The University of Texas at Austin
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Documentation of Calculation of Historical, Baseline, and Future Energy Flows to 2050 by Region for Energy Futures Dashboard of the Energy Infrastructure of the Future study, February 2021 (paper 2020.4.1)

ENERGY FUTURES DASHBOARD

Calculation of Historical, Baseline, and Future Energy Flows to 2050 by Region

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Abstract

This document describes the data and methods used for calculating historical annual energy consumption, for the years 2000-2016, and energy consumption for the baseline (or default) case for the future year 2050. These data are specified for each region within the U.S.-48 as defined for the Energy Infrastructure of the Future project. The data include annual primary energy consumption per primary energy source, end-use energy consumption data per energy carrier and sector (residential, commercial, industrial, & transportation) as well as 8760 hour per year profiles of electricity generation required to serve sectoral-level electricity demand.

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Introduction

The Energy Infrastructure of the Future (EIoF) study seeks to provide a robust understanding of the state of the cost and other impacts of energy infrastructure and consumption in the United States. The flagship product of the EIoF project is the Energy Futures Dashboard, a user interactive web-based tool that allows users to see the impacts of their choices for three major categories of energy production and use for the year 2050: electricity generation mix, the percentage of light-duty vehicles driven on electricity versus liquid fuels, and the percentage of homes heated by electricity and natural gas. For the purposes of this study, the country is divided into geographic regions established by the EIoF project (see Figure 1). The regional definitions enable us to investigate broad geographical differences in energy infrastructure quantities, costs, regulations, and customers that can be compared to trends for the continental United States. In total, there are 13 regions comprised of one or more states.

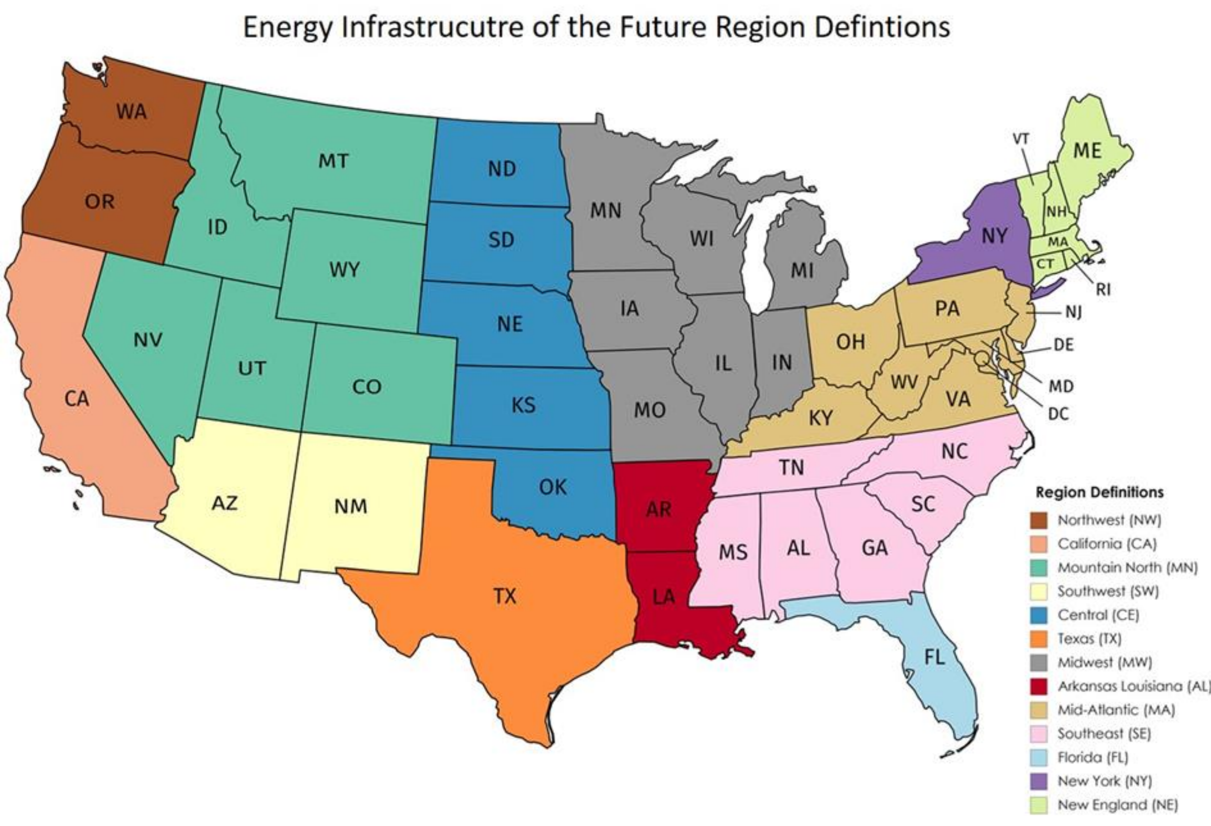

Figure 1. Regional definitions used for analysis in the Energy Infrastructure of the Future (EIoF) study.

This white paper summarizes the methodology for estimating the “baseline” or default total primary energy consumption, end-use energy demands, and hourly electricity generation profiles for the year 2050 for each defined geographic region within the EIoF project. These default energy data inform the online interactive decision support tool, or Energy Futures Dashboard (EFD), that is the interface for users to interact and learn from the data (see Figure 2).

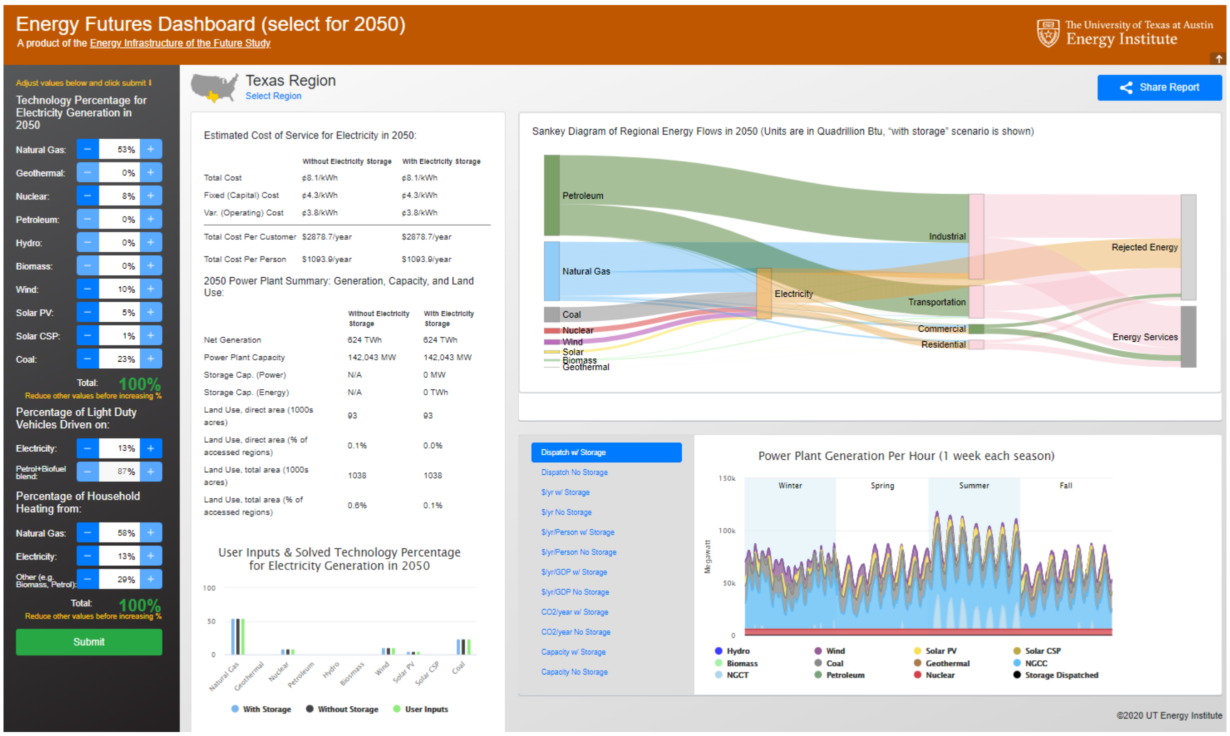

Figure 2. A screen shot of the Energy Futures Dashboard of the EIoF project.

One of displays by which the EFD provides feedback to the user is a Sankey diagram (see Figure 3). Since the EFD provides data in a format to inform such a diagram, this document largely describes how we arrange the data in that format of input-output matrices that are commonly used in economics. In doing this we follow the Physical Supply Use Table, or PSUT, approach of Heun *et al.* (2018) and use Heun's "Recca" R package[1] that facilitates the mathematics within that paper.

[1] Recca R package for performing Sankey diagram calculations: https://rdrr.io/github/MatthewHeun/Recca/.

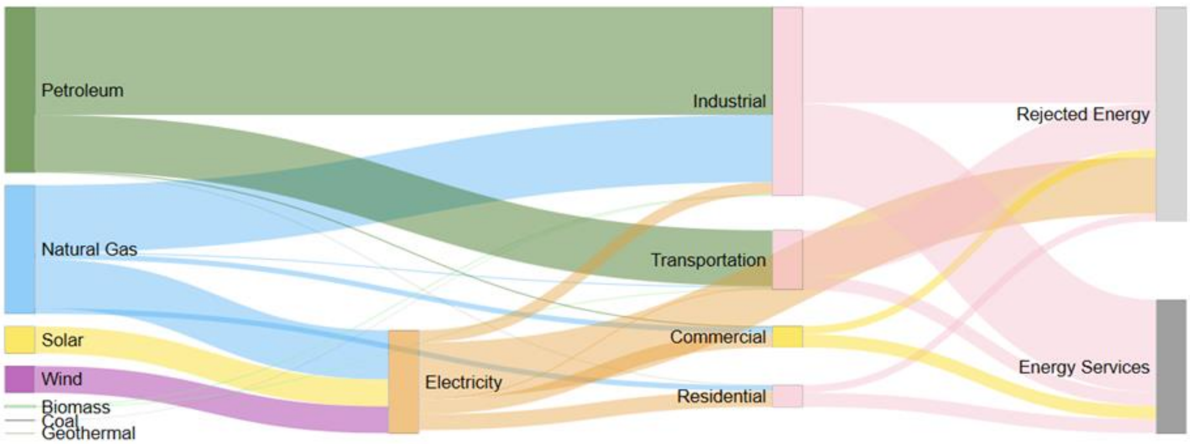

Figure 3. Sankey diagram, as used in the EIoF project Energy Futures Dashboard (EFD) to communicate and summarize the user's choices for future energy use.

The PSUT framework is one focused on organization of data in a manner that specifies the input and output flows of each node within the Sankey diagram. For example, it enables consistent accounting of the energy value of primary energy wind into the electricity node and the energy value of wind electricity flowing out form the electricity node such that it can be added to the energy value of electricity flowing from all types of power plants represented by the electricity node. There are three matrices of interest, the U, V, and Y matrices, and each represents the same information in formats that facilitate the matrix mathematics for energy accounting.

The U matrix is the "use" matrix. Each row specifies a "product" and each column specifies an "industry". For our purposes, products are primary energy, electricity and end use consumption of energy carriers, and the services received from consuming energy. In essence, the U matrix specifies how much energy input flows into a given process. For example, one column "industry" or process is "wind plant." The sum of all rows in this column equals all electricity generation from wind power plants. There is some amount of primary energy associated with the operation of the wind plant that is listed in a "product" row specified as "wind flow." For the column representing energy inputs into natural gas power plants (e.g., "natural gas plant"), we would list a value of 0 for "wind flow" but a positive number for "natural gas flow".

The V matrix is the "supply" or "make" matrix. Each row of the V matrix specifies an "industry" and each column specifies a "product." The rows of the V matrix are the columns of the U matrix, and the columns of the V matrix are the rows of the U matrix. The V matrix defines which industries (the rows) contribute to making any given product (the columns). Generally speaking, more than one industry can contribute to making a given product.

The Y matrix is the “final demand” matrix. Each rows of the Y matrix specifies a “product” and each column specifies a “sector”. This matrix can specify the quantity of each of the sectoral outputs (from “industrial”, “residential”, “commercial”, and “transportation”) that flows into the rightmost nodes of the Sankey diagram (e.g., “energy services” and “rejected energy”). In our case, this Y matrix is calculated given the input information into the U and V matrices, and thus this document does not describe any estimation of data input into the Y matrices for the historical data (e.g., year 2016) or assumed future energy services demand (e.g., year 2050).

For more information on the PSUT approach, the definitions of the U, V, and Y matrices used in the EIoF project, and the codes that perform these calculations, see Heun *et al.* (2018).

Summary Explanation of Methods and Codes

The EFD must be populated with a default, or baseline, 2050 scenario when a user first opens the website. The EFD is informed by both total annual energy flows (primary energy and end-use energy carriers) that are input into the U (use) and V (make) PSUT, or input-output, matrices that define the Sankey diagrams well as an hourly profile (8760 hours per year) for electricity generation and end-use demand. The annual flows within the U and V matrices must be consistent with the sum of the hourly electricity generation profiles (by primary energy type) and end-use profiles (by end-use sector).

The files and codes described below are of two types. The first are files that might reside in the researcher’s “*programming directory*” on his/her computer for performing calculations that prearrange and save data that are loaded when the EIoF EFD program is actually run. Files in this directory are not involved in the actual final calculations of the EIoF EFD. The second set of files are those that are required to actually take user input (via a URL or the web interface), perform calculations, and export outputs to the EIoF EFD web interface. These files are ultimately available via the GitHub site that houses all of the files, and this document refers to files that are required to perform the calculations, as triggered by the EFD, as being in the “*operating directory*” and its subdirectories in which they are located.

1) ***programming directory***: this is the home directory of codes and data files (as determined by a researcher on his/her own computer) for performing data analysis and preparatory calculations of input data for the EIoF EFD
2) ***operating directory***: this is the home directory of the final set of files that one would download from the GitHub repository that houses all of the final codes needed to run the EIoF EFD. This has two subdirectories:

a. ***/master_R_scripts***: this houses the underlying R codes of the EIoF EFD, and there are subdirectories that house input data for individual codes
    i. **/generate_FinalUVY_2050_data**:
    ii. **/generate8760_data**:
    iii. **/solveGen_data**:
b. ***/R_packages_static***: this houses all R packages that are needed to run the underlying R codes for the EIoF EFD

The following list summarizes the order of steps and the use of corresponding codes, in the order in which they must be used to develop the baseline information that informs the EIoF EFD. Following sections have more detail on each step.

Step 1 (summary): Organize Historical Energy Data by Geographic Regions

1. Create historical year (e.g., 2016-2020) U and V matrices using data from the Energy Information Administration (EIA) State Energy Data System (SEDS) data aggregated into geographic regions of states, EIoF regions, and U.S. Census Divisions (EIA SEDS, 2019). At the time of the EIoF project, a full set of SEDS data were only available through 2016 such that historical energy data by EIoF region are collected through that year and approximated to year 2020 (the starting year of the EFD). These data can be updated to years after 2016 as more data become available. These data represent the total annual flow of energy consumed per each primary energy source, net generation of electricity from each technology and fuel, and end use demand of energy by each sector and end-use service we have defined. All data are in units of British Thermal Unit (BTU) per year.
    a. **Code:** "Create_Sankey_Inputs_HistoricalData.R"
    b. **Output from this code:** "XX_Sankey_Input_U_2016.csv" and "XX_Sankey_Input_V_2016.csv" where XX represents a state, Census Division, and EIoF region. These are historical energy flows for the year 2016, and can be repeated for years after 2016 as more data are available in the EIA SEDS.
    c. **Rdata file:** These output .csv files are (later) saved in an R list called "U_2016_list" within the .Rdata file "Base_UV_Matrices.Rdata" that is stored in directory "***operating directory/master_R_scripts /generate_FinalUVY_2050_data***".

Step 2 (summary): Organize Future Projected Energy Data to 2050 by Census Region

2. Create historical 2017 year data and 2050 projected data in U and V matrices from EIA 2019 Annual Energy Outlook (AEO2019) reference scenario by geographic region of U.S. Census Division. The AEO projects future energy use by Census

Division, but not state, so we use these Census Division projections to translate to EIoF regions in code "Create_Sankey_Inputs_for_2050_EIoFRegions.R" in the next step.

a. **Code:** "Create_Sankey_Inputs_for2050_AEOCensusDivisions.R"
b. **Output from this code:** Outputs from this code are in the form of "East North Central_Sankey_Input_U_2050.csv", "East North Central_Sankey_Input_U_2017.csv", and "East North Central_Sankey_Input_V_2050.csv". These data are only needed to create other input data into the EIoF EFD, and thus they are not stored within a researcher's programming directory.

<u>Step 3 (summary): Organize Future Projected Energy Data to 2050 by EIoF Region</u>

3. Create an ***initial set*** of values for 2050 U and V matrices that are based on EIoF regions. This initial set does not yet include full assumptions about the baseline mix of electricity generation for 2050.
    a. **Code:** "Create_Sankey_Inputs_for_2050_EIoFRegions.R"
    b. **Inputs into this code:** This code uses both historical (year 2016) *State* and *Census Division* level U and V matrix inputs generated within code "Create_Sankey_Inputs_HistoricalData.R" and Census Division level U and V matrix calculations for years 2017 and 2050 generated from "Create_Sankey_Inputs_for2050_AEOCensusDivisions.R".
    c. **Output from this code:** The output from "Create_Sankey_Inputs_for_2050_EIoFRegions.R" is of the form "XX_Sankey_U_2050_InputTo_generate8670_baseline.csv" and "XX_Sankey_V_2050_InputTo_generate8670_baseline.csv" where each XX is a Census Division and which then get input into "generate8760_2050_baseline.R". These represent the annual flows of energy, in the form of the U and V matrices, for the baseline data that informs the EIoF EFD, except adjustments need to be made with regard to all flows related to electricity in "generate8760_2050_baseline.R". These data only need be stored within the researcher's programming directory.

<u>Step 4 (summary): Create Future Hourly Electricity Generation Data for 2050 per EIoF Region</u>

4. This step scale up hourly electricity demand profiles from those in a past year (e.g., 2016) to a **2050 baseline hourly electricity demand** for each EIoF region**.** Also, ensure the annual electricity-related values (e.g., total generation from wind, coal, solar, etc. power plants) in the baseline 2050 U and V matrices are consistent with the

2050 hourly electricity generation profiles such that the total electricity generation form the hourly data is equal to the annual electricity generation specified in the U and V matrices, by fuel/technology type). Further, the electricity demand profiles by end-use sector and end-use (i.e., residential, commercial, industrial, transportation) need to be consistent between the hourly demand and total annual demand in the U and V matrices.

a. **Code:** "generate8760_2050_baseline.R"
    i. This code only need be stored within the researcher's programming directory.
b. **Inputs into this code:**
    i. **U and V matrix templates**: "U_template.csv" and "V_template.csv"
    ii. **Mapping of EIoF region to Census Division:** "State_EIoF_CensusDivision_Mapping.csv"
    iii. **EIoF Population projections from 2020 to 2050 (each decade):** Data are in "WeldonCenterStatePopulation_ExtendedTo2050.csv" and described in the document titled "Historical and Assumed Future (to 2050) Population and Electricity Customers by EIoF Region".
    iv. **Hourly electricity demand profile per EIoF region (8760 hours per year):** "Load_Profiles_2016.csv" (and for 2017) are described in document titled "Constructing Hourly Electricity Demand Profiles for Energy Infrastructure of the Future regions".
    v. **Preliminary U matrices for 2050 energy flows per EIoF region:** "XX_Sankey_Input_U_2050.csv" where XX = each EIoF region.
    vi. **Total annual electricity generation in 2017 and 2050, in TWh**, from the major fuel categories (Petroleum, Natural Gas, Coal, Nuclear, Solar, Wind, Hydro, Geothermal, & Biomass) from the EIA AEO 2019: "EIA_AEO2019_CensusElecDemand2017_TWh.csv", "EIA_AEO2019_CensusElecDemand2050_TWh.csv"
    vii. **EIA State Energy Data System (SEDS) data** (the complete .csv file available from the EIA SEDS website (EIA SEDS, 2019): "Complete_SEDS_1960_2017_download20190702.csv"
c. **Output from this code (1):** "XX_Sankey_Final_U_2050.csv" and "XX_Sankey_Final_V_2050.csv".
    i. These data files are the total annual energy values (Btu) for region "XX" in the U and V matrices of the Sankey diagram. These are the default data that will show up when a user first selects on a region in the online Energy Futures Dashboard (EFD) of the EIoF project.
d. **Output from this code (2):** "Baseline_Fraction_HeatingTypes_byEIoF.csv".
    i. **Rdata file:** These output .csv files are (later) saved in an R list called "U_2050_list" and "V_2050_list" within the .Rdata file

"Base_UV_Matrices.Rdata" that is stored in directory "***operating directory/master_R_scripts /generate_FinalUVY_2050_data***".

ii. These data summarize the fraction of homes that are heated via the three heating categories as run in the ResStock code (described later in this document). The three categories are "FracHeatPump" (fraction of homes using electric heat pump), "FracNG" (fraction of homes using natural gas furnaces), and "FracOther" (fraction of homes using "other" fuels that include propane, fuel oil, and biomass). These data are stored in the programmer's directory and inform the EIoF EFD default inputs that appear when a user first opens the EFD.

e. **Output from this code (3):** The total annual energy (from natural gas) that is required to heat residential homes in 2016 and 2050, and these data are used as inputs into the cost calculations.
   i. These data are stored within the researcher's programming directory.

f. **Output from this code (4-12):** Hourly electricity generation profiles required to create an estimate for the hourly electricity generation (8760 hours) in the year 2050. The total required electricity generation, for each EIoF region in 2050, is equal to the historical year 2016 hourly electricity demand times a scaling factor to increase the 2016 demand hourly profile to a 2050 hourly profile, times a factor for transmission and distribution (T&D) losses (= (2016 electricity demand) × (scaling factor to 2050) × (1 + T&D loss factor)). We break down the electricity demand into each of the major end-use sectors (industrial, commercial, transportation, and residential) and because the user can select how much household heating she wants from electric heat pumps, we separate the residential electricity hourly demand into a "heating" and "non-heating" portion. A later section of this document describes the assumptions and sequence of deriving sector-specific hourly electricity demand profiles to match total electricity demand for the region.
   i. **Rdata file:** The following "EIoF8760Generation … .csv" files hourly electricity generation .csv files are (later) saved in an .Rdata file "Baseline_8760MW_Generation_2050.Rdata" that is stored in directory "***operating directory/master_R_scripts / generate8760_data/***".
   ii. <u>"EIoF_8760Generation_2050_BaseResStock.csv":</u> An estimate for 2050 hourly total electricity generation (generation = demand + T&D loss factor)
   iii. <u>"EIoF_8760GenerationResidential_2050_BaseResStock.csv":</u> An estimate for 2050 hourly electricity generation need to meet only residential demand (generation = residential demand + T&D loss factor). This is hourly electricity generation needed to operate homes from the "base" ResStock simulation run that represents the existing

housing stock of single family detached homes that has been scaled up to represent 100% of all residential dwellings.

iv. "EIoF_8760GenerationTransportation_2050_BaseResStock.csv": An estimate for 2050 hourly transportation (only) electricity generation (generation = demand + T&D loss factor)

v. "EIoF_8760GenerationIndustrial_2050_BaseResStock.csv": An estimate for 2050 hourly industrial (only) electricity generation (generation = demand + T&D loss factor)

vi. "EIoF_8760GenerationCommercial_2050_BaseResStock.csv": An estimate for 2050 hourly commercial (only) electricity generation (commercial demand = Total electricity demand - Residential - Transportation – Industrial). Thus, the 2050 hourly commercial (only) electricity generation is = commercial generation = demand + T&D loss factor.

vii. "EIoF_8760GenerationResidential_NonHeating_2050_BaseResStock.csv": This is hourly electricity generation needed to operate homes, EXCEPT for that needed for heating, from the "base" ResStock simulation run that represents the existing housing stock of single family detached homes that has been scaled up to represent 100% of all residential dwellings.

viii. "EIoF_8760GenerationResidential_Heating_2050_BaseResStock.csv": This is hourly electricity generation needed to heat homes from the "base" ResStock simulation run that represents the existing housing stock of single family detached homes that has been scaled up to represent 100% of all residential dwellings.

ix. "EIoF_8760GenerationResidential_Heating_2050_NGResStock.csv": This is hourly electricity generation needed to heat homes from the ResStock simulation run that assumes 100% of homes that are not already using natural gas (NG) furnaces are converted to using NG furnaces. These data include a calculation such that the energy use for the existing housing stock of single family detached homes (which is < 100% of all residential dwellings) has been scaled up to represent 100% of all residential dwellings. Some electricity is needed for heating even if using NG furnaces for the purposes of operating fans that move air within the HVAC system.

x. "EIoF_8760GenerationResidential_Heating_2050_HeatPumpResStock.csv": This is hourly electricity generation needed to heat homes from the ResStock simulation run that assumes 100% of homes that are not already using an electric heat pump with efficiency equal to or better than a defined heat pump are then converted to the using the defined electric heat pump. These data include a calculation such that the energy use for the existing housing stock of single family detached homes (which is < 100% of all residential dwellings) has been scaled up to represent 100% of all residential dwellings.

Step 5 (summary): Translate User Inputs Into Future Hourly Electricity Generation Data for 2050

5. The code that performs this step is part of the "core" set of codes that reside on the server that hosts the EIoF EFD. Given user inputs for (1) the percentage of household heating from each possible type (natural gas, electric heat pumps, and "other") and (2) the percentage of light duty vehicles that are electric vehicles (= percent of vehicle miles driven on electricity), this code produce a total electricity demand profile (hourly for 8760 hours in year 2050) for the user's chosen EIoF region.
   a. **Code:** "generate8760.R"
      i. This codes resides in directory "***operating directory/master_R_scripts/***".
   b. **User inputs into this code:**
      i. the percentage of household heating from each type: electricity (heat pumps), natural gas furnaces, and "other" (propane, fuel oil, and biomass)
      ii. the percentage of light duty vehicles that are electric vehicles (= percent of vehicle miles driven on electricity)
   c. **Underlying stored data required as inputs into this code:**
      i. **"**Baseline_ResStock_Fraction_HeatingTypes_byEIoF.Rdata": A data frame of the same data in "Baseline_Fraction_HeatingTypes_byEIoF.csv" that states the assumed baseline percentage of homes heated by each type of fuel and system. These data are stored in directory "***operating directory/master_R_scripts/generate8760_data/***".
      ii. "Baseline_8760MW_Generation.Rdata": This data file includes the following data frames (from the .csv files listed as output from "generate8760_2050_baseline.R") that define the necessary 8760 hourly electricity generation required per sector and per EIoF region. This data file is stored in "***operating directory/master_R_scripts / generate8760_data/***".
         1. EIoF_8760MW_GenerationTransportation_2050
         2. EIoF_8760MW_GenerationIndustrial_2050
         3. EIoF_8760MW_GenerationCommercial_2050

4. EIoF_8760MW_GenerationResidential_Heating_ResStockBase_2050
5. EIoF_8760MW_GenerationResidential_NonHeating_ResStockBase_2050
6. EIoF_8760MW_GenerationResidential_Heating_ResStock100pctNG_2050
7. EIoF_8760MW_GenerationResidential_Heating_ResStock100pctHeatPump_2050

iii. "SingleEVChargeProfiles_MWh_8760_Input_to_solveGEN.RData": This data file includes the assumed hourly EV charging profile, and is described later in this document.

d. **Output from this code:** A total electricity generation hourly (8760 hours) profile that is to be met in 2050 in the user's chosen EIoF region by the generation profile that is next solved for in the code "solveGEN.R".

Step 1a: Organize Historical Energy Data by EIoF Regions (non-transportation)

This first step organizes historical energy consumption data, given per state and census divisions, into aggregations for each of our 13 EIoF regions. This end result of this organization is to input data into the U and V matrices for each EIoF region.

<u>Data</u>

The data used for creating these matrices were came from the Energy Information Administration In total there were four datasets which can be found in the following files:

1. *Complete_SEDS.csv:* This file contains the complete data from the State Energy Data System (SEDS) from 1960 to 2016 (at the time the calculations were performed, 2016 was the latest year of a full data set). The data is represented using an MSN code which explains what the value represents and its units. A full list of MSN codes and their meanings can be found in the file *EIA SEDS Codes_and_Descriptions.xlsx* and via the SEDS website.
2. *Electricity_Generation_by_FuelType_2016.csv:* This file contains data for the net electrical generation by natural gas, biofuels, petroleum liquids, and coal by state for 2016. It was found using the EIA's electricity data tool and downloaded using the API download tool by running the code file *EIA_API_Download_Electricity_Generation_by_FuelType_DDG.R.*
3. *Census_Regions_Fuel_to_Enduse.xlsx:* This dataset was created using the two files *DB_Residential_ref2019_d111618a.xlsm* & *DB_Commercial_ref2019_d111618a.xlsm.* These two original files contain data representing the energy consumed for a specific end use by fuel type and sector (e.g. natural gas for residential space heating). These two datasets

were received by emailing the EIA Annual Energy Outlook team at this address: AnnualEnergyOutlook@eia.gov, and represent the baseline projections of the 2019 Annual Energy Outlook. The data used to create *Census_Regions_Fuel_to_Enduse.xlsx* came from the "NEMSConsFcast" tab in the Residential spreadsheet and the "EndUseEnergyPivot" tab in the commercial spreadsheet by directly copying and pasting them. The data in these tables are listed by census division and are used in a calculation to estimate the same data at the state level.

R Code

A single R-code file, called *Create_Sankey_Inputs_HistoricalData.R*, performs all of the processing, calculations, and data entry for inputting 2016 data into the U and V matrices (for EIoF regions) using the three data files described above. It does so by first adding identifying features to the data (e.g. EIoF region, census division) to enable the aggregation and create new datasets or data frames for more easily performing the calculation later on. In the code, you will see these data frames:

1. *SEDSCensus*: This data frame simply contains the SEDS data aggregated by Census division.
2. *EndUseMSN*: This data frame contains all of the desired specific end uses by fuel type, by residential and commercial sector, that we need to calculate along with the MSN code that points to the total energy consumed by the same fuel type in that sector in the SEDS data.
3. *StatesFuelEndUse*: This data frame contains all of the estimated energy consumed for a specific end use by fuel type and sector and the state level. It is then aggregate by EIoF region to create the data frame *EIoFFuelEnduse*. Both of these data frames are used to input data into the matrices.

Example: Estimating energy consumed for specific end use by fuel type and sector at the state level

To perform this calculation, three pieces of data were needed: the total consumption by fuel type and sector for a state, the total consumption by fuel type and sector for a census division, and the consumption for a specific end use by fuel type and sector for a census division.

Example: Estimate natural gas consumed for residential space heating in Texas

- TX_{ResNG} = The total natural gas consumed by Texas in the residential sector is 498,060 billion btu
- WS_{ResNG} = The total natural gas consumed by the West South Central Census Division, in the residential sector, is 741,077 billion btu.
- We use these to values to provide us with a ratio of how much energy is consumed in Texas compared to its total census division.

$$x = \frac{TX_{ResNG}}{WS_{ResNG}} = 0.67$$

- $WS_{NGEndUse}$ = The natural gas consumed by the West South Central Census Division for residential space heating is 156,610 billion btu. Multiplying this value by the calculated ratio *x* provides us with an estimate to how much NG is consumed for residential space heating in Texas.

$$TX_{NGEndUse} \ = \ WS_{NGEndUse} \times x = 104{,}928 \ billion \ btu$$

This calculation is done for every specific end use by fuel type and sector combination described in the U and V matrices, for every state, and input into the StatesFuelEndUse data frame.

<u>Inputting data into U, V, and Y Matrices required to make a Sankey Diagram in code *Sankey_Function.r*</u>

When inputting the data into the three matrices (U=use, V=make, and Y=net output), the program will first prompt the user to choose to create the matrices by state, EIoF region, or U.S. Census Division by pressing either 1, 2, or 3 respectively. The input then runs on a loop that builds all 3 matrices for the chosen geographic region and saves them as .csv files. It will do this automatically for all states, EIoF regions, or Census Divisions depending on the user's choice. This loop redefines the SEDS data every iteration as "newSEDS" by sub setting it based on the current state or EIoF region. This avoids changing the raw SEDS data. The cells to be filled with data, as specified in the document *Instruction for Templates of UVY Matrices.pdf*, are hard coded with the specific data frame and cell with the corresponding data from SEDS, *Electricity_Generation_by_FuelType_2016.csv*, or estimated end use data. The units for the majority of the data used from the SEDS data as inputs into these matrices are in billion Btu. Some data have units of million kWh, and the code converts them to billion Btu. Then all data within each U, V, and Y matrix are converted to Btu.

After running the program, there should be three .csv files for every state, EIoF region, or Census Division of the format *XX_Sankey_Input_U_2016.csv*, *XX_Sankey_Input_V_2016.csv*, *XX_Sankey_Input_Y_2016.csv*, where "XX" is a label for a state or EIoF region (e.g., *TX_Sankey_Input_U_2016.csv* is the U matrix for state and EIoF region Texas using 2016 data; *MN_Sankey_Input_V_2016.csv* is the V matrix input for the Mountain North EIoF region for the year 2016).

Step 1b: Organize Historical Energy Data by EIoF Regions (light-duty vehicle transportation)

The EIoF EFD allows the user to alter the percentage of light-duty vehicles (LDVs) that are driven on petroleum liquid fuels (plus standard biofuel blend into gasoline) versus electricity. Thus, with this focus the EFD does not allow the user to change any other fuels used for non-LDV travel such as heavy trucking, buses, aviation, and rail.

Data

Historical data for this analysis come from the Energy Information Administration State Energy Data System, with some information from the Oak Ridge National Lab Transportation Energy Data Book as described later:

1. *Use_all_btu.csv:* This file contains the reorganized data from the State Energy Data System (SEDS) from 1960 to 2017. The data are represented using an MSN code which explains what the value represents and its units. A full list of MSN codes and their meanings can be found in the file *EIA SEDS Codes_and_Descriptions.xlsx.* The data have been rearranged from the raw EIA format as follows:
    a. Data curation: The file contains only the data with MSN codes ending in "B", meaning they are in units "billions of Btu" of energy consumed for a given year. All other data have been removed.
    b. Columns
        i. Column 1: Data_Status
        ii. Column 2: State
        iii. Column 3: MSN
        iv. Columns 4-61: Years 1960 to 2017
    c. Rows
        i. Each row represents a unique MSN code.

R-Code (transportation)

The code file, *Create_SEDS_Transport_Data_20190828CWK.R*, performs all of the processing, calculations and csv file writing. It contains three internal functions. The first ("addRegion") adds a "Region" label, representing the defined EIoF regions, to the main data frame. The second ("add_CensusRegion_StateLabel") adds the label "Census_region" (= the 9 U.S. Census Divisions) the main data frame. The third internal function ("createData") performs other processing and calculations that extract relevant transportation energy use data for the selected geographic boundary (state, EIoF region, Census Division) of the user. In the end, the output data file named *Region_Transport_YEAR.csv* (in this case, the YEAR equals to 2016 and 2017 per available data) will be saved in the current working directory, for further programming by code *Create_Sankey_Inputs.R.*

There are several intermediate data frames in the codes:

1. SEDS: simply contains the SEDS data with "EIoF region" feature in 2016 and 2017
2. SEDS_Transport: the subset of SEDS, with concentration on Transportation sector.
3. Region_Transportation_2016/2017: the final data frame, covering "LDV_Petrol", "LDV_Elec", "LDV_Ethanol", "Other_Petrol", and "Other_NG".

Methodology & Results (transportation)

We make several simplifying assumptions to estimate different forms of energy used for light duty vehicle transportation:

1. 100% of electricity used in the transportation sector is used within light-duty vehicles (LDV)
2. Petroleum consumed within LDVs can be split to two parts: distillate fuel oil and the portion of motor gasoline that excludes ethanol.
3. About 92.6% of motor gasoline used in the transportation sector is used for LDVs, and it is composed of gasoline from refined petroleum and ethanol.
4. Biomass for LDV is equal to the portion of ethanol within motor gasoline as reported used in the transportation sector

We use following data (MSN codes) within the EIA SEDS to estimate energy consumption for LDV transportation in 2016 and 2017:

- MGACB: Motor gasoline consumed by the transportation sector, Billion Btu
- EMACB: Fuel ethanol gasoline consumed by the transportation sector, Billion Btu
- DFACB: Distillate fuel oil consumed by the transportation sector, Billion Btu
- PAACB: All petroleum products consumed by the transportation sector, Billion Btu
- ESACB: Electricity consumed by (i.e., sold to) the transportation sector, Billion Btu
- NGACB: Natural gas consumed by the transportation sector, Billion Btu

Equation (1) shows our estimate for the total petroleum-based energy consumed for light duty vehicle travel for 2016 and 2017 using historical data in SEDS as well as information from the 2019 Reference Case of the EIA Annual Energy Outlook. This represents 92% of the energy in motor gasoline (MGACB) plus 6.4% of the energy in diesel fuel minus 100% of the ethanol consumed for transportation. The factor 0.92, or 92%, represents the fraction of motor gasoline that is consumed in LDVs compared to all consumption of motor gasoline. This number is estimated from Table 7 of the AEO 2019 Reference Case (ref2019-d111618a) that summarizes energy use for LDVs, and assumes motor gasoline consumption in 2017 and 2050 as 15,335 and 10,381 trillion Btu, respectively. The AEO Reference case also assumes total motor gasoline consumption in the transportation sector as 16,690 and 12,289 trillion Btu, respectively. The factor of 0.064, or 6.4%, represents the fraction of diesel fuel consumed in LDVs. In 2016, there were 443.2 TBtu of diesel used for "light vehicles" out of a total of 6951.4 TBtu of total diesel fuel consumed for "Total HWY & NONHWY" use from Table 2.7 of the Oak Ridge National Lab Transportation Energy Data Book, Edition 37 (ORNL, 2019).

$$Petroleum\ for\ LDV = MGACB \times .92 + DFACB \times 0.064 - EMACB \quad (1)$$

Equation (2) shows the calculation for petroleum consumed for "other" (not LDVs) transportation, which inherently includes all other road travel, rail transport, and aviation.

$$Petroleum\ for\ other = PAACB - Petroleum\ for\ LDV \quad (2)$$

Equations (3), (4), and (5) show, respectively, the calculations for ethanol consumed in LDVs, electricity consumed for LDVs, and natural gas consumed in any form of transportation (= "other"), including possibly LDVs but we assume for other types of vehicles (such as buses).

$$Ethanol\ for\ LDV = EMACB \quad (3)$$

$$Electricity\ for\ LDV = ESACB \quad (4)$$

$$Natural\ Gas\ for\ all\ non\text{-}LDV\ transportation = NGACB \quad (5)$$

Table 1 and Table 2 show the energy consumed per Equations (1) - (5) for the years 2016 and 2017, respectively, for each EIoF region as depicted in Figure 1.

Table 1. The calculation of energy (billion Btu) for the year 2016, for each EIoF region, for the five categories of energy consumption for transportation considered in the EIoF online tool.

EIoF Region	Petroleum in LDVs	Ethanol in LDVs	Electricity in LDVs	Petroleum in non-LDVs	NG in all transportation
NW	390,903	31,478	43	514,821	95,062
CA	1,524,244	125,504	2,667	1,538,068	42,655
MN	533,682	39,456	0	546,615	101,044
SW	889,738	66,239	325	606,892	19,824
CE	2,510,598	195,094	7,454	1,875,779	117,473
TX	649,740	52,558	443	582,153	51,492
MW	2,340,417	188,305	2,010	1,722,723	83,464
AL	654,701	53,427	1,882	362,133	17,458
MA	444,533	35,863	103	536,002	18,852
SE	566,066	44,635	9,402	505,166	28,620
FL	2,072,927	156,852	605	1,437,176	63,952
NY	386,882	31,374	25	283,700	25,748
NE	1,463,719	118,453	620	1,706,725	92,088

Table 2. The calculation of energy (billion Btu) for the year 2017, for each EIoF region, for the five categories of energy consumption for transportation considered in the EIoF online tool.

EIoF Region	Petroleum in LDVs	Ethanol in LDVs	Electricity in LDVs	Petroleum in non-LDVs	NG in all transportation
NW	381,585	30,932	45	570,697	110,066
CA	1,531,433	126,878	2,848	1,592,743	42,886
MN	521,522	38,917	-	551,684	107,491
SW	906,360	69,563	294	622,250	18,762
CE	2,484,852	195,917	7,310	1,864,654	134,551
TX	652,664	53,153	471	596,551	50,945
MW	2,305,561	187,624	2,024	1,693,136	89,494
AL	634,484	52,247	1,886	361,623	18,598
MA	447,286	36,702	110	516,331	19,871
SE	571,988	45,895	9,440	496,095	30,271
FL	2,091,186	161,646	589	1,479,698	61,086
NY	394,357	32,269	26	289,632	25,429

NE	1,473,706	119,961	622	1,803,692	91,090

Step 2: Organize Future Projected Energy Data to 2050 by Census Region

The benefit of the Energy Futures Dashboard (EFD) of the EIoF project is that it provides the user the ability to explore differences among geographic regions of the United States. In order to inform these differences, the EFD assumes unique baseline projections for 2050 energy production and demand for each region. In general, for simplicity, we follow the baseline scenario from the Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2019. While the actual energy extraction and demand in 2050 is highly uncertain, we can leverage the information within the AEO to approximate the distribution of total energy demand across the U.S. (e.g., what regions consume what percentage of total energy and electricity).

This step uses data within the Census Division EIA AEO 2019 reference case scenario and aggregates those data into the PSUT (U, and V matrices) framework for 2017 and 2050 data such that we can use the with the same PSUT data from 2016 at the state level (using EIA SEDS data) that has been aggregated to the EIoF region level to then calculate U and V matrices for 2050 at the EIoF region level as required inputs to the EFD in the next step.

The files that are involved in performing these calculations are:

- Create_Sankey_Inputs_for2050_AEOCensusDivisions_20190709.R
    - Input files required
        - EIA_AEO2019_CensusDemand_sup_t2t3.csv
        - EIA_AEO2019_CensusElecDemand2017_quads.csv
        - EIA_AEO2019_CensusElecDemand2050_quads.csv
        - U_template.csv
        - V_template.csv
        - Y_template.csv
        - XXX_Sankey_Input_U_2016.csv (where XXX is each (1) Census Division and (2) State)
        - XXX_Sankey_Input_V_2016.csv (where XXX is each (1) Census Division and (2) State)
        - XXX_Sankey_Input_Y_2016.csv (where XXX is each (1) Census Division and (2) State)

Step 3: Organize Future Projected Energy Data to 2050 by EIoF Region

To create baseline projections for energy use in *2050 by EIoF region*, we use the historical data (2016 by state and aggregated per EIoF region) and baseline data from the Annual Energy Outlook 2019 (2017 and 2050 by Census Division). The files that are involved in performing these calculations are:

- Create_Sankey_Inputs_for_2050_EIoFRegions_20190717.R
    - Input files required
        - State_EIoF_CensusDivision_Mapping.csv
        - U_template.csv
        - V_template.csv
        - Y_template.csv
        - XXX_Sankey_Input_U_2016.csv (where XXX is each (1) Census Division, (2) State, and (3) EIoF region)
        - XXX_Sankey_Input_V_2016.csv (where XXX is each (1) Census Division, (2) State, and (3) EIoF region)
        - XXX_Sankey_Input_Y_2016.csv (where XXX is each (1) Census Division, (2) State, and (3) EIoF region)
        - XXX_Sankey_Input_U_2017.csv (where XXX is each (1) Census Division from EIA AEO 2019)
        - XXX_Sankey_Input_V_2017.csv (where XXX is each (1) Census Division from EIA AEO 2019)
        - XXX_Sankey_Input_Y_2017.csv (where XXX is each (1) Census Division from EIA AEO 2019)
        - XXX_Sankey_Input_U_2050.csv (where XXX is each (1) Census Division)
        - XXX_Sankey_Input_V_2050.csv (where XXX is each (1) Census Division)
        - XXX_Sankey_Input_Y_2050.csv (where XXX is each (1) Census Division)

R-Code: Create_Sankey_Inputs_for_2050_EIoFRegions_20190717.R

This code calculates 2050 energy uses to fill in data into the U, V, and Y matrices of the Sankey diagram for each EIoF region. Assuming “X” represents one of the U, V, or Y matrices, the method for projecting current data (~ 2016 state level energy use) to 2050 is as in Equation **Error! Reference source not found.**):

$$X_{EIoF\ region\ j,2050} = \sum_{i=1}^{N_{states}} X_{state\_i,2016} \times \left(\frac{X_{census\_i,2050}}{X_{census\_i,2017}} \right) \qquad (6)$$

Equation (6) is a relatively simplified method to use the EIA Annual Energy Outlook (2019 reference case) projection and convert to each defined EIoF region. The equation is not meant to represent matrix multiplication, but it represents that each element of a matrix (U, V, or Y) is multiplied or divided by the corresponding element in the other matrices (e.g., via a dot product). The equation simply scales up historical energy uses in $X_{state\_i,2016}$ by a "multiplying factor" of 2050 to 2017 energy use ($X_{census\_i,2050}$ / $X_{census\_i,2017}$) of the Census Division within which that state resides. We used 2016 state level data from the EIA State Energy Data System (SEDS) instead of 2017 state level data because at the time of performing these calculations, the full 2017 data set was not finalized within the EIA SEDS. The 2017 and 2050 Census Division data come from the EIA AEO 2019 reference case, and we use 2017 data for Census division energy use in Equation (6) since 2017 is the earliest year represented in the EIA AEO 2019. Because both the EIA SEDS and EIA AEO break down energy use by sectors of residential, industrial, commercial, transportation, and electricity, we follow these sectoral breakdowns within the U, V, and Y matrices such that we can display total energy consumption (for all sectors) to the user in the online tool.

Future versions of the online tool might allow the user to alter these multiplying factors of energy use change from "today" to 2050 (per sector and/or per region), or directly specify some future growth or decline in end use energy demands, and thus the required energy supply.

Here we describe an example for the "Central" EIoF region. Assume it is the current region *j*. The Central region is composed of five states (North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma), so $N_{states} = 5$. We use file "*Create_Sankey_Inputs_HistoricalData.R"* to aggregate historical energy use data (e.g., year 2016) for each state and census division. We use file "*Create_Sankey_Inputs_for2050_AEOCensusDivisions.R*" to aggregate 2017 and 2050 energy use projections from the AEO, which are projected by EIA at the level of census divisions (not states). After using both of these files, one has all matrices necessary for the right-hand side of Equation (6) and this equation is executed for each region in file "Create_Sankey_Inputs_for_2050_EIoFRegions.R".

R-Code: Create_Sankey_Inputs_for2050_AEOCensusDivisions.R

The code "*Create_Sankey_Inputs_for2050_AEOCensusDivisions.R*" is used to estimate the 2050 energy flows for each U.S. Census Division. We use data from the EIA's Annual Energy Outlook (AEO) for 2019. The raw AEO 2019 data come from file "EIA_AEO2019_CensusDemand_sup_t2t3.xlsx" which EIA labels as "Regional energy consumption and prices by sector (tables 2-18.9)."[2] This file includes Table 2 (2. Energy Consumption by Sector and Source) that lists energy consumption by sector and source, or fuel, for the U.S. overall and then Tables 2.1-2.9 with the same data for each of the 9 Census Divisions. This file is saved as a .csv file for import into the R code such that the raw data can be accessed. The AEO scenario we used is the reference case scenario: Scenario = ref2019 (reference case), Datekey = d111618a, Release Date = January 2019. The combined scenario and Datekey are "ref2019.d111618a".

Step 4 & 5: (4) Create Future Hourly (8760 hrs/yr) Electricity Generation Data for 2050 per EIoF Region; (5) Translate User Inputs Into Future Hourly Electricity Generation Data for 2050

This section summarizes the method and mathematics used to generate "baseline" hourly electricity demand profiles (8760 hours per year) for each Energy Infrastructure of the Future (EIoF) region of the U.S.-48.

At this point we have already assumed a baseline 8760 hourly profile for *total* electricity generation for each EIoF region. Because the user can choose a quantity for both electric vehicle travel and residential heating by electric heat pumps, the user's inputs can affect the total electricity generation assumed for 2050. For example, if a user chooses 0% for both light-duty vehicle (LDV) travel by electric vehicles (EVs) and residential heating by electric heat pumps, the total hourly and annual electricity for that region will be less than if the user selected 100% for both of those inputs. Thus, we must form hourly electricity profiles associated both with charging EVs and heating homes with electric heat pumps.

The total hourly electricity generation profiles, in average MW each hour, or MWh/hr, is based on demand of end-use sectors but scaled up to account for transmission and distribution losses of 2% and 5%, respectively. Total regional electricity generation is composed of the five components as shown by Equation (7): industrial, commercial, transportation, residential (non-heating), and residential (heating).

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[2] See Annual Energy Outlook "Reference Case Projections Tables": https://www.eia.gov/outlooks/aeo/tables_ref.php, and for 2019 the specific URL to the Excel file with this set of tables (accessed October 10, 2019) was https://www.eia.gov/outlooks/aeo/supplement/excel/sup_t2t3.xlsx.

EIoF_8760Generation_2050_Total = EIoF_8760GenerationIndustrial_2050 + EIoF_8760GenerationTransportation_2050 + EIoF_8760GenerationCommercial_2050 + EIoF_8760GenerationResidential_2050_Heating + EIoF_8760GenerationResidential_2050_NonHeating (7)

For simplicity, we assume the hourly electricity generation to serve industrial load is constant value each hour, and this constant value can be derived from the derived baseline 2050 data as already described in this document. We use simulations of the National Renewable Energy Laboratory's (NREL) ResStock Analysis Tool to determine hourly electricity demand for residential heating and non-heating purposes. We assume an hourly profile for electricity demand for charging light-duty EVs that is assume equal to the total transportation demand in Equation (7). After all assumptions to this point, the electricity generation needed to serve commercial demand is the only factor left undescribed in Equation (7). Thus, to solve for electricity generation for commercial electricity demand, we rearrange Equation (7) to solve for commercial generation by isolating it on one side of the equation. We now describe the methods for estimating hourly electricity generation for residential electricity demand (heating and non-heating applications) and hourly electricity generation for charging EVs as the sole electricity demand for transportation.

Determining Residential Heating and Non-Heating hourly Generation Profiles

Summary of use of ResStock

The National Renewable Energy Laboratory's (NREL) ResStock Analysis Tool is a data-based probabilistic method to develop geographically representative housing stock that is simulated using the physics-based EnergyPlus modeling software to create an aggregate building energy model that represents the single-family detached housing sector in the contiguous United States. The Energy Infrastructure of the Future (EIoF) study used ResStock to model the hourly energy usage of residential buildings across the lower 48 states with a building stock 1) as it is now 2) if all were to switch to electric heat pumps, and 3) if all were to switch to natural gas furnaces. By running these three sets of simulations, this allows web-based user inputs of the percent of residential heating from (1) electric heat pumps, (2) natural gas furnaces, and (3) other methods (representing effects of the default housing stock that heat via "other" fuels and technologies such as fuel oil, propane, and biomass).

Residential Hourly Demand by Use of ResStock: Methods

The Energy Infrastructure of the Future (EIoF) Project requires modeling the energy usage of the residential sector according to different types of heating profiles—namely via electric heat pumps or natural gas-fueled central air heaters. Both heating methods have tradeoffs. Natural gas furnaces are very effective at heating spaces regardless of outdoor air temperature but emit carbon dioxide into the atmosphere from fossil fuel combustion. Electric heat pump performance is affected by very cold outdoor air temperatures (i.e. < 20 degrees Fahrenheit can necessitate a shift to electric resistance heating and a resulting spike in electric power demand), but use of heat pumps can trigger lower greenhouse gas emissions than natural gas or propane furnaces if the electrical grid is powered by a mix of low-carbon fuels like sunlight, wind, and nuclear fuel. Unlike natural gas furnaces, heat pumps can also act as air conditioners—if an efficient heat pump is installed in a household, it will also provide efficient air conditioning.

NREL's ResStock Analysis Tool enables the EIoF project to model energy performance from geographically representative housing stock in the contiguous United States. For each simulation batch, we change the heating source from its current setting (in the existing housing stock of the late 2000s) to either a standard efficiency heat pump or a standard efficiency natural gas furnace. This allows us to analyze the residential energy usage of the entire lower US-48 single family detached residential sector that we calibrate (scale up via a multiplying factor) to all residential energy use.

ResStock Workflow

In this EIoF analysis, we model single family detached residential building energy use through NREL's ResStock tool (Wilson *et al.*, 2017). ResStock utilizes the industry standard EnergyPlus™ building energy simulation engine and housing stock parameters for 216 locations in the contiguous United States. ResStock probabilistically samples housing parameters (e.g., insulation type, house design, etc.) based on weights assigned to each parameter as a function of the location to develop unique housing archetypes. Each archetype is simulated through the EnergyPlus™ engine to calculate its energy usage data. From these data, we analyze the energy consumption of the contiguous United States' residential sector. We also analyze the energy consumption if every heating system was replaced by an electricity powered heat pump and if every heating system was replaced by a natural gas furnace.

Each simulation created by the ResStock analysis tool generates a model of a single-family detached home from statistically sampling a residential housing parameter space (NREL, "ResStock"). The parameter space uses housing stock data from 11 different sources to determine probability distributions for each residential housing parameter as a function of location (Wilson *et al.*, 2017).

The parameters for the home simulations are input into the EnergyPlus™ simulation engine (DOE, "EnergyPlus"). The ResStock simulations were performed using NREL high-performance computing resources. Each ResStock run used in this analysis uses 350,000 simulations to represent the single-family detached residential sector of the contiguous United States, about 80 million households. This results in an approximate simulation weight of 230 homes per simulation. Each simulation creates a base case that represents a heating profile for a representative home of the current stock of single-family detached residential sector. Along with the base case the model creates two "extreme" cases for residential heating: one in which 100% of heating is performed by electric heat pumps and one in which 100% of household heating is performed by natural gas furnaces. This allows us to create hourly profiles that realistically allow the user of the EIoF EFD online tool to explore the implications of different forms of residential heating on infrastructure cost, energy supply, and electric grid operation.

Parameters for the all-electric and all-gas heating ResStock simulations

The new, all-electric ResStock simulation assumes a SEER 22, HSPF 10 electric heat pump as the heating, ventilation, and air conditioning (HVAC) unit for the home. Any home from the base run that does not have the SEER 22, HSPF 10 heat pump is run again through the EnergyPlus™ energy modeling software. SEER stands for *seasonal energy efficiency ratio* and HSPF stands for *heating seasonal performance factor*. A SEER rating reflects the ratio between cooling output during a typical cooling-season divided by the total electrical input into the heat pump. Similarly, the HSPF rating reflects the ratio between the heating output during a typical heating-season divided by the total electrical input into the heat pump.

The new, all-natural gas ResStock simulation assumes a 92.5% AFUE gas furnace paired with a SEER 15 air conditioning unit. Any household without a 92.5% AFUE gas furnace and SEER 15 air conditioning unit is run again through EnergyPlus™. AFUE stands for *annual fuel utilization efficiency.* AFUE reflects the amount of consumed energy from natural gas that is turned into heat.

ResStock Data Processing

To process the data output by ResStock we collect the hourly usage data of each simulation and multiply it by the simulation weight to receive the amount of energy used by approximately 230 homes of the same parameters as the corresponding simulated home. Energy use for each simulation is then summed and grouped by time and location.

For each location, the energy usage hourly time series is divided into energy usage for each county in the location's region. For example, for Austin, TX, the energy usage is divided proportionally according to U.S. Census data into Travis County, Williamson County, Bastrop County, etc. Each county's time series data is then aggregated into one of the thirteen EIoF regions. At the end of this data processing, we produce 13 time series of energy usage data—one for each EIoF region.

The data outputs (energy consumption each hour) saved from the simulations are the following:

- Baseline scenario: Heating scenario hourly energy consumption for each EIoF region for the weather year 2016 assuming the baseline stock of housing and heating system configurations within ResStock.
- All NG heating scenario: All-natural gas heating scenario hourly energy consumption for each EIoF region for the weather year 2016 assuming the baseline stock of housing system configurations within ResStock except for the HVAC system
- All electric heating scenario: All-electric heating scenario hourly energy consumption for each EIoF region for the weather year 2016 assuming the baseline stock of housing system configurations within ResStock except for the HVAC system

Weather Files input into ResStock

Actual Meteorological Year (AMY) weather files for the year 2016 for the 216 locations were acquired as an input into the EnergyPlus™ model. This allows our simulations to reflect the energy usage of buildings according to weather from 2016. The weather files represent actual weather station data from each of the U.S. location during that year. The weather data (hourly time resolution) for years 2016 and 2017 were purchased from White Box Technologies, Inc.

Using ResStock simulations for baseline fractions of Household Heating from different fuels

The following describes how the ResStock simulation outputs are used to develop the baseline fractions of residential households that are heated using heat pumps (electricity), natural gas furnaces, or 'other' fuels (propane and fuel oil).

The three ResStock simulation runs, based on 2016 weather data are:

1. **ResStock_2016_EIoF_base**: energy use for the estimated base (existing) housing stock
2. **ResStock_2016_EIoF_NG**: energy use for the base housing stock, except where all heating is provided by natural gas furnaces
3. **ResStock_2016_EIoF_HeatPump**: energy use for the base housing stock, except where all heating is provided by heat pumps (electricity).

The categories of output data from the ResStock simulations for each fuel as each relate to heating and non-heating energy services are listed as the following:

1. Total (summary columns of total consumption of each energy carrier each hour of the year):
    a. Electricity: total_site_electricity_kwh
    b. NG: total_site_natural_gas_therm
    c. Propane: total_site_propane_mbtu (where "mbtu" = millions of Btu)
    d. Fuel oil: total_site_fuel_oil_mbtu (where "mbtu" = millions of Btu)
    e. Total energy consumed: total_site_energy_mbtu (where "mbtu" = millions of Btu)
    f. Net energy consumed: net_site_energy_mbtu (where "mbtu" = millions of Btu)
        i. Because we don't explicitly simulate distributed generation of electricity, net_site_energy_mbtu = total_site_energy_mbtu
2. Heating:
    a. Electricity consumption
        i. electricity_heating_kwh
        ii. electricity_central_system_pumps_heating_kwh
        iii. electricity_pumps_heating_kwh
        iv. electricity_fans_heating_kwh
    b. Natural gas consumption
        i. natural_gas_heating_therm
    c. Other (hydrocarbon) consumption
        i. fuel_oil_heating_mbtu (where "mbtu" = millions of Btu)
        ii. propane_heating_mbtu (where "mbtu" = millions of Btu)
3. Non-heating:
    a. Electricity consumption
        i. electricity_cooling_kwh
        ii. electricity_central_system_pumps_cooling_kwh
        iii. electricity_pumps_cooling_kwh
        iv. electricity_fans_cooling_kwh
    b. Natural gas consumption
        i. This is calculated as = total_site_natural_gas_therm - natural_gas_heating_therm (note: 1 therm = 99,976.1 Btu)
    c. Other (hydrocarbon) consumption
        i. This is calculated as = total_site_propane_mbtu + total_site_fuel_oil_mbtu - propane_heating_mbtu - fuel_oil_heating_mbtu (where "mbtu" = millions of Btu)

<u>Determining the residential heating demand profile that can be changed by the user:</u>

Here we describe the mathematics for determining how to create the electricity profile for heating households as influenced by the user's choice of heating fuel: electricity, natural gas, or "other" primarily dominated by propane and fuel oil). We do this by weighting the electricity profiles related to household heating (only) for each of the three ResStock simulation runs based upon the user inputs. The code "ResStock_MetadataAnalyze.R" uses the metadata from ResStock that indicate the housing parameters used for the "base" simulations default. These housing parameters indicate the estimated heating equipment and fuels used for the *existing housing stock* as displayed in Table 3.

Table 3. The baseline assumed percentage use of fuels and technology for residential household heating in 2050 as derived from the baseline housing stock generated within ResStock.

EIoF Region	Percentage using Electric Heat Pumps	Percentage using NG Furnaces	Percentage using "Other" (fuel oil & propane)
NW	13.5%	47.7%	38.8%
CA	0.9%	71.4%	27.7%
MN	2.1%	75.0%	22.8%
SW	21.6%	53.3%	25.1%
CE	8.3%	63.5%	28.3%
TX	12.6%	58.2%	29.2%
MW	3.7%	71.8%	24.5%
AL	12.8%	46.6%	40.6%
MA	11.2%	50.4%	38.4%
SE	17.1%	41.2%	41.6%
FL	28.4%	8.0%	63.6%
NY	1.1%	61.1%	37.8%
NE	0.0%	22.4%	77.6%

The total amount of electricity generation needed for residential home heating for each hour *t*, $G_{res.heating,t}$, is represented by a weighted sum of the heating electricity generation requirement in the base, natural gas (NG) heating only, and electric heat pump (HP) heating only ResStock simulations as in Equation (8), where, for example, $G_{res.heating,t,base\ run}$ represents the electricity requirement at hour *t* to heat homes within the "base" ResStock simulation. Note that even a home in which 100% of heat is provided by a natural gas furnace requires electricity to operate fans that move the heated air through the house. Thus, a 100% NG heated home has a non-zero electricity consumption associated with space heating.

$$G_{res.heating,t} = w_{base\ run}\left(G_{res.heating,t,base\ run}\right) + w_{NG\ run}\left(G_{res.heating,t,NG\ run}\right) + w_{base\ run}\left(G_{res.heating,t,HP\ run}\right) \quad (8)$$

To use Equation (8) we must determine the weightings of $w_{base\ run}$, $w_{NG\ run}$, and $w_{HP\ run}$ that represent multipliers for the base, NG heating only, and electric heat pump heating only ResStock simulated electricity profiles. These weightings depend upon the user's inputs for the fraction of household heating served by each heating type (e.g., $f_{user,NG\ res.heating}$ as the user's desired fraction of homes to be heated using NG furnaces) as determined by the constraints in Equations (9)-(11). These three constraint equations contain the three weightings as unknowns such that the weightings are solved as in Equations (12)-(14). By inserting the results from Equations (12)-(14) into Equation (8), one can solve for the hourly electricity generation requirement for all household heating.

$$f_{user,NG\ res.heating} = (f_{base\ run,NG\ heating}) \cdot w_{base\ run} + (1) \cdot w_{NG\ run} + (0) \cdot w_{HP\ run} \tag{9}$$

$$f_{user,HP\ res.heating} = (f_{base\ run,HP\ heating}) \cdot w_{base\ run} + (0) \cdot w_{NG\ run} + (1) \cdot w_{HP\ run} \tag{10}$$

$$\begin{aligned} f_{user,other\ res.heating} &= 1 - f_{user,NG\ res.heating} - f_{user,HP\ res.heating} \\ &= (f_{base\ run,other\ heating}) \cdot w_{base\ run} + (0) \cdot w_{NG\ run} + (0) \cdot w_{HP\ run} \end{aligned} \tag{11}$$

$$w_{base\ run} = \frac{1 - f_{user,NG\ res.heating} - f_{user,HP\ res.heating}}{f_{base\ run,other\ heating}} \tag{12}$$

$$w_{HP\ run} = f_{user,HP\ res.heating} - f_{base\ run,HP\ heating} \cdot w_{base\ run} \tag{13}$$

$$w_{NG\ run} = f_{user,NG\ res.heating} - f_{base\ run,NG\ heating} \cdot w_{base\ run} \tag{14}$$

Light-Duty Electric Vehicle 8760 Hourly Charging Profiles

This subsection describes the process and assumptions governing the hourly charging assumed for electric vehicles for the Energy Infrastructure of the Future (EIoF) Energy Futures Dashboard (EFD) interactive online tool. The approach first assumes an **hourly charging profile for the 168 hours in a week** for the average plug-in electric vehicle (PEV). Second, this weekly profile is replicated to all 8760 hours of the year. The current EFD does not assume temperature-related differences in the amount of kWh needed to drive a mile, but future versions could do so. The end result is a specific charging profile of 8760 hours per year, for the year 2050, for each EIoF region. This profile characterizes only light-duty vehicles (LDVs), such as cars and light trucks. The EIoF EFD assumes that all other transportation, other than LDVs, is fueled by energy carriers other than electricity. Many existing transportation systems use electricity, such as subways and some rail travel, but these are out of the scope of the EIoF study.

Daily and Weekly Charging Profile

We assume an hourly EV charging profile based upon repeating a 1 week, or 168 hour, profile for each week of the year. This is to incorporate information on the differences between how much an EV is charged on weekdays versus weekends. We use insights from two reports, EPRI (2018) and DOE (2017), to inform this hourly profile over one week.

The 2018 report by the Electric Power Research Institute summarizes data from 70 EV drivers, within the Salt River Project service territory in Arizona (EPRI, 2018). This report indicated that less charging occurs on weekends versus weekdays: 23% of EV charging occurred on the two weekend days even though they represent 29% of the hours of the week (EPRI, 2018). This same report also shows a slight decrease in the amount of average charging per EV in the night hours, from around 6 pm to 2 am, for weekend days versus weekdays (Figure 4).

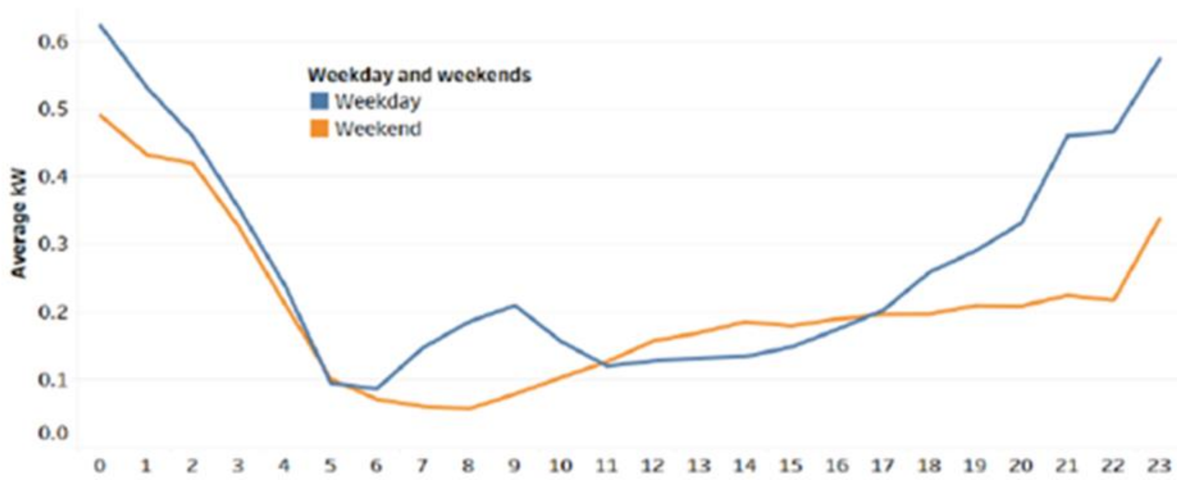

Figure 6-11
Average load shape over all vehicles colored by weekdays and weekends

Figure 4. Average load shape over all electric vehicles studied in a 2018 Technical Report shows less average charging for weekend days versus weekdays (EPRI, 2018). This is a copy of Figure 6-11 from (EPRI, 2018).

The 2018 EPRI report states that "More than half of the vehicles enrolled in the study were enrolled in a time-of-use (TOU) rate. For these customers, the TOU rate was very effective in shifting peak load into the nighttime and early morning hours." Figure 5 shows a figure from the EPRI report that summarizes average daily charging profiles for customers enrolled in four different rate plans as summarized in Table 4. Most notably, the rate plans that incentivized EV drivers to avoid charging in the afternoon and early evening hours did reduce charging during those hours (3-6 pm and 1-8 pm).

Table 4. Description of all of the EV charging rate plans. Only rate plans with at least 10 vehicles participating were included in the average load shape analysis. This is information from Table 6-1 of EPRI (2018).

Rate Plan Name	Description
E21-(3-6) EZ3	Avoid 3–6 p.m.
E23-Basic Plan	All charging times are the same
E26-Res-TOU	Avoid 1–8 p.m.
E29-EV-TOU	Avoid 1–8 p.m., Target 11 p.m. – 5 a.m.

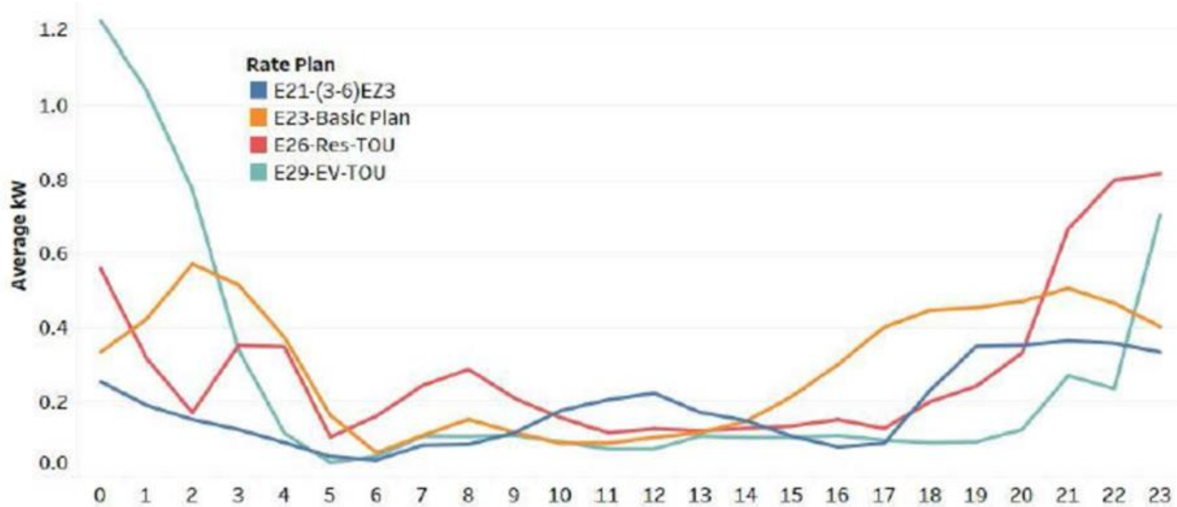

Figure 6-20
Weekday average load shape colored by four rate plans

Figure 5. The load shape for charging electric vehicles studied in a 2018 Technical Report shows that time of use (TOU) rates did influence charging behavior over the course of a weekday (EPRI, 2018). This is a copy of Figure 6-20 from (EPRI, 2018).

Figure 6 shows the simulated result, from Figure 7 of DOE (2017), for an EV charging scenario in which 88% of charging is assumed to occur at residential homes and that was "… consistent with early market findings in the EV Project" under study by the Department of Energy (DOE) team. Further, they state:

> "The resulting charging load profile from home-dominant EVI-Pro simulations is shown in Figure 7. Note that 88% of charging in the EVI-Pro simulations is from residential EVSE [electric vehicle supply equipment] (either L1 or L2). The simulations do not account for

> electricity pricing mechanisms or consumer incentives (such as time-of-use pricing) designed to shift load from the early evening into overnight hours. These effects have significant impacts on the operation of the electricity grid, but do not impact the non-residential EVSE/PEV [plug-in electric vehicle] ratios estimated in this report." (DOE, 2017)

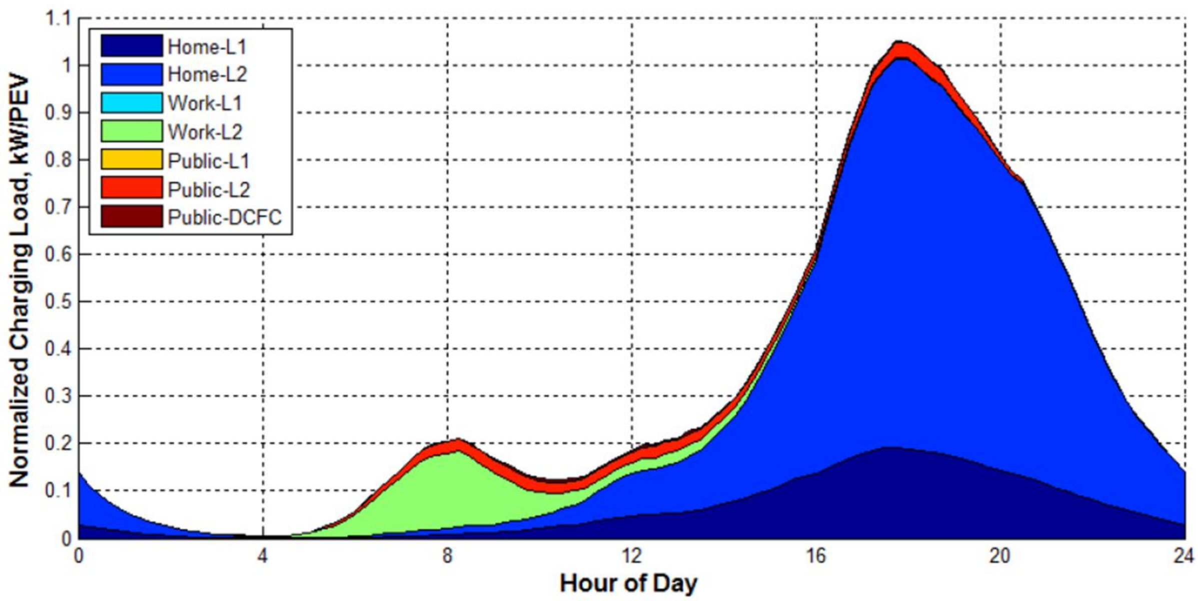

Figure 7. Nominal charging load profile from EVI-Pro simulations (home dominant charging behavior).

Figure 6. Nominal charging load profile from EVI-Pro simulations (home dominant charging behavior). This is a copy of Figure 7 from (Wood *et al.*, 2017).

Informed by the EV charging profiles in Figure 4 – Figure 6, we derive both a weekday and weekend charging profile (see Figure 7) that resides between those of the EPRI (2018) and DOE (2017) examples. We then concatenate these into an hourly EV charging profile for an entire week as shown in Figure 8, and Table 5 displays the exact values. Notice that in Table 5 we change one value for Monday, the first hour of the day, from 0.42 kW to 0.36 kW to create a smoother transition from the weekend to weekday charging profile.

Figure 7. The assumed nominal weekday and weekend hourly charge profile, kW per EV, for each EIoF region.

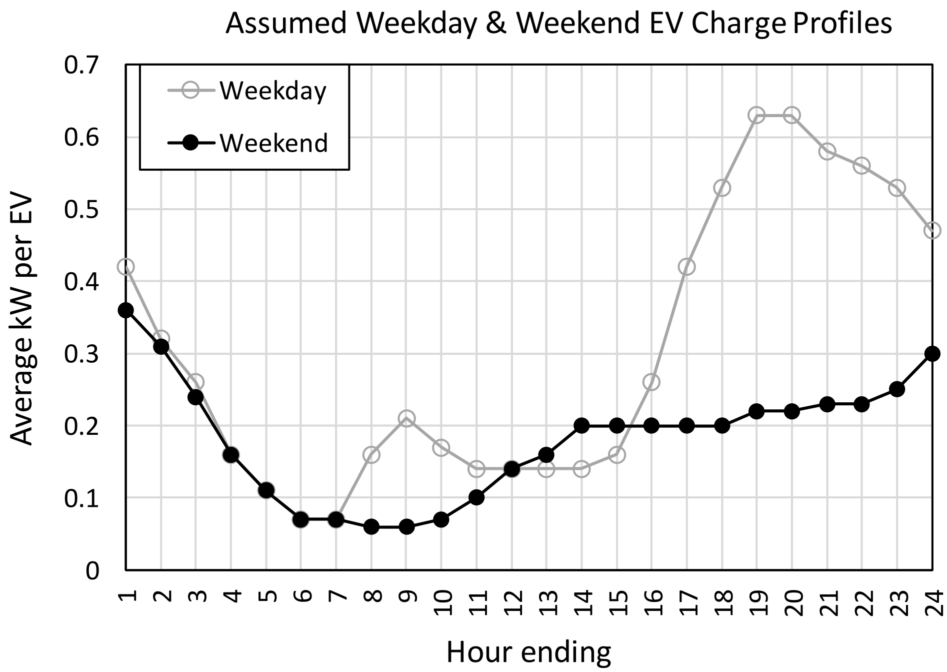

Figure 8. The assumed nominal hourly charge profile, kW per EV, over a week for each EIoF region.

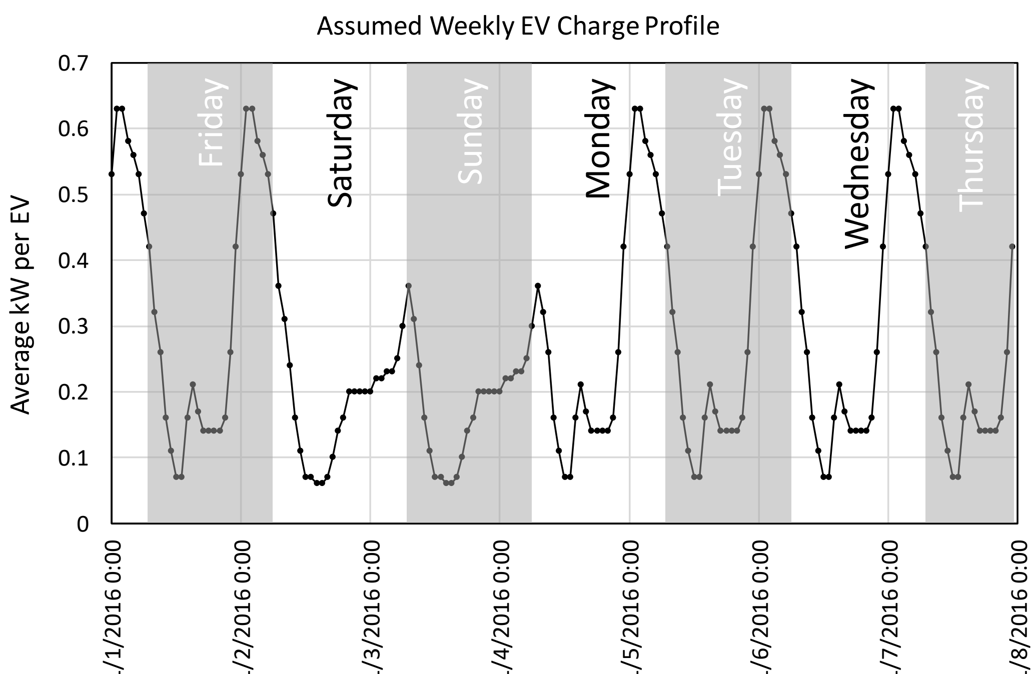

Table 5. The data for the assumed EV charging profiles, as shown in Figure 7 and Figure 8, that are used for the EIoF Energy Futures Database. NOTE: The first hour of Monday is altered (from 0.42 kW to 0.36 kW) to create a smoother transition from the weekend to weekday charging profile. No smoothing is needed to transition from weekday to weekend.

Hour Ending	Saturday & Sunday	Monday	Tuesday, Wednesday, Thursday, & Friday
1	0.36	***0.36***	0.42
2	0.31	0.32	0.32
3	0.24	0.26	0.26
4	0.16	0.16	0.16
5	0.11	0.11	0.11
6	0.07	0.07	0.07
7	0.07	0.07	0.07
8	0.06	0.16	0.16
9	0.06	0.21	0.21
10	0.07	0.17	0.17
11	0.1	0.14	0.14
12	0.14	0.14	0.14
13	0.16	0.14	0.14
14	0.2	0.14	0.14
15	0.2	0.16	0.16
16	0.2	0.26	0.26
17	0.2	0.42	0.42
18	0.2	0.53	0.53
19	0.22	0.63	0.63
20	0.22	0.63	0.63
21	0.23	0.58	0.58
22	0.23	0.56	0.56
23	0.25	0.53	0.53
24	0.3	0.47	0.47

Number of LDV Miles per EIoF Region

We calculate an assumed annual vehicle miles traveled (VMT) in LDVs for each EIoF region in 2050. We start with the assumed total LDV miles from the EIA AEO 2019 reference case of 3,473 billion miles for the entire U.S. and reduce this by 0.5% to represent only the LDV miles driven in the continental U.S.-48. We then use data from 2016 to inform the distribution of

VMTs and fuel consumption among the EIoF regions (see Table 6). State level data for 2016 liquid fuel consumption come from the Federal Highway Administration (FHWA) Table MF-21[3] and for 2016 light duty vehicle miles from FHWA Table VM-3[4]. These state data were aggregated into EIoF regions as shown in Table 6. We calculate the 2016 regional fuel economy, in miles per gallon, and the 2016 percentage of vehicle miles traveled (VMT) from the FHWA data. We use these 2016 data, along with the reference scenario of the EIA AEO 2019, to project a baseline set of assumptions for LDV travel in 2050 (see Table 7). The EIA AEO 2019 projects annual VMT of LDVs to 2050, and we assume that the change in VMTs per EIoF region occur proportionally to projected state-level (translated to EIoF regions) population changes from the University of Virginia Weldon Cooper Center for Public Services[5]. See the separate EFD documentation of our EIoF population assumptions for 2050.

Table 6. The distribution of VMT, fuel consumption, and regional fuel economy using data from 2016.

EIoF Region	LDV Miles Traveled, 2016 (millions of miles)	LDV Fuel Consumption, 2016 (thousands of gallons)	LDV fuel economy, 2016 (miles per gallon)	Percentage of U.S. LDV VMTs (%)
Northwest (NW)	87,318	3,985,426	21.9	1.5
California (CA)	303,857	13,854,477	21.9	13.5
Mountain North (MN)	133,570	5,821,032	22.9	19.1
Southwest (SW)	83,685	3,491,371	24.0	2.9
Central (CE)	108,156	4,684,049	23.0	10.4
Texas (TX)	242,345	12,824,295	18.9	12.7
Midwest (MW)	464,887	20,846,673	22.3	15.0
Arkansas-Louisiana (AL)	75,858	3,428,549	22.1	5.4
Mid-Atlantic (MA)	467,526	22,338,617	20.9	35.5
Southeast (SE)	429,695	18,339,505	23.43	7.8
Florida (FL)	192,572	8,097,697	23.8	3.5
New York (NY)	109,825	5,112,038	21.5	64.0
New England (NE)	122,505	5,890,604	20.8	23.9

[3] https://www.fhwa.dot.gov/policyinformation/statistics/2016/mf21.cfm
[4] https://www.fhwa.dot.gov/policyinformation/statistics/2016/vm3.cfm
[5] https://demographics.coopercenter.org/national-population-projections

Table 7. The distribution of VMT, fuel consumption, and regional fuel economy assumed for 2050.

EIoF Region	LDV Miles Traveled, 2050 (millions of miles)	LDV Fuel Consumption, 2050 (thousands of gallons)	LDV fuel economy, 2050 (miles per gallon)	Percent of LDV VMTs (%)	LDV EV fuel economy (mile/kWh)
Northwest (NW)	126,229	3,306,991	38.2	3.7	3.47
California (CA)	380,257	9,951,750	38.2	11.0	3.47
Mountain North (MN)	191,992	4,802,596	40.0	5.6	3.63
Southwest (SW)	113,420	2,716,040	41.8	3.3	3.79
Central (CE)	127,849	3,178,108	40.2	3.7	3.65
Texas (TX)	397,554	12,075,275	32.9	11.5	2.99
Midwest (MW)	431,770	11,113,295	38.9	12.5	3.53
Arkansas-Louisiana (AL)	83,235	2,159,309	38.5	2.4	3.50
Mid-Atlantic (MA)	504,793	13,844,081	36.5	14.6	3.31
Southeast (SE)	544,371	13,335,933	40.8	15.8	3.71
Florida (FL)	305,230	7,367,112	41.4	8.8	3.76
New York (NY)	117,366	3,135,702	37.4	3.4	3.40
New England (NE)	131,221	3,621,687	36.2	3.8	3.29

Creating Baseline 2050 Electricity Generation Mix

When a user first opens the EIoF EFD, a set of default input data appears representing a mix for electricity generation percentages for each region. Given the Final U (use) matrices for 2050, we estimate the percentage of total electricity generation serving each EIoF region for each of the possible electricity generation technologies. In the real world, there might be net electricity imports into the states composing an EIoF region, but we do not directly use this import information as a basis for determining the default 2050 mix of electricity consumption. However, the algorithms within the EIoF EFD do assume that renewable electricity from CSP and wind power plants can be generated in one EIoF region but sent for consumption in another EIoF region. For example the Southeast region (SE) has poor wind resources, so if the EIoF EFD user wants the SE region to consume wind power, then we assume some wind farms are installed in the Central (CE), Midwest (MW), and Middle Atlantic (MA) regions that ultimately serve load in the SE region. For the purposes of estimating a default, or baseline, mix of electricity generation for each EIoF region, however, we neglect both real-world data on imported electricity (net electricity flow across state boundaries) and the concept of renewable electricity from one EIoF region serving another region.

We estimate the percentage of total electricity generation for technology *i* in EIoF region *j*, $PctG_{i,j,2050}$, as calculated in Equation (15) where $G_{i,j,2050}$ is the electricity generation from technology *i* within EIoF region *j* in 2050, $EC_{j,2050}$ is the total electricity consumption assumed within EIoF region *j* in 2050, and $EImports_{j,2050}$ is the net electricity assumed imported into EIoF region *j* in 2050 from all other EIoF regions. Table 8 shows the results of performing the calculation of Equation (15).

$$PctG_{i,j,2050} = \frac{100 \times G_{i,j,2050}}{EC_{\ j,2050}} = \frac{100 \times G_{i,j,2050}}{\sum_{i=1}^{n} G_{i,j,2050}} \tag{15}$$

Table 8. The baseline assumed percentage of electricity generation from each type of fuel and technology for the year 2050 (e.g., before the user changes the inputs).

	EIoF Region												
Technology	NW	CA	MN	SW	CE	TX	MW	AL	MA	SE	FL	NY	NE
Natural Gas	19	38	35	35	22	53	27	59	35	29	66	57	47
Geothermal	0	4	1	0	0	0	0	0	0	0	0	0	0
Nuclear	5	5	0	29	2	8	21	18	24	37	18	29	40
Petroleum	1	1	1	0	0	0	0	0	0	0	0	0	0
Hydro	53	8	5	2	2	0	0	1	1	1	0	9	3
Biomass	1	1	0	0	0	0	0	1	0	1	0	0	3
Wind	19	10	7	2	23	10	6	0	3	2	0	2	5
Solar PV	0	30	3	4	1	5	2	1	2	11	1	1	2
Solar CSP	0	3	0	1	0	1	0	0	0	0	0	0	0
Coal	2	0	48	26	50	23	44	20	35	19	15	2	0

Creating Baseline 2050 Mix of Fuels used for Light-Duty Vehicles

From the 2050 baseline U matrix derived as discussed earlier in this document, and the assumed miles driven per kWh (mpkWh) of an electric vehicle, we estimate a baseline percentage of LDV travel that occurs in electric vehicles for 2050 as calculated in Equation (16) with results displayed in Table 9. In Equation (16), $PctLDV_{elec,i,2050}$ is the percentage of LDV miles driven on electricity region *i* in 2050, $EC_{elecLDV,i,2050}$ is the energy consumption (in kWh/yr) consumed in region *i* by LDVs in 2050, $mpkWh_{elecLDV,i,2050}$ is the miles per kWh that can be traveled in an electric LDV in region *i* in 2050, and $LDV\ miles_{i,2050}$ is the number of miles driven by all LDVs in region *i* in 2050.

$$PctLDV_{\mathrm{elec},i,2050} = \frac{100 \times EC_{elec_{LDV},i,2050} \times mpkWh_{elec_{LDV},i,2050}}{LDV\ miles_{i,2050}} \quad (16)$$

Table 9. The baseline assumed percentage of light-duty vehicle miles driven on electricity and liquid fuels (petroleum plus biofuels) in the year 2050 (e.g., before the user changes the inputs).

	EIoF Region												
Fuel	NW	CA	MN	SW	CE	TX	MW	AL	MA	SE	FL	NY	NE
Liquid Fuels (petroleum and ethanol)	99	86	81	97	90	87	85	95	65	92	96	36	76
Electricity	1	14	19	3	10	13	15	5	35	8	4	64	24

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