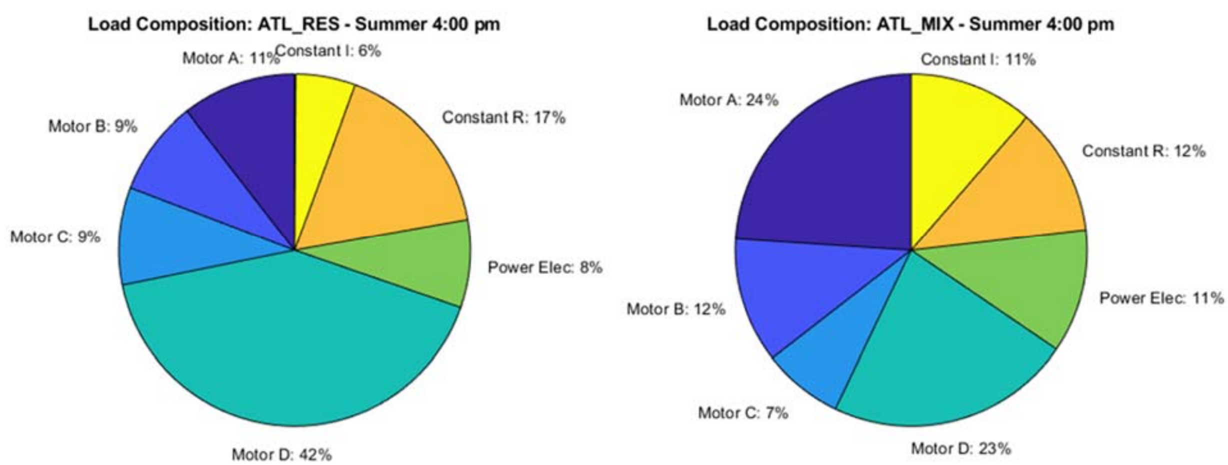

Figure 8. Summer Peak Hour (4 pm), Atlanta – RES Feeder (left); Summer Peak Hour (4 pm), Atlanta – MIX Feeder (right)

Figure 9 shows, for the MIX feeder model in a different region/weather-city (Toronto), how the hourly loads vary over the hours of the summer peak, winter peak, and spring light load day.

shows how the composite load model proportions vary at the time of peak demand for these three seasons.

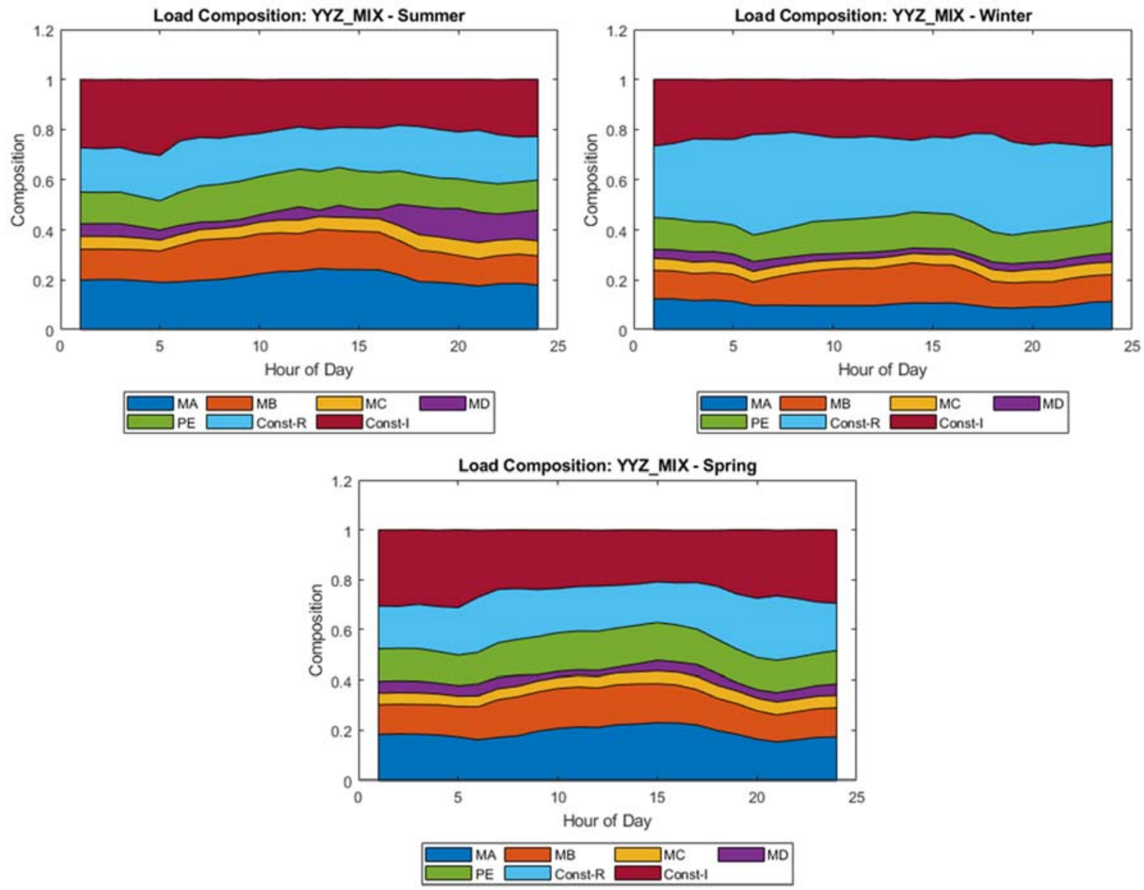

Figure 9. MIX Feeder, Toronto, Summer Peak Day (top left); MIX Feeder, Toronto, Winter Peak Day (top right); MIX Feeder, Toronto, Spring Light Load Day (bottom)

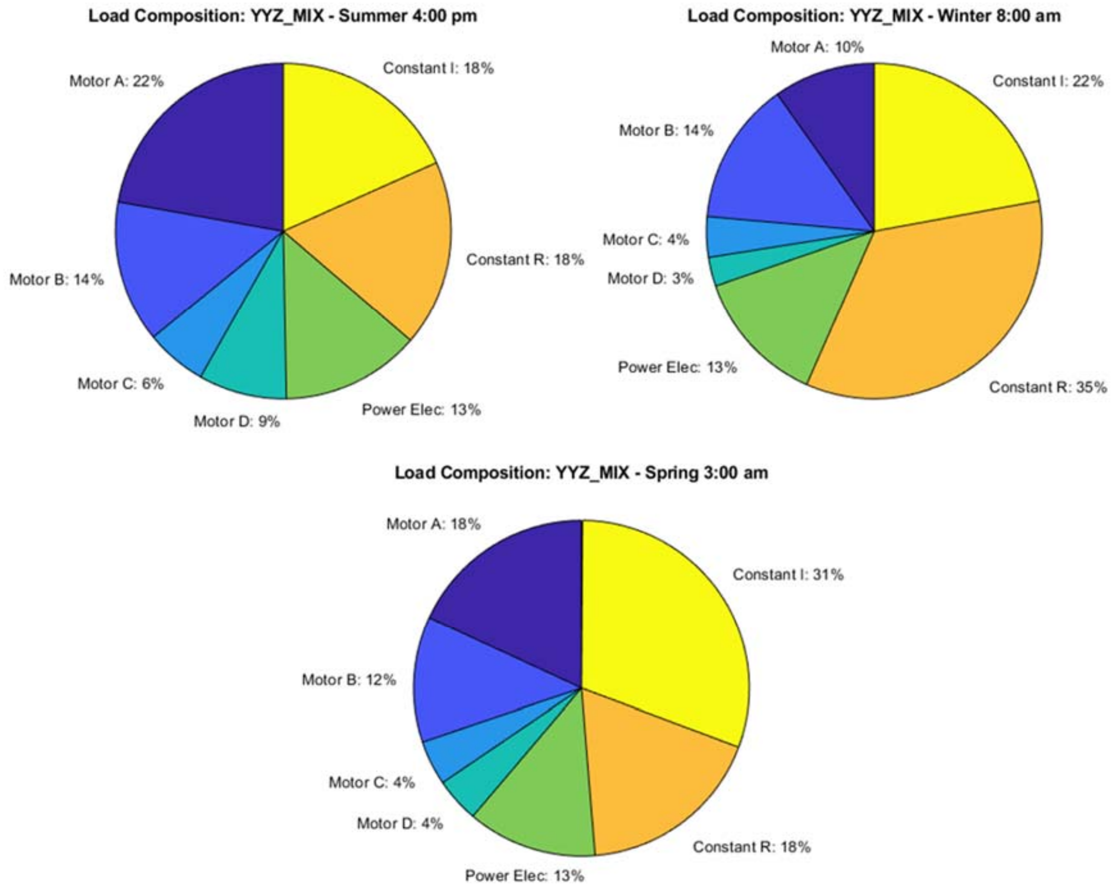

Figure 10. MIX Feeder, Toronto, Summer Peak Hour (4 pm) (top left); MIX Feeder, Toronto, Winter Peak Hour (8 am) (top right); MIX Feeder, Toronto, Spring Light Load Hour (3 am) (bottom)

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Appendix A

This appendix documents the mapping of information used in the analysis across the various data sources. Specifically, Table A - 1 links the weather cities used to develop hourly weather sensitive loads for each region to the U.S. census regions and Canadian provinces that were used to develop electrification factors for space heating, space cooling, water heating, and cooking.

Table A - 1. Regions, Weather Cities, and U.S. Census Regions/Canadian Provinces

Region	Weather City	Airport Code	US Census Region/ Canadian Province
ERCOT	Abilene, TX	ABI	West South Central
	Austin, TX	AUS	
	Corpus Christy, TX	CRP	
	Dallas, TX	DFW	
	Houston, TX	IAH	
	Midland, TX	MAF	
	San Antonio, TX	SAT	
	Tyler, TX	TYR	
	Wichita Falls, TX	SPS	
MRO	Duluth, MN	DLH	West North Central
	Fargo, ND	FAR	
	Minneapolis, MN	MSP	
	Omaha, NE	OMA	
	Green Bay, WI	GRB	East North Central
	Madison, WI	MSN	
NPCC	Bangor, ME	BGR	New England
	Bridgeport, CT	BDR	
	Boston, MA	BOS	
	Burlington, VT	BTV	
	Concord, NH	CON	
	Hartford, CT	BDL	
	Portland, ME	PWM	
	Providence, RI	PVD	
	Worcester, MA	ORH	
	Albany, NY	ALB	Middle Atlantic
	Buffalo, NY	BUF	
	New York City, NY	JFK	
	Plattsburgh, NY	PBG	
	Rochester, NY	RST	
	Syracuse, NY	SYR	

Region	Weather City	Airport Code	US Census Region/ Canadian Province
	Utica, NY	UCA	
	Fredericton, NB	YFC	Prov. of New Brunswick
	Halifax, NS	YHZ	Prov. of Nova Scotia
	Ottawa, ON	YOW	Prov. of Ontario
	Sudbury, ON	YSB	
	Thunder Bay, ON	YQT	
	Toronto, ON	YYZ	
	Montreal, QC	YUL	Prov. of Quebec
	Quebec City, QC	YQB	
	Rouyn Noranda, QC	YUY	
	Sept Iles, QC	YZV	
PJM	Chicago, IL	ORD	East North Central
	Cleveland, OH	CLE	
	Detroit, MI	DTW	
	Milwaukee, WI	MKE	
	Philadelphia, PA	PHL	Middle Atlantic
	Pittsburgh, PA	PIT	
	Baltimore, MD	BWI	South Atlantic
	Charleston, WV	CRW	
SERC	Atlanta, GA	ATL	South Atlantic
	Charleston, SC	CHS	
	Charlotte, NC	CLT	
	Elizabeth City, NC	ECG	
	Jacksonville, FL	JAX	
	Miami, FL	MIA	
	Tampa, FL	TPA	
	Louisville, KY	SDF	East South Central
	Montgomery, AL	MGM	
	Nashville, TN	BNA	
	Little Rock, AK	LIT	West South Central
	New Orleans, LA	MSY	
	St. Louis, MO	STL	West North Central
SPP	Kansas City, MO	MCI	West North Central
	Wichita, KS	ICT	
	Amarillo, TX	AMA	West South Central
	Oklahoma City, OK	OKC	
WECC	Cheyenne, WY	CYS	Mountain
	Denver, CO	DEN	

Region	Weather City	Airport Code	US Census Region/ Canadian Province
	Phoenix, AZ	PHX	
	Salt Lake City UT	SLC	
	Bakersfield, CA	BFL	Pacific
	Los Angeles, CA	LAX	
	Ontario, CA	ONT	
	Portland, OR	PDX	
	Riverside, CA	RAL	
	Sacramento, CA	SMF	
	San Diego, CA	SAN	
	San Francisco, CA	SFO	
	Seattle, WA	SEA	
	Spokane, WA	GEG	
	Calgary, AB	YYC	Prov. of Alberta