Chapter 4: Python Software Package: Load Following Decision

4.1 Introduction and Motivation

The purpose of this software package is to examine the techno-economic factors that influence the success of small-scale (<100 kWe) combined heat and power (CHP) systems coupled with thermal storage (TES) for multi-family residential applications in the United States. Existing CHP installations at this scale in the US relative to other countries has not been quantified, but the literature reveals limited feasibility assessments in the context of US climate zones, policies, and economic conditions. Additionally, existing models used for CHP economic, energy, and/or emission assessments in the literature are not typically available for open use. The software tool described here is openly available for use within the academic community and beyond. This chapter begins with an overview of the tool's intended use and functionality. A brief overview of differences between this tool and existing open-source tools follows, leading into the calculation methodology used in the tool and a discussion of its assumptions and limitations. Next, the required inputs and expected outputs are laid out and the software design is reviewed. Following are instructions on how to use the tool with examples of the plots and tables generated by the program.

4.2 Overview

The Load Following Decision (LFD) software package is intended to assess the economic feasibility of installing a small-scale (<100 kWe) combined heat and power (CHP) system for multifamily building applications in the United States. It is currently intended for use by the academic community and those familiar with Python software, but for future work I aim to improve the user interface such that it can be used by anyone interested in installing a small-scale CHP system. It is open-source available for use through GitHub. The software imports the annual electrical demand and thermal demand data for a simulated apartment building. Note that the LFD package assumes that the electrical and thermal demand for the building has been simulated in EnergyPlus [105, 106] and that the hourly demand profile has been exported as a .csv file. Using this data, the software calculates the energy load dispatch of a small-scale CHP system coupled with a thermal storage (TES) system and a pre-existing backup boiler. The CHP system has 3 dispatch options: operate so that the electricity produced by the system matches the electrical demand of the building (electrical load following, or ELF), operate so that the thermal energy produced by the system matches the building's thermal demands (thermal load following, or TLF), or operate constantly at full capacity (referred to here as power purchase, or PP). The latter of the 3 options assumes that the excess electricity generated by the CHP system is sold to the electrical grid, so operating at maximum capacity maximizes revenue. The LFD package performs four assessments:

- Equipment sizing: Calculates the needed capacity for the CHP and TES systems, including whether CHP needs a coupled TES system. These sizes vary depending on whether the operating mode is ELF, TLF, or PP.
- Energy analysis: Calculates the energy flow between the CHP, TES, and boiler systems. This energy flow will also vary depending on the operating mode of the system, each of which is described in further detail in Section 4.4 of this chapter.
- Economic assessment: Calculates the installed cost, operation and maintenance (O&M) cost, and energy costs of all three operating modes as well as the energy savings and payback period. These results are compared with the energy costs and energy use of the non-CHP, or Baseline, case.
- Emissions assessment: Calculates the emissions associated with electricity bought from the grid and the fuel used to operate the CHP and boiler systems. These emissions are compared with those associated with the Baseline (non-CHP) case.

4.3 Existing Methodology and Prior Work

Current literature discusses methods such as multi-integer optimization to find a balance between low-cost, low-emission, and energy-saving load dispatch schedules for small-scale CHP systems [29]. CHP systems are typically used in industrial and commercial scale applications. However, residential scale applications have comparatively large demand fluctuations that negatively impact load-following operating strategies; the literature indicates that coupling small-scale CHP systems with thermal or electrical storage improves performance by reducing emissions and increases energy savings [27–30]. This work compares the energy and emissions from each of the three CHP operation strategies.

The LFD package stands out from other open-source software through its format and its functionality. NREL's free web tool, ReOpt [138], lacks the emissions assessment and operation mode comparison that the LFD package provides, while the EPA's CHP Energy and Emission Savings tool [68] does not account for thermal storage and lacks a cost assessment feature. However, it is important to note that there is existing commercial software that may be used to perform analyses akin to those of the LFD tool. The LFD software stands out from these packages by being free to use and widely available. I have not encountered literature where the software package used for research is open-source, and the specific model used for the research is rarely provided for reference. For example, Onovwiona et al. created a parametric model that can be used in the design and techno-economic evaluation of internal combustion engine (ICE) based cogeneration systems for residential use [90]. It provides information about the system's performance in response to changing thermal and electrical demands. While the ESP-r modeling program is open source, the author gives no way to access the model created for this analysis.

4.4 Methods

A detailed description of the methodology used in this software program can be found in Chapter 3 of this thesis. However, a brief overview of the three operating modes inherent to the CHP-TES energy system is described below.

When analyzing the energy use, energy generation, and energy costs of the small-scale CHP and thermal storage (TES) system in electrical load following (ELF) mode, the program examines the energy use of the system as follows: If the electrical demand is below the minimum operating capacity of the CHP unit, the owner will buy electricity from the local utility company. If the electrical demand is above the CHP unit's maximum operating capacity, then the owner will buy electricity from the local utility company to make up the difference. Naturally, if the electrical demand is between the CHP unit's minimum and maximum operating capacity values, then no electricity needs to be bought from the local utility. Any excess thermal energy produced by the CHP system in any of these scenarios will be stored in the TES system. If the thermal energy produced by the CHP unit is insufficient to meet the building's thermal demand, the TES system will dispatch stored thermal energy to make up the difference. If the TES system does not contain sufficient thermal energy to make up the discrepancy, then the auxiliary boiler will turn on and generate the heat necessary to meet the thermal demand.

For thermal load following (TLF) operation, the empty thermal storage is aggregated with the heating demand of the building when computing the desired CHP thermal output. When the aggregated thermal demand is less than the minimum output of the CHP system, the boiler is operated to meet thermal demand. When the aggregated thermal demand is between the minimum CHP output and the maximum CHP output, then the CHP output meets demand exactly. The heat is dispatched to meet the building's heating demand and is also stored in the TES system if heat is needed. However, note that the boiler is never operated to fill the thermal storage unit – only CHP heat is used for this. If aggregated thermal demand is greater than the CHP maximum output, then the CHP system is operated at maximum output. However, the boiler only operates in this case if the building demand is greater than the maximum CHP output and only operates to meet the building demand (rather than operating to fill the TES system).

For Power Purchase (PP) operation, the CHP system is sized to the peak electrical demand of the building. This allows a significant amount of revenue to be collected from selling electricity to the grid. The operation logic of the CHP system in this case is as follows: if the building electrical demand is less than the minimum electrical output of the CHP system, then electricity is bought from the grid. If the electrical demand is greater than the minimum CHP output and less than the maximum CHP output (which it should always be since the CHP system is sized to peak annual demand), then the CHP system operates at full capacity. Any excess electricity generated is sold to the grid.

The Load Following Decision (LFD) software package compares the operating costs of the coupled CHP and TES system for a given operating mode with that of the control case, referred to as the "Baseline" case. For the Baseline case, electricity and thermal energy are generated separately via the electrical grid and a natural gas boiler, respectively. The boiler is referred to as the auxiliary boiler within the software program, and it is assumed that the boiler used with the coupled CHP-TES system is already installed in the building. The costs considered in the economic analysis include the installed costs (material and installation) and operation and maintenance (O&M) costs of the CHP and TES systems. The revenue from selling excess electricity for the PP operation mode and the costs of purchasing electricity and fuel as needed are also considered. Labor costs associated with operating the system are excluded in this version of the software tool.

The key equations used in my analysis are listed in Table 4.1 with their associated units.

Further information regarding variables and their names is found in Table 4.2 for those not defined in the Key Equations table.

Table 4.1: Key Equations

Name	Equation	Units
Annual Electrical Demand $[D_e]$	$D_e = \sum_1^{8760} D_{e,hr}$	kWh
Annual Thermal Demand $[D_{th}]$	$D_{th} = \sum_1^{8760} D_{th,hr}$	Btu
CHP Size $[P_{chp,max}]$	$P_{chp,max} = max(t_{hr} \times D_{e,hr})$	kW
CHP Fuel Consumption $[F_{chp}]$	$F_{chp} = \sum_1^{8760}(3.6376 \times P_{e,chp})$	Btu
CHP Heat Generation $[E_{th,chp}]$	$E_{th,chp} = 1.8721 \times \sum_1^{8760} P_{e,chp}$	Btu
CHP Electrical Generation $[E_{e,chp}]$	$E_{e,chp} = 0.5188 \times \sum_1^{8760} P_{th,chp}$	kWh
TES Size $[(E^{tes})_{max}]$	$(E^{tes})_{max} = max[min(D^{ncov}, E^{nrec})]$	Btu
TES Thermal Storage $[E_{th,st}]$	$E_{th,st} = \sum_1^{8760}(P_{th,chp} - D_{th,hr})_{if>0}$	Btu
TES Thermal Dispatch $[E_{th,dis}]$	$E_{th,dis} = \sum_1^{8760}(D_{th,hr} - P_{th,chp})_{if>0}$	Btu
Aux Boiler Size $[P_{max,ab}]$	$P_{max,ab} = max(D_{th,hr})$	Btu/hr
Aux Boiler Fuel Consumption $[F_{ab}]$	$F_{ab} = \sum_1^{8760}(E_{th,ab}/\eta_{th,ab})$	Btu
Aux Boiler Thermal Output $[E_{th,ab}]$	$E_{th,ab} = \sum_1^{8760}(D_{th,hr} - (P_{th,chp} + P_{th,st}))$	Btu
Electrical Energy Use $[E_{e,gross}]$	$E_{el,gross} = F_{chp} + F_{ab} + E_{e,buy}/\eta_{grid}$	kWh
Electrical Energy Savings $[E_{e,S}]$	$E_{e,S} = D_e/\eta_{grid} - E_{e,gross}$	kWh
Thermal Energy Use $[E_{th,gross}]$	$E_{th,gross} = F_{chp} + F_{ab}$	Btu
Thermal Energy Savings $[E_{th,S}]$	$E_{th,S} = D_{th}/\eta_{ab} - E_{th,gross}$	Btu
Electrical Cost Savings $[S_e]$	$S_e = C_{e,D} - C_{e,buy}$	\$
Thermal Cost Savings $[S_{th}]$	$S_{th} = C_{F,D} - (C_{F,chp} + C_{F,ab})$	\$
Total Cost Savings $[S]$	$S_{th} + S_e$	\$
Installed Costs $[C_I]$	$C_I = (IC_{I,tes} \times E_{tes,max}) + (IC_{I,chp} \times P_{chp,max})$	\$
O&M Costs $[C_{OM}]$	$C_{OM} = IC_{OM,chp} \times \sum_1^{8760} P_{e,chp}$	\$
Simple Payback $[t_{PB}]$	$t_{PB} = C_I/S$	yr
Electricity Emissions $[CO2_e]$	$CO2_e = E_{e,gross} \times CO2_{I,th}$	tons
Fuel Emissions $CO2_{th}$	$CO2_{th} = E_{th,gross} \times CO2_{I,th}$	tons

Table 4.2: Nomenclature

Name	Symbol
CHP Electricity Generation, hourly [kW]	$P_{e,chp}$
CHP Heat Generation, hourly [Btu/hr]	$P_{th,chp}$
Unused Thermal Energy [Btu]	E^{nrec}
Uncovered Thermal Demand [Btu]	D^{ncov}
Electricity Bought [kWh]	$E_{e,buy}$
Electricity Cost (Baseline case) [$]	$C_{e,D}$
Electricity Cost (CHP case) [$]	$C_{e,buy}$
Incremental Cost [$/kW, $/Btu]	IC
Emission Intensity [tons/kWh, tons/Btu]	$CO2_I$

4.4.1 Assumptions and Limitations

The LFD package is constrained by the assumptions and limitations listed below. The most significant assumptions include the following:
CHP unit

- Fuel type is natural gas.
- CHP prime mover is a reciprocating engine.
- Turn-down ratio is 3.3.*

TES unit

- Unrestricted discharge rate (Btu/hr).
- No heat loss.
- Cost values assume hot water storage.*
- O&M cost is assumed to be zero.*

Boiler

- Fuel type is natural gas.

- Efficiency is 0.8.*
- No restrictions on turn-down.
- Power rating assumed to be equal to the annual peak thermal demand.

Other

- Building type is a mid-rise (4-floor) multifamily building.
- Electricity buyback rate is equal to the price paid by the consumer.
- No power purchase is considered for the ELF operating mode.
- Energy demand data must be hourly and span the course of one year.
- Weather data and building construction must be specified in EnergyPlus [105, 106] when simulating the building's energy demand.
- Building is sub-metered for both electricity and natural gas.*

Items indicated with an asterisk (*) can be modified by the user through the .yaml input file as needed.

4.5 Implementation

4.5.1 Program Inputs and Outputs

As depicted in Figure 4.1, the software package relies on two files for data input. The first is a .csv file containing hourly electricity and thermal demand data for the building that the CHP system would be installed in. The second file is a .yaml file containing the operating parameters of the CHP system, pre-existing boiler, and thermal storage (TES) system. The file also contains the city and state where the building is being assessed, the installed cost and O&M cost of the CHP and TES units, the electricity and natural gas rate schedules used for calculating energy costs, and file name of the .csv file that this information is associated with.

The inputs of the program described in Table 4.3

Note that the electricity meter types are limited to "single_metered_el" or "mater_metered_el" to indicate sub-metered or master-metered buildings, respectively. Similarly for natural gas

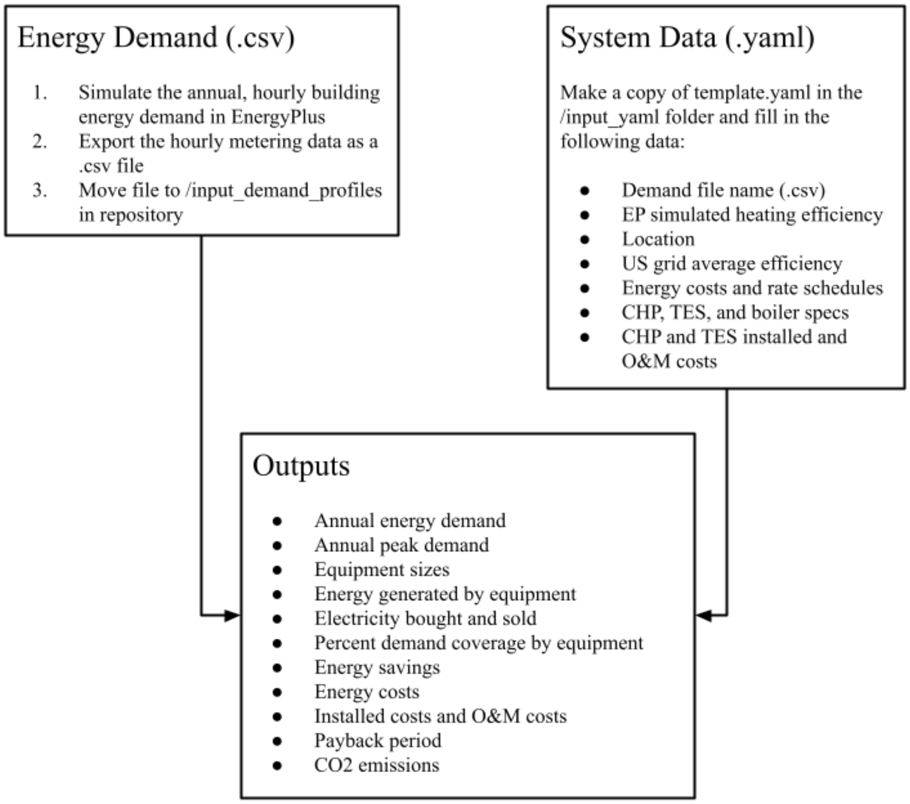


Figure 4.1: Required inputs and expected outputs for the LFD software package.

metering, accepted string values are “single_metered_fuel” or “master_metered_fuel”, respectively. For the rate schedule types, there are a finite number of types that are accepted. These are listed in Table 4.4

The expected outputs of the program include:

- An excel sheet with the cost breakdown, energy savings, payback period, percent demand coverage, and emissions analysis results.
- Two demand curve graphs (electrical and thermal) for the building at the given location.
- Three graphs for each of the three operating modes comparing the 1) electricity generated by the CHP and electricity bought from / sold to the grid, the 2) thermal energy generated by the CHP, dispatched by the TES, and generated by the boiler,

Table 4.3: LFD Input Variables.

Description	Variable Name	Data Type	Units
Demand file name (.csv)	demand_filename	string	N/A
City location	city	string	N/A
State location	state	string	N/A
US grid average efficiency	grid_efficiency	float	dimensionless
EP simulated heating efficiency	energy_plus_efficiency	float	dimensionless
CHP turn-down ratio	chp_turn_down	float	dimensionless
CHP installed cost	chp_installed_cost	float	$/kWe
CHP O&M cost	chp_om_cost	float	$/kWhe
TES initial state of charge (SOC)	tes_init	float	dimensionless
TES installed cost	tes_installed_cost	float	$/kWhth
TES O&M cost	tes_om_cost	float	$/kWth
Boiler efficiency	ab_eff	float	dimensionless
Electricity meter type	meter_type_el	string	N/A
Natural gas meter type	meter_type_fuel	string	N/A
Electrical rate schedule type	schedule_type_el	list of strings	N/A
Natural gas rate schedule type	schedule_type_fuel	list of strings	N/A
Summer start month (if needed)	summer_start_inclusive	integer	dimensionless
Winter start month (if needed)	winter_start_inclusive	integer	dimensionless

and 3) the state of charge (SOC) of the TES over time. This totals in nine graphs generated for all three cases.

Examples of graphs produced by the software can be found in Section 4.6

4.5.2 Software Design, Layout, and Functionality

As depicted in Figure 4.2, the program has a total of 9 modules. The primary module is *command_line.py*, which is called when the program is run. This program uses the .csv and .yaml inputs to initialize the classes located in *classes.py*, which contains the EnergyDemand, Emissions, EnergyCosts, CHP, AuxBoiler, and TES classes. The EnergyDemand

Table 4.4: Accepted Rate Schedule Types.

Rate Schedule Name	Description	Variable Name	Electrical Meter Type(s)	Natural Gas Meter Type(s)
Basic rate	Base monthly charge with fixed energy rate	schedule_basic	Master meter, Sub-meter	Master meter, Sub-meter
Seasonal energy rate	Base monthly charge with energy rate that varies by season	schedule_seasonal_energy	Master meter	N/A
Seasonal demand rate	Base monthly charge with demand rate that varies by season	schedule_seasonal_demand	Master meter	N/A
Seasonal energy block rate	Base monthly charge with energy rate that varies with monthly energy use and season	schedule_seasonal_energy_block	Master meter	N/A
Seasonal demand block rate	Base monthly charge with demand rate that varies with peak monthly demand and season	schedule_seasonal_demand_block	Master meter	N/A
Energy block rate	Base monthly charge with energy rate that varies with monthly energy use	schedule_energy_block	Sub-meter	N/A

class contains the *.csv* filename and stores the hourly demand data, the EnergyCosts class pulls the rate schedule information from the .yaml file and stores them as dictionaries, the

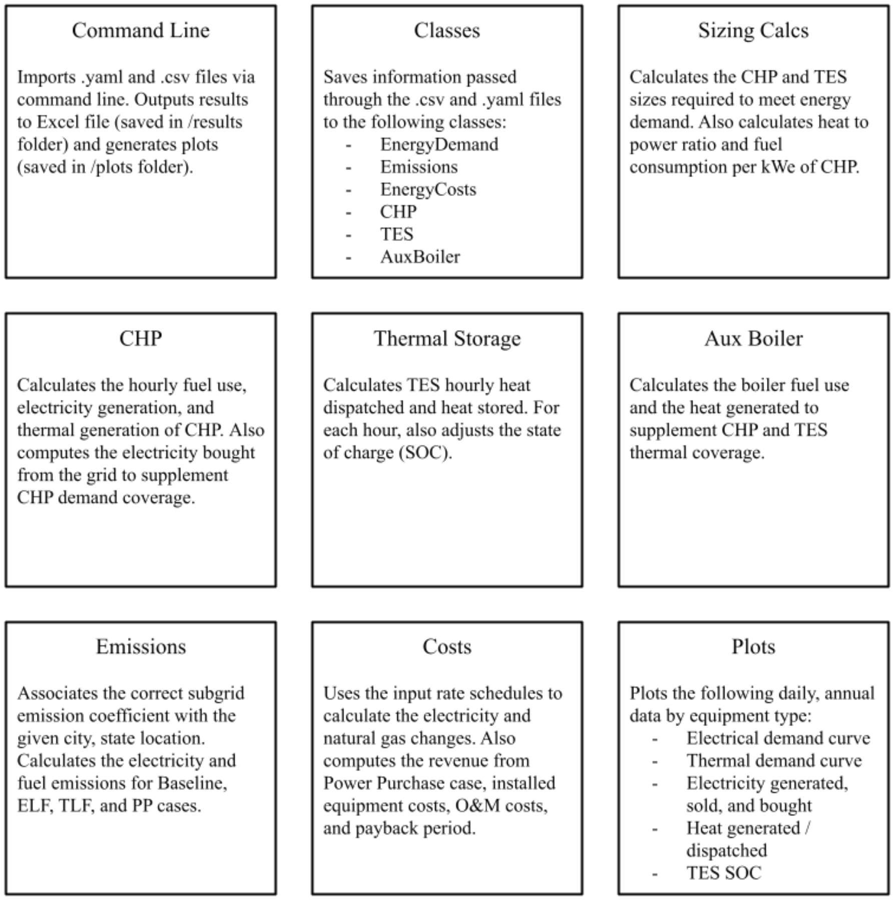


Figure 4.2: Module descriptions

Emissions class contains hard-coded emission intensities for US electrical grid subregions, and the remaining classes contain the operating parameters of their associated systems. The initialized classes are saved as a dictionary in *command_line.py* and passed to other modules as function arguments.

A simplified directory tree showing file and folder locations within the LFD package is shown below:

```
load_following_decision/
|   .gitignore
|   LICENSE
|   pyproject.toml
```

```
|   README.md
|   setup.cfg
|
+---docs/
|   |   example_tables
|   |   how_to_guide.md
|   |   project_motivation.md
|   |
|   \---example-plots/
|
\---lfd_package
    |   command_line.py
    |   __init__.py
    |
    +---input_demand_profiles/
    |
    +---input_yaml/
    |
    +---modules/
    |   |   aux_boiler.py
    |   |   chp.py
    |   |   classes.py
    |   |   costs.py
    |   |   emissions.py
    |   |   plots.py
    |   |   sizing_calcs.py
    |   |   thermal_storage.py
    |   |   __init__.py
    |
    +---plots/
    |
    \---results/
```

4.5.3 Getting Started

Before using this package, read the README.md file and the documentation located in the repository */docs* folder. This has installation instructions and most (if not all) of the information I will be sharing below.

Once the package and its dependencies have been installed per the instructions included in the README.md file, add the energy demand .csv file to the $/input\_demand\_files$ folder in the repository. If the user intends to analyze their own hourly demand data, make a copy of an existing .csv file in the folder and enter the hourly data in the appropriate column. Be sure to rename the file appropriately.

Next, make a copy of the .yaml template (named "*template.yaml*") and change the file name of the copy. Fill out the new .yaml file with the operating parameters of the CHP and TES units to be analyzed as well as the existing boiler (referred to within the program as the "auxiliary boiler"). Also add in the operating parameters of the building's existing boiler (herein referred to as the "auxiliary boiler").

In addition to the operating parameters of the equipment, the .yaml file has entries for the electrical and natural gas rate schedules for the local utility. When entering rate schedule information, make sure to specify the units (either energy or power) in the "units" key. Files have already been created for twelve cities across the US from which data may be copied for convenience or used as examples.

Finally, enter the file name of the energy demand .csv file to be analyzed. This needs to be entered as a string value and include the file type extension (e.g. "$STD2019\_Fairbanks\_AK.csv$").

4.5.4 Using the Command Line Interface

Now that the input data has been entered into their respective files in the */inputs* folder, it is time to run the program from the command line.

In your terminal, navigate to the $/load\_following\_decision\_packagefolder$. This folder contains the package modules. For most terminals you can change directories using the following command:

```
cd directory_path
```

where *directory_path* is the absolute or relative path to the desired folder.

Display the help menu by running the following command in your terminal:

```
python command_line.py --help
```

This will print the following instructions for using the command line interface (CLI).

```
usage: command_line.py [-h] --in INPUT

Import equipment operating parameter data

optional arguments:
  -h, --help  show this help message and exit
  --in INPUT  filename for .yaml file with equipment data
```

If we assume that we are using an hourly demand profile named ($default\_demand.csv$) and a .yaml file named "$default\_inputs.yaml$", then we would run the program by entering the name of the .yaml file like this:

```
python command_line.py --in default_inputs.yaml
```

The energy demand file ($default\_demand.csv$) is specified within the .yaml file, so only the name of the .yaml file is necessary in the command line.

4.5.5 Testing

This program does not currently include a comprehensive testing suite. However, included is the Excel file used for data validation. This file uses the "STD2019_Fairbanks_AK.csv" demand profile and re-creates the energy generation calculations for each of the three operating modes. It also recreates the cost analysis for determining the payback period of the installation. The file was created in Excel 2016 [139] and should be opened in the same program version for consistency and to avoid errors caused by incompatibility.

In future work I will develop a testing suite for unit testing within Python.

4.5.6 Dependencies

This package is dependent on several libraries that must be installed for the package to function as intended (see the program's README.md file for installation instructions). Below is a list of dependencies and their minimum version requirements. Note that the

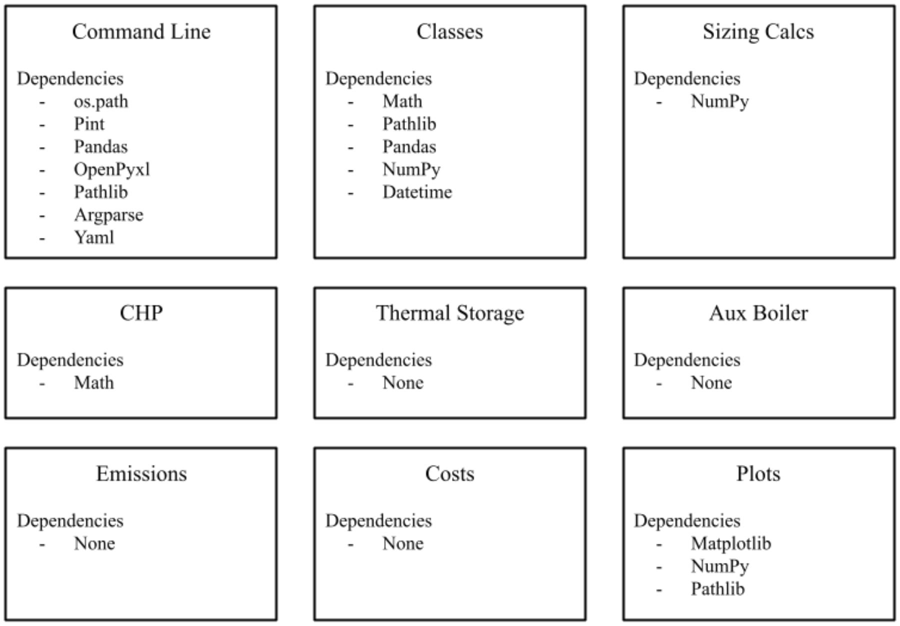


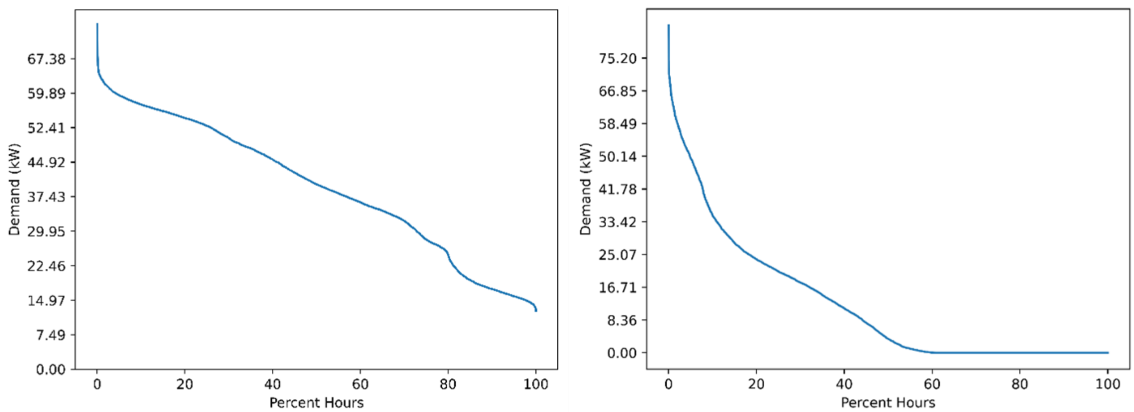
Figure 4.3: Dependencies by module.

datetime, math, argparse, pathlib, and os.path packages are not included in this list – these packages are included with Python upon installation. Figure 4.3 breaks down which dependencies are associated with each module.

- python >= 3.7.4
- pandas >= 1.3.5 [140, 141]
- numpy >= 1.21.5 [142]
- PyYAML >= 6.0 [143]
- matplotlib >= 3.5.1 [144, 145]
- pint >= 0.18 [146]
- openpyxl >= 3.1.2 [147]

4.6 Results

The following results from the Load Following Decision (LFD) software package were produced using the $STD2019\_Fairbanks\_AK.csv$ file containing hourly, annual electrical and thermal demand profile data exported from EnergyPlus [106]. These results also used the input data from the $fairbanks\_ak.yaml$ file. The results were checked for accuracy by recreating the calculations separately in an excel sheet. Only results for the TLF operating mode are included for simplicity.



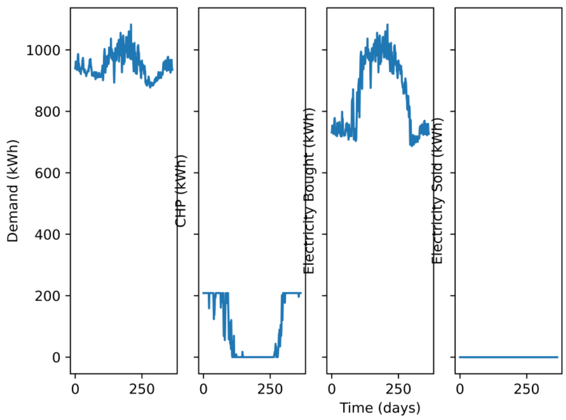
(a) Electrical Demand Curve (b) Thermal Demand Curve

Figure 4.4: Electrical and thermal demand curves for Fairbanks, AK (2019 building construction).

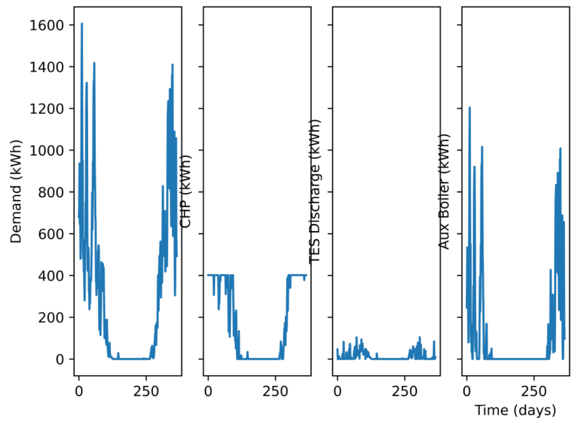
Examining the Figures 4.4 - 4.5, notice that for the Thermal Demand and Generation graphs, the values tend to dip below zero. This is because the data graphed shows both the charging and discharging of the thermal storage unit (heat being stored and heat being dispatched). The negative values represent dispatched heat while the positive values represent heat being stored. Note that in the table results that the value for TES Thermal Energy Dispatched is the sum of the discharged heat only.

An easy check to do is to sum the electricity bought percent coverage and CHP electricity generated percent coverage for each operating mode. For ELF and TLF these sum to 100%, while for PP these sum to 162%. This makes sense since PP mode expects overproduction of electricity for selling to the grid. If we then subtract the electricity sold to the grid, we get the expected 100% coverage.

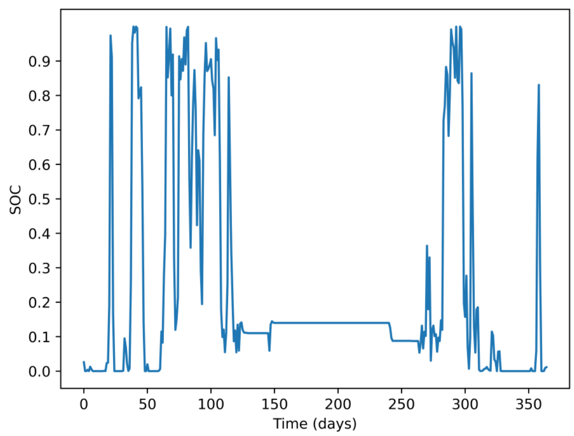
Checking the thermal coverage, we sum the CHP thermal generation, TES thermal



(a) TLF Electrical Demand, Generation, and Exports, Daily Sums



(b) TLF Thermal Demand and Generation, Daily Sums



(c) TLF TES SOC, Daily Avg

Figure 4.5: Thermal Load Following (TLF) energy generation data and storage SOC

dispatch, and the boiler thermal generation percent coverage values. For ELF we can see significant overproduction of heat with 452% thermal coverage. Since ELF is designed to meet electrical demand, this is expected. For TLF operation, the thermal percent coverage is 105%. This seems unusual at first but knowing that the TES started off 50% filled the seeming over-production of heat then makes sense. Looking at the SOC graph for TLF, we can confirm this by checking that the final SOC status is less than 50%. Moving on to PP operation, we see that the CHP generated 946% of thermal demand for the building. From this we can conclude that sizing the CHP system to peak electrical demand may be

Table 4.5: Results Table.

Variable Name	Baseline	ELF	TLF	PP
Peak Electrical Demand (kW)	346,574.39	N/A	N/A	N/A
Annual Thermal Demand (kWh)	74.87	N/A	N/A	N/A
Peak Thermal Demand (kW)	107,891.75	N/A	N/A	N/A
CHP Size (kW)	83.56	N/A	N/A	N/A
TES Size (kWh)	N/A	68.25	91.96	0
Aux Boiler Size (kW)	N/A	83.56	83.56	83.56
CHP Electrical Energy Generation (kWh)	N/A	257,991.64	34,939	531,475.21
Electrical Energy Bought (kWh)	N/A	88,582.75	311,635.39	28,992.27
Electrical Energy Sold (kWh)	N/A	0	0	213,893.09
CHP Thermal Energy Generation (kWh)	N/A	482,986.14	67,345.80	994,974.73
TES Thermal Energy Dispatched (kWh)	N/A	2,563.49	4,417.30	0
Boiler Thermal Energy Generation (kWh)	N/A	1,866.89	41,250.27	25,678.23
CHP Electrical Pct Coverage (%)	N/A	74.44	10.08	153.35
Electricity Bought Pct Coverage (%)	N/A	25.56	89.92	8.37
CHP Thermal Pct Coverage (%)	N/A	447.66	62.42	922.2
TES Thermal Pct Coverage (%)	N/A	2.38	4.09	0
Boiler Thermal Pct Coverage (%)	N/A	1.73	38.23	23.8

unnecessary – a smaller size may save the wasted thermal energy while still gaining revenue from a power purchase agreement.

Looking at the economic results, the TLF operation mode is most favorable according to

Thermal Energy Savings (kWh)	N/A	-805,939.30	-43,792.26	-1,830,527.31
Electrical Energy Savings (kWh)	N/A	644,979.09	87,347.50	793,955.3
Total Energy Savings (kWh)	N/A	-160,960.21	43,555.24	-1,036,572.01
Electricity Cost ($)	95550.21	30,855.67	86,790.04	15,910.97
Fuel Cost ($)	13851.54	69,090.08	16,853.03	139,314.67
CHP Installed Cost ($)	N/A	113,721.40	30,870.70	258,538.47
CHP O&M Cost ($)	N/A	7,739.75	1,048.17	15,944.26
TES Installed Cost ($)	N/A	1,430.44	1,927.57	0
TES O&M Cost ($)	N/A	0	0	0
PP Revenue ($)	N/A	0	0	53,630.65
Simple Payback (yrs)	N/A	67.10	6.96	-31.77
Simple Payback (37.5% incentive)	N/A	41.93	4.35	-19.86
CO2 (Mt)	181	91	166	111

the payback period. The PP operation mode is least favorable with the a negative payback period. This indicates that the revenue from the power purchase agreement is insufficient to make up for the energy costs associated with almost constantly running the system at full load. This indicates that the CHP system size is too large as-is and needs to be adjusted if this operation mode is to be used.

4.7 Conclusions and Recommended Future Work

This chapter has reviewed the intended purpose, methodology, and user instructions for the Load Following Decision (LFD) software package. The results for the Fairbanks, AK location calculations performed in the results section indicate that the *sizing_calcs.py* module may need some adjustments. Results showed that the CHP system was over-sized for the power purchase (PP) operation mode and that the thermal storage (TES) system was either under-sized or unnecessary for the electrical load following (ELF) operation mode.

In future versions of this software, I recommend exploring alternate equipment sizing options for the CHP and TES systems and investigate the impact on economic feasibility and emissions. I also recommend removing some of the simplifying assumptions used in this version, such as:

- No heat loss in TES
- Unrestricted power rating (Btu/hr) of TES
- Unrestricted turn-down ratio of the boiler
- Natural gas fuel type restriction
- Reciprocating engine prime mover limitation

I also recommend modifying the user interface to be more user-friendly for non-academics with limited Python programming experience to increase accessibility.