

Applying DER-CAM for IIT Microgrid Expansion Planning

Energy Systems Division

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Applying DER-CAM for IIT Microgrid Expansion Planning

submitted by
Mohammad Shahidehpour and Zuyi Li
Illinois Institute of Technology

contributing authors
Jianhui Wang and Chen Chen
Energy Systems Division, Argonne National Laboratory

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LIST OF ABBREVIATIONS

CAM	Customer adoption model
CHP	Combined heat and power
CO ₂	Carbon dioxide
DER	Distributed energy resources
HRDS	High-reliability distribution system
HRSG	Heat recovery steam generator
IIT	Illinois Institute of Technology
kpph	kilopounds per hour
MPPT	Maximum power point tracking
O&M	Operation and maintenance
PMU	Phasor measurement unit
PV	Photovoltaics
PWN	Pulse-width modulation

EXECUTIVE SUMMARY

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is an economic and environmental model of customer DER adoption. This model has been in development at the Lawrence Berkeley National Laboratory since 2000. The objective of the model is to find optimal DER investments while minimizing total energy costs or carbon dioxide (CO₂) emissions, or achieving a weighted objective that simultaneously considers both criteria.

The Illinois Institute of Technology (IIT) Microgrid project started in August 2008, and the majority of the project was completed in May 2013. IIT Microgrid, funded mostly by a grant from the U.S. Department of Energy as well as State and philanthropic contributions, empowers the campus consumers with the objective of establishing a smart microgrid that is highly reliable, economically viable, environmentally friendly, fuel-efficient, and resilient in extreme circumstances with a self-healing capability.

In this project, we apply DER-CAM to study the expansion planning of the IIT Microgrid. First, the load data, environmental data, utility data, and technology data for the IIT Microgrid are gathered and organized to follow the DER-CAM input requirements. Then, DER-CAM is applied to study the expansion planning of the IIT Microgrid for different cases, where different objectives in DER-CAM and different utility conditions are tested. Case 1 considers the objective of minimizing energy costs with fixed utility rates and 100% electric utility availability. Case 2 considers the objective of minimizing energy costs with real-time utility rates and 4 emergency weeks when the IIT Microgrid does not have access to the electric utility grid and has to operate in island mode. In Case 3, the utility rates are restored to fixed values and 100% electric utility availability is assumed, but a weighted multi-objective (Obj: $a \times \text{costs} + b \times \text{CO}_2 \text{ emissions}$, where a and b are weights for cost minimization and CO₂ emissions minimization) is utilized to consider both energy costs and CO₂ emissions.

On the basis of the test results, the IIT Microgrid has the potential to benefit from investments in more DER technologies. The current annual energy costs and CO₂ emissions for the IIT Microgrid are 6,495.1 k\$ and 39,838.5 metric tons, respectively. This represents the baseline for this project.

- With the plan from Case 1, investments in 3,600 kW of conventional DER units are suggested. Accordingly, the annual energy costs and CO₂ emissions are reduced to 5,428.9 k\$ and 37,733.9 metric tons (**16.41% reduction from current annual energy costs; 5.29% reduction from current annual CO₂ emissions**).
- With the plan from Case 2, investments in 5,800 kW of conventional DER units, 517 kW of renewable DERs, and 984 kWh of storage technologies are suggested. As a result, the annual energy costs and CO₂ emissions are reduced to 5,360.9 k\$ and 36,668.9 metric tons (**17.46% reduction from current annual energy costs; 7.96% reduction from current annual CO₂ emissions**).

- With the plan from subcase 3.1 (weighted objective: $a = 0.75$, $b = 0.25$), investments in 5,800 kW of conventional DER units and 515 kW of renewable DERs are suggested. As a result, the annual energy costs and annual CO₂ emissions are reduced to 5,877.4 k\$ and 34,701.0 metric tons (**9.51% reduction from current annual energy costs; 12.90% reduction from current annual CO₂ emissions**).
- With the plan from subcase 3.2 (weighted objective: $a = b = 0.5$), investments in 6,800 kW of conventional DER units, 515 kW of renewable DERs, and 854 kWh of storage technologies are suggested. As a result, the annual energy costs and annual CO₂ emissions are reduced to 5,911.2 k\$ and 32,537.4 metric tons (**8.99% reduction from current annual energy costs; 18.33% reduction from current annual CO₂ emissions**).
- With the plan from subcase 3.3 (weighted objective: $a = 0.25$, $b = 0.75$), investments in 6,800 kW of conventional DER units, 840 kW of renewable DERs, and 19,569 kWh of storage technologies are suggested. As a result, the annual energy costs and annual CO₂ emissions are reduced to 6,265.6 k\$ and 32,166.9 metric tons (**3.53% reduction from current annual energy costs; 19.26% reduction from current annual CO₂ emissions**).
- With the plan from subcase 3.4 (weighted objective: $a = 0$, $b = 1$), investments in 6,800 kW of conventional DER units, 1,932 kW of renewable DERs, and 13,241 kWh of storage technologies are suggested. As a result, the annual energy costs rise to 6501.3 k\$ (**0.1% increment from current annual energy costs**) and CO₂ emissions are reduced to 31,725.5 metric tons (**20.36% from current annual CO₂ emissions**).

In summary, if we want to maximize economic benefits, assuming fixed utility rates and 100% electric utility availability (current utility conditions), **the investment plan from Case 1 is the most attractive plan; it can save the IIT Microgrid 16.41% in annual energy costs**. If we want to consider economic and environmental benefits simultaneously, assuming fixed utility rates and 100% electric utility availability (current utility conditions), **the investment plan from subcase 3.2 (equal weights) is the most attractive plan; it can lead to 8.99% reduction from current annual energy costs and 18.33% reduction from current annual CO₂ emissions for the IIT Microgrid**.

This report is organized as follows: Section 1 describes the background of DER-CAM. Section 2 introduces the current IIT Microgrid. Section 3 first reports the data gathered from the IIT Microgrid, and then presents and analyzes the test results of applying DER-CAM.

1 INTRODUCTION TO DER-CAM

1.1 DER-CAM BACKGROUND

DER-CAM (Distributed Energy Resources Customer Adoption Model) is a decision support tool for planning and investing in distributed energy resources (DER) in buildings and microgrids. The problem addressed by DER-CAM is formulated as a mixed-integer linear program that finds optimal DER investments while minimizing total energy costs or carbon dioxide (CO₂) emissions, or achieving a weighted objective that simultaneously considers both criteria. Figure 1.1 shows the general DER-CAM schematic [1].

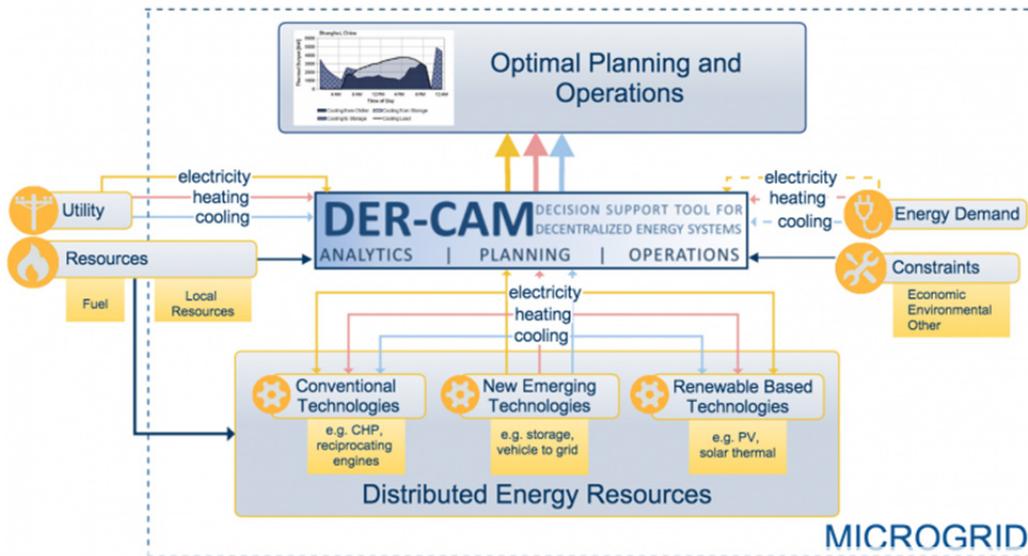


FIGURE 1.1 DER-CAM Schematic

1.2 KEY INPUTS TO DER-CAM

A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid and operate in either grid-connected or island mode. DERs are commonly defined as a set of locally available technologies and strategies with the potential to make energy use more efficient, accessible, and environmentally sustainable. These solutions include power generation and combined heat and power (CHP) using conventional fuel-fired technologies, but also renewable technologies such as photovoltaics (PV), and energy management strategies such as demand response, load shifting, and peak-shaving. Storage technologies, including stationary storage, mobile storage in the form of electric vehicle batteries, and thermal storage tanks, are also considered DERs.

DER-CAM has six categories of input data (as shown in Figure 1.2 [1]):

1. Customer's general investment and planning parameters (typically addressing investment payback period, interest rate, available PV space, technologies to be considered, and economic and environmental objectives).
2. Customer's solar radiation, temperature, and wind speed data.
3. Customer's end-use hourly load profiles (typically for electricity-only, cooling, refrigeration, space heating, hot water, and gas-only) defined over three day-types: weekdays, weekend days, and peak/outlier days.
4. Utility electricity tariff, natural gas prices, and other relevant price data.
5. Basic technical performance indicators, capital costs, operation and maintenance (O&M) costs, and fuel costs of various generation and storage technologies
6. Demand response features, critical load level, and outage events.

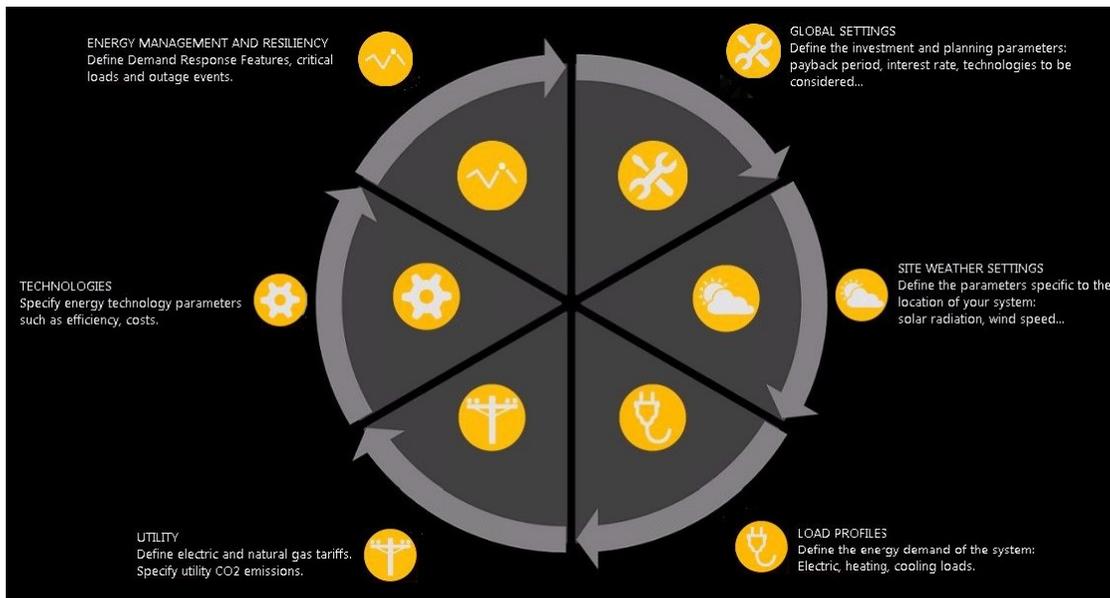


FIGURE 1.2 DER-CAM Input Data Interface

1.3 OUTPUT DETERMINED BY DER-CAM

To optimize DER investments, DER-CAM chooses the portfolio of technologies that maximize economic and/or environmental benefits, on the basis of optimized hourly dispatch decisions that consider specific site load, price information, and performance data for available equipment options. The output results are simultaneously comprised of the optimal technology portfolio as well as the corresponding dispatch that justifies the investment.

As results, DER-CAM provides:

1. Capacities of DER technologies to be installed.
2. Optimized strategic dispatch of all DERs, taking energy management measures into account.
3. Detailed economic results, including costs of energy supply and all DER-related costs.

1.4 KEY ASSUMPTIONS IN DER-CAM

The following assumptions have been made in DER-CAM:

1. Customer decisions are based on economic and environmental criteria. In other words, the possible benefits are a reduction in the energy bills and a reduction in CO₂ emissions.
2. No deterioration in output or efficiency during the lifetime of the equipment is considered. Furthermore, start-up and other ramping constraints are not included.
3. Reliability and power quality benefits, as well as economies of scale in O&M costs for multiple units of the same technology, are not directly taken into account.
4. Possible reliability or power quality improvements accruing to customers are not considered.

2 IIT MICROGRID

2.1 OVERVIEW OF THE IIT MICROGRID

Founded in 1890, Illinois Institute of Technology (IIT) is a private, independent, nonprofit, Ph.D.-granting research university with programs in engineering and science, architecture and design, business and law, human sciences, and applied technology. IIT Microgrid is classified as commercial load by ComEd, the local electric utility company. Starting from the North and South campus substations (marked with “N” and “S” in Figure 2.1), IIT owns, manages and operates its microgrid underground distribution system. The distribution system topology consists of several loops which provide redundant electricity supply to the end consumers. A cross-tie feeder between the two campus substations allows seamless operation of the IIT Microgrid in case of a failure in the shared feeder with the utility or one of the IIT feeders in the North or the South Substation.

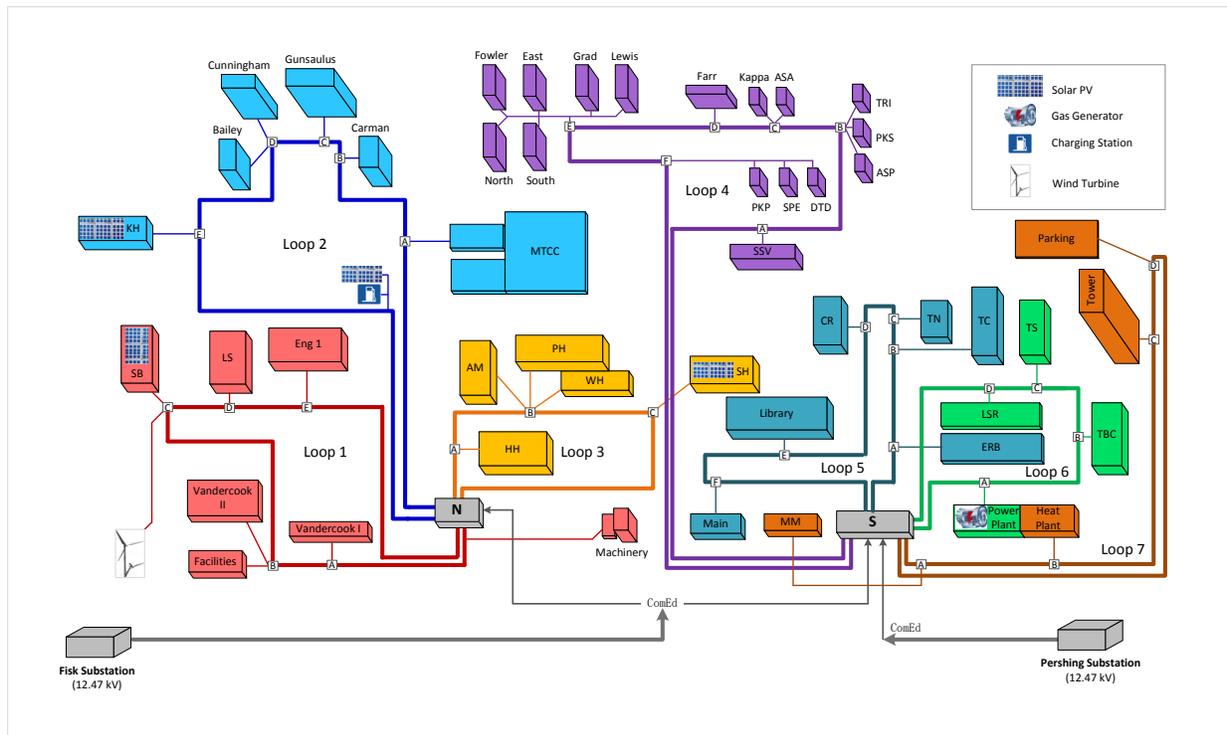


FIGURE 2.1 IIT Microgrid-based Looped Distribution System

The IIT Microgrid, funded mostly by a grant from the U.S. Department of Energy as well as State and philanthropic contributions, empowers the campus consumers with the objective of establishing a microgrid that is economically viable, environmentally friendly, fuel-efficient, highly reliable, and resilient, with a self-healing capability. The IIT microgrid enhances its

operational reliability by applying a real-time reconfiguration of power distribution assets, real-time islanding of critical loads, and real-time optimization of power supply resources.

The IIT Microgrid project is structured around developing and implementing core strategies and investments involving three separate but closely linked milestones: (1) The IIT Microgrid project specifies the priorities and types of investments that can enhance its power quality and reliability while optimizing economical energy flow; (2) the IIT Microgrid manages its resilience in extreme circumstances on the basis of holistic design and operation of physical infrastructures; and (3) the IIT Microgrid project offers educational programs for introducing various smart grid options to electricity consumers at large and enticing the campus community to participate in implementing the listed milestones.

2.2 CURRENT IIT DISTRIBUTED ENERGY RESOURCES DESIGN

The total generation capacity of the 12-MW IIT Microgrid is 12,344 kW, including 8,000 kW of natural gas turbines, 300 kW of solar generation, 10 kW of wind generation, and 4,034 kW of backup diesel generation. The campus system also includes a 500-kWh flow battery and several small-size storage devices. The IIT Microgrid is connected via its two substations to the ComEd utility grid, and can be islanded in extreme circumstances. Its operation is optimized by the IIT Microgrid Master Controller.

A. Natural Gas Turbine Power Plant

Figure 2.2 (left) shows a full-scale model of the power plant located on the IIT campus. The IIT Microgrid is equipped with two 4-MW natural gas turbine units on campus, capable of generating total of 8 MW of power. The natural gas units on campus are Rolls Royce Allison 501-KB5 units (Figure 2.2, right), which were designed and built in the early 1980s and are based on jet engines. These are dual-fuel units which use natural gas as the primary fuel, but can also use diesel fuel. Both turbines were reprogrammed for a quick start. A natural gas booster (compressor) is implemented and the startup takes approximately 20 minutes to come up to full load and go online. Also, each turbine is equipped with a heat recovery steam generator (HRSG) that includes a supplemental steam firing output range of 20 to 69 kilopounds per hour (kpph).



FIGURE 2.2 Natural-gas Turbine Power Plant at IIT

B. Solar PV Generation

A total of 300 kW of solar PV cells are installed on four building rooftops (shown in Figure 2.3), including a 40-kW solar canopy installed at the electric vehicle charging station (shown in Figure 2.4), to supply portions of the IIT campus load. Solar PV units are not dispatchable and use a maximum power point tracking (MPPT) control system with pulse-width modulation (PWM) (shown in Figure 2.5) to maximize the solar power output for a given insolation.



FIGURE 2.3 Solar Panels on Siegel Hall



FIGURE 2.4 Solar Panels on Charging Station

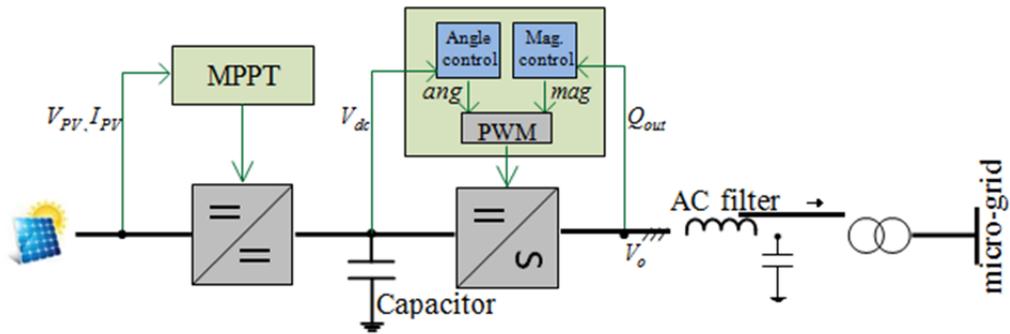


FIGURE 2.5 Equivalent Circuit and Power Output Characteristics of Solar PV Cell

C. Wind Turbine Unit

A 10-kW wind turbine unit, which is manufactured by BERGEY and shown in Figure 2.6, was installed on the north side of the campus in the Stuart soccer field at the end of January 2016, replacing a former 8-kW wind turbine unit. The wind turbine gets aligned into the wind by an empennage (also known as a tail assembly), which helps the turbine to adjust in yaw and pitch axis automatically. The start-up, cut-in, and rated wind speeds are 3.4 m/s (7.5 mph), 3.1 m/s (7 mph), and 13.8 m/s (31 mph), respectively. Notably, this BWC EXCEL wind turbine has no cut-out wind speed. It is equipped with an auto furling technique to process overspeed control, which keeps the turbine working securely even when the wind speed reaches 54 m/s (120 mph).



FIGURE 2.6 Wind Turbine Unit at IIT

D. Building Backup Generators

The IIT Microgrid is equipped with 11 backup generators with a total capacity of 4,036 MW, scattered among various buildings around the IIT campus. General test and inspection of these generators are performed weekly or monthly and transfer load tests are performed quarterly or annually. A detailed description of these generators is given in Table 2.1.

TABLE 2.1 Building Backup Generators in the IIT Microgrid

Building	Generator Size	Make	General Test and Inspection Frequency	Transfer Load Test Frequency
Life Science Research	200 kW	Energy Dynamics	Weekly	Quarterly
Life Science Research	1020 kW	Kohle	Weekly	Quarterly
IIT Tower	300 kW	Katolight	Weekly	Quarterly
McCormick Lounge	55 kW	Onan	Weekly	Annually
Rettaliata Engineering Center	80 kW	Kohler	Weekly	Annually
Rettaliata Engineering Center	125 kW	Cummins	Every 4 Weeks	Annually
Wishnick Hall	206 kW	Generac	Every 4 Weeks	Annually
Co-Gen	300 kW	Cummins	Every 4 Weeks	Annually
Technology Business Center	750 kW	Caterpillar	Every 4 Weeks	Annually
Stuart Building	500 kW	Genrac	Every 4 Weeks	Annually
IIT Tower	500 kW	Caterpillar	Every 4 Weeks	Annually

E. Flow Battery Storage

The IIT Microgrid is equipped with a 500-kWh flow battery storage system (including ten 50-kWh battery cells) with 250 kW power capacity, which is connected to Loop 1. Figure 2.7 shows a stack of the flow battery and the battery inverter, which can regulate the real and reactive power output.



FIGURE 2.7 Flow Battery Storage and Inverter

2.3 IIT MICROGRID ELECTRICAL CIRCUIT DIAGRAM

The IIT Microgrid is connected to the ComEd utility grid through two substations and three 12.47-kV circuits shown in Figure 2.8. Each 12.47-kV circuit is rated at 7 MW. The IIT Microgrid has a peak load of 12 MW, can be operated in grid-connected and island modes, and is capable of integrating new sustainable energy sources. The IIT Microgrid is equipped with a high-reliability distribution system (HRDS), which includes seven loops (shown in Figure 2.9) for enhanced reliability; three loops are connected to the North Substation and four loops are connected to the South Substation. The two substations are tied together to enhance the microgrid operation.

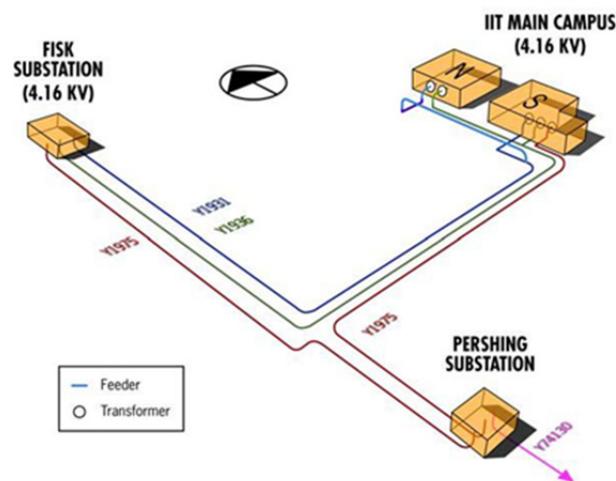


FIGURE 2.8 IIT Microgrid Connection to Utility Grid

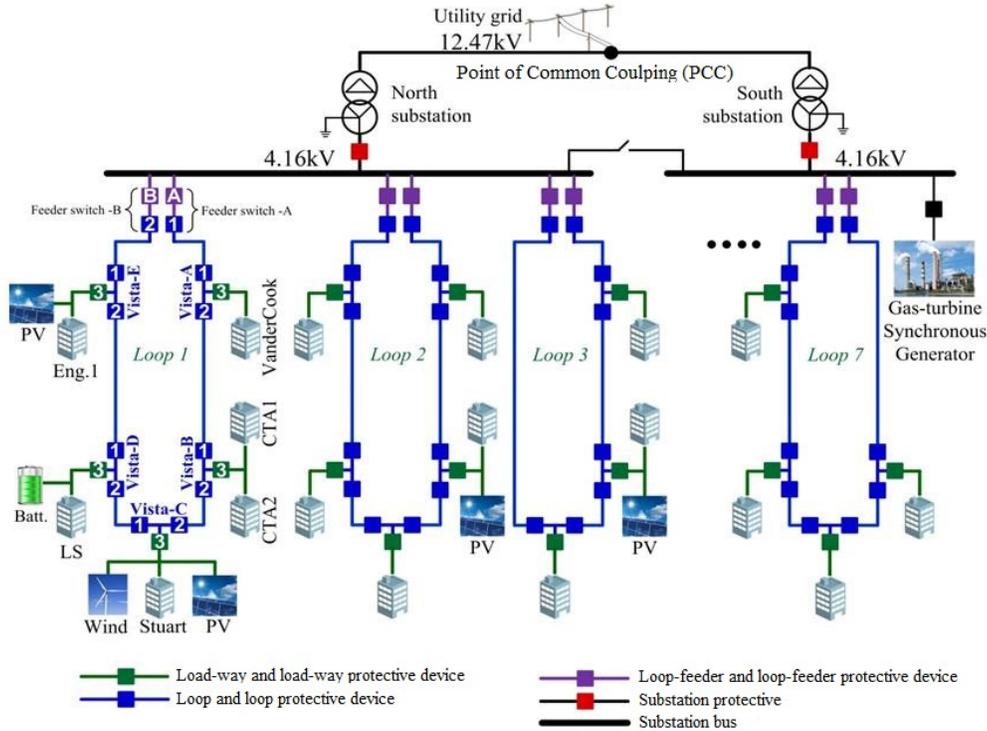


FIGURE 2.9 DER Units and HRDS in IIT Microgrid

The components of the IIT Microgrid shown in Figure 2.9 include DERs, HRDS switches, meters, phasor measurement units (PMUs), and building controllers. DER units include dispatchable units such as natural gas turbine generator and battery storage units, and non-dispatchable units such as solar PV and wind turbine units. The storage unit includes a flow battery and several lead-acid batteries. Building controllers provide control and monitoring functions for building loads on campus. Each HRDS loop utilizes Vista underground closed-loop fault-clearing switchgear with SEL-351 directional over-current protection relays. The fault isolation takes place in a quarter of a cycle via automatic breakers. The communication system is via fiber optic cables, which facilitate the coordination between switches. IIT has not experienced any outages since the loops were installed. The IIT Microgrid is equipped with building meters and 12 PMUs, which report building electricity consumption and instantaneous voltage and current of DER units (at a sampling rate of one signal per cycle) to the Master Controller.

The architecture for the IIT Master Controller is depicted in Figure 2.10. The Master Controller optimizes the economical energy flow at three levels (i.e., microgrid, micro-source/building, and load component/sub-building). Building meters provide the Master Controller with individual building load profiles. The Master Controller communicates and adjusts sub-building loads through building controllers. The Master Controller also receives the day-ahead price of electricity, weather data, wind speed, cloud coverage and other data for utilizing the renewable sources in the microgrid. The Master Controller then runs a day-ahead scheduling optimization algorithm which optimizes the use of microgrid local generation and

balances the hourly demand response (load curtailment and shifting of non-essential microgrid loads) for minimizing the cost of supplying the microgrid load. At times, the Master Controller considers demand response rather than power purchases from the grid. The hierarchical protection scheme is based on localized differential protections in seven loops and four coordinated protection levels which are implemented by communication-assisted digital directional relays and HRDS switches.

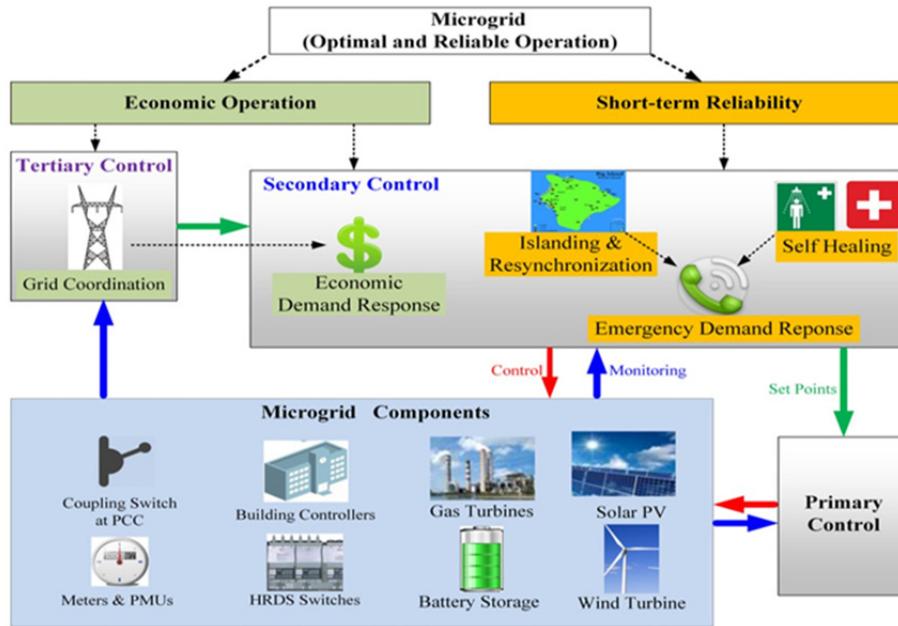


FIGURE 2.10 Objectives and Functions for Operation and Control of IIT Microgrid

The Master Controller in Figure 2.10 applies a tri-level (Primary, Secondary, and Tertiary) control for a seamless transfer to an island mode. The primary control utilizes the droops for sharing loads among DER units and avoiding circulating currents among DER units because of different set points on real and reactive power dispatch. The secondary control restores the nominal frequency of power supply in islanded operation. The tertiary control applies an economic dispatch in grid-connected and islanded modes.

3 IIT MICROGRID EXPANSION PLANNING WITH DER-CAM

In this section, we present the results of applying DER-CAM to expand the DERs in the IIT Microgrid.

3.1 INPUT DATA COLLECTION

The IIT Microgrid project started in August 2008 and the majority of the project was completed in May 2013. For this project, we have collected all the data from one year, i.e., **June 1, 2013, to May 31, 2014**. All the detailed data are provided in the Appendix.

3.1.1 Electrical and Thermal Loads

DER-CAM requires the load data in 6 categories: electricity-only, cooling, refrigeration, space-heating, water-heating, and natural gas-only. For each category, the hourly load data for each day type (peak, weekday, and weekend) and each month need to be specified. Here, ‘weekday’ indicates Monday through Friday, ‘weekend’ indicates Saturday and Sunday, and ‘peak’ indicates the three days with the highest demand within a month. All the load must be provided in kW and is assumed to be the average load in each hour.

A. Electrical Load

Figures 3.1–3.3 represent the electricity-only load for weekday, peak, and weekend, respectively.

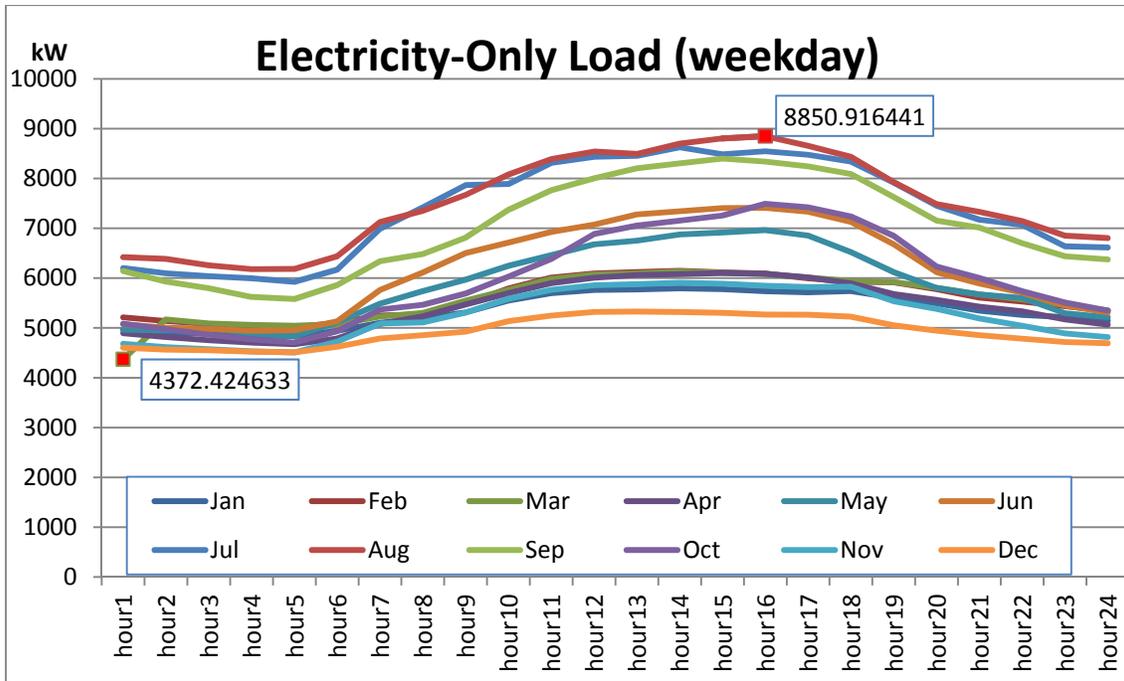


FIGURE 3.1 IIT Microgrid Electricity-only Load (weekday)

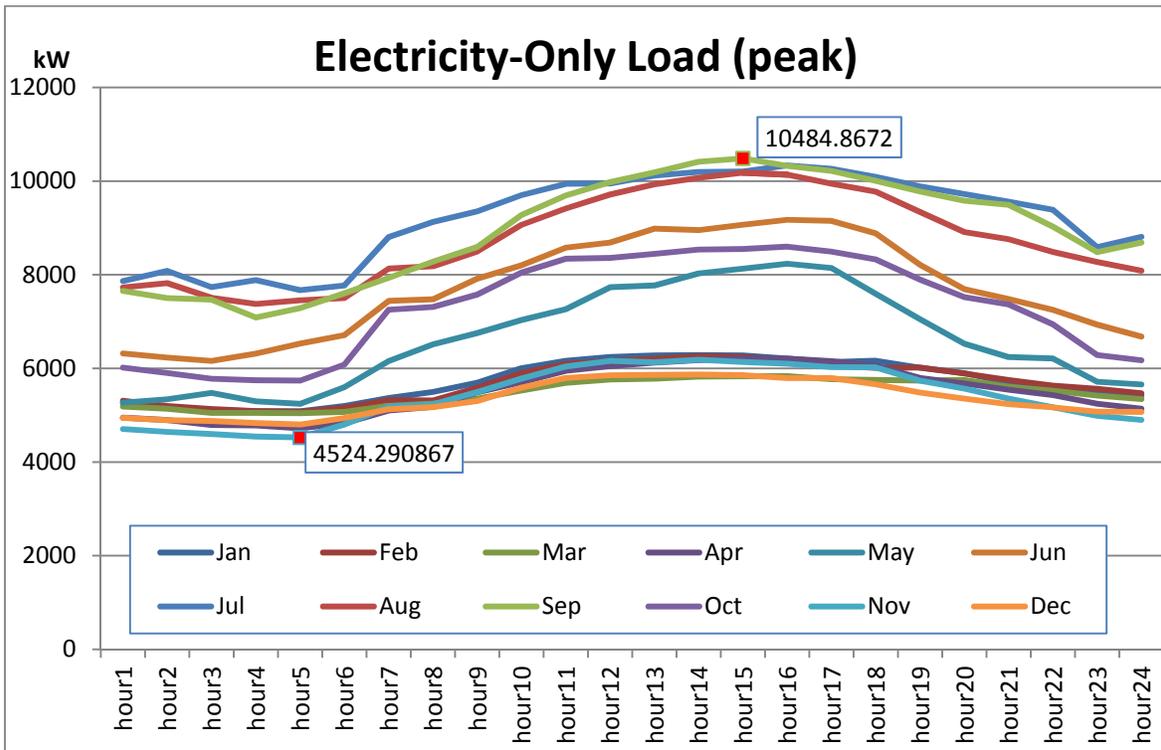


FIGURE 3.2 IIT Microgrid Electricity-only Load (peak)

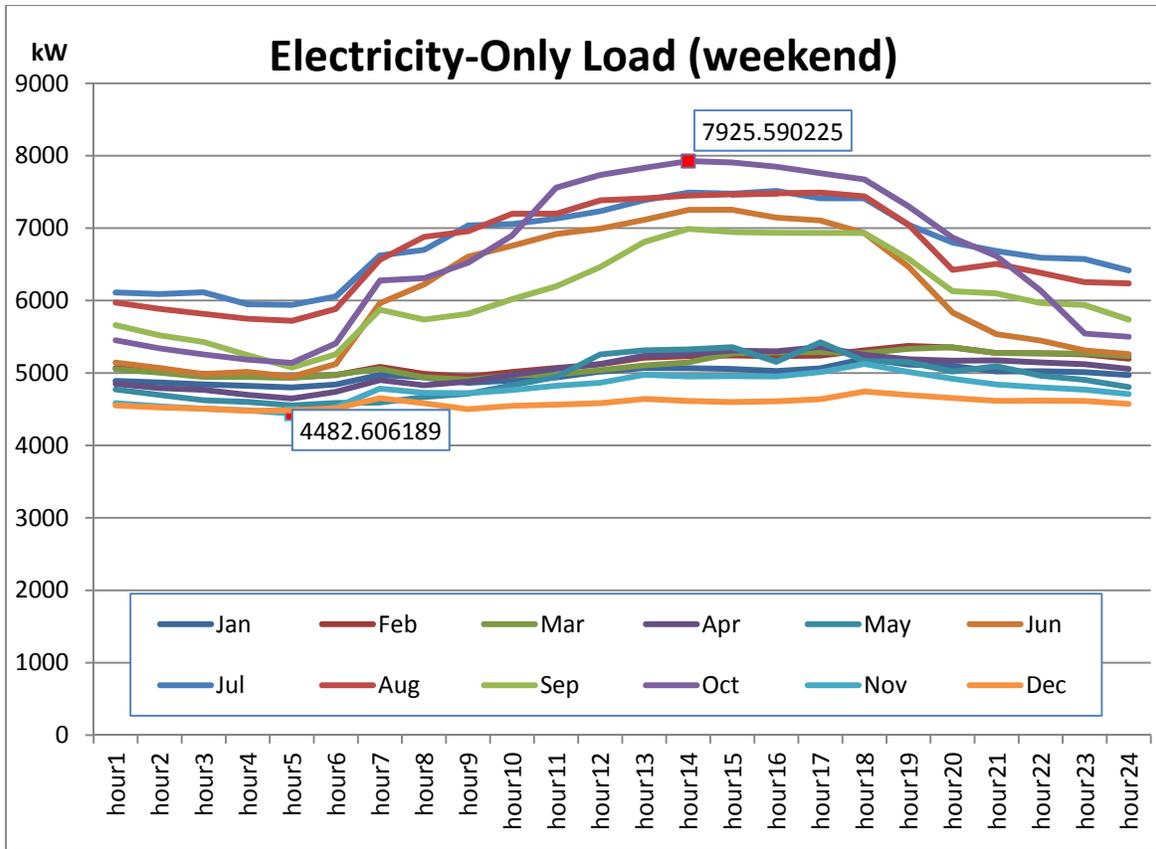


FIGURE 3.3 IIT Microgrid Electricity-only Load (weekend)

B. Thermal Load

The thermal loads on the IIT Microgrid are mostly steam loads for heating and domestic hot water (steam to hot water converter). The primary sources of steam include 2 HRSGs, 2 Johnston boilers and 1 Keeper boiler located in the IIT power plant. The plant generates 105 psig steam. The thermal loads are between 7 kpph (min) and 75 kpph (max). Most of the buildings on the northwest side of the campus use 15 psig steam. Some research buildings on the southwest side of the campus, such as the IIT Tower, need 60 psig steam because of research or cage-washing activities or other requirements.

The original thermal load data at IIT are in kpph of steam. However, DER-CAM requires that all load data be in kW. Here we perform a simple transformation to convert the load in kpph to the load in kW. The raw makeup water enters the water tank at 60°F, and the steam flow leaves the power plant at 230°F.

$$\begin{aligned}
 1 \text{ kpph} &= 1 \cdot 453.59 \cdot \left\{ [(230 - 60) - 32] \cdot \frac{5}{9} \right\} \cdot 4.2 \cdot \frac{1}{3600} \\
 &= 40.57 \text{ kW}
 \end{aligned}$$

where the second term, 453.59, is the kilogram-to-kilopound ratio; the third term is temperature difference in Celsius ($^{\circ}\text{C} = (^{\circ}\text{F} - 32) \cdot \frac{5}{9}$); the fourth term is specific heat capacity for water ($4.2 \text{ KJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$); and the last term is total seconds in one hour.

Figures 3.4 to 3.6 represent the space-heating load for weekday, peak, and weekend days, respectively. Similarly, Figures 3.7 to 3.9 represent the water-heating load for weekday, peak, and weekend days, respectively.

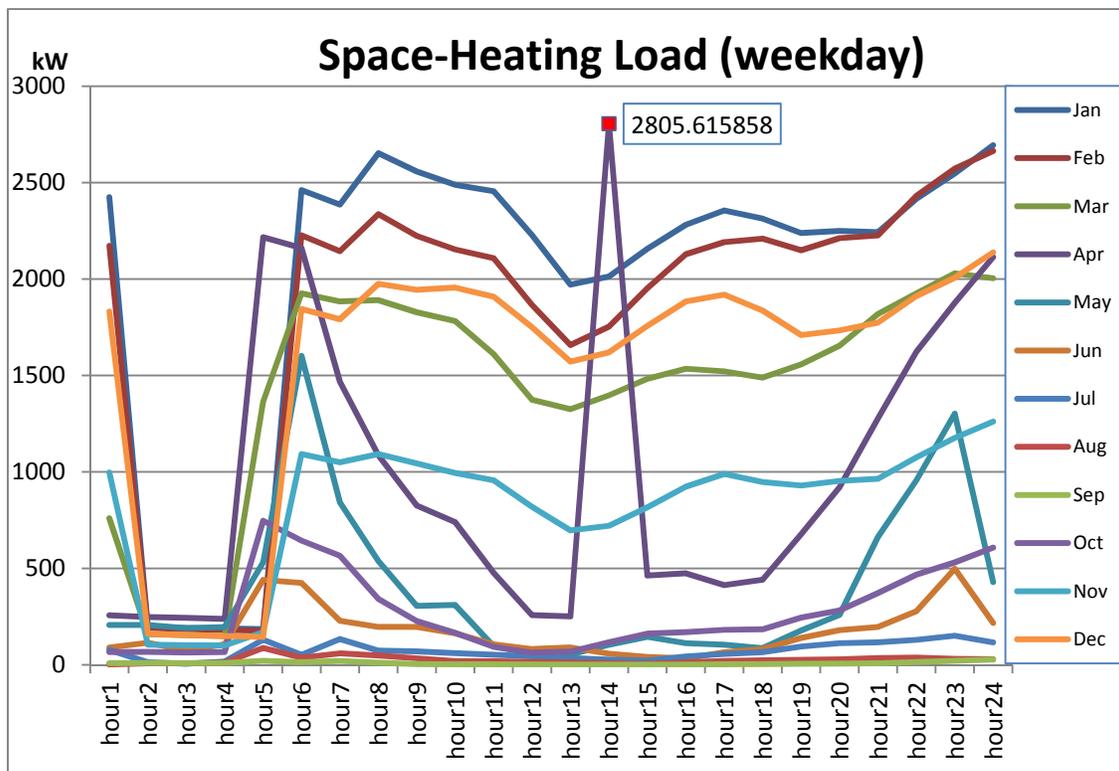


FIGURE 3.4 IIT Microgrid Space-Heating Load (weekday)

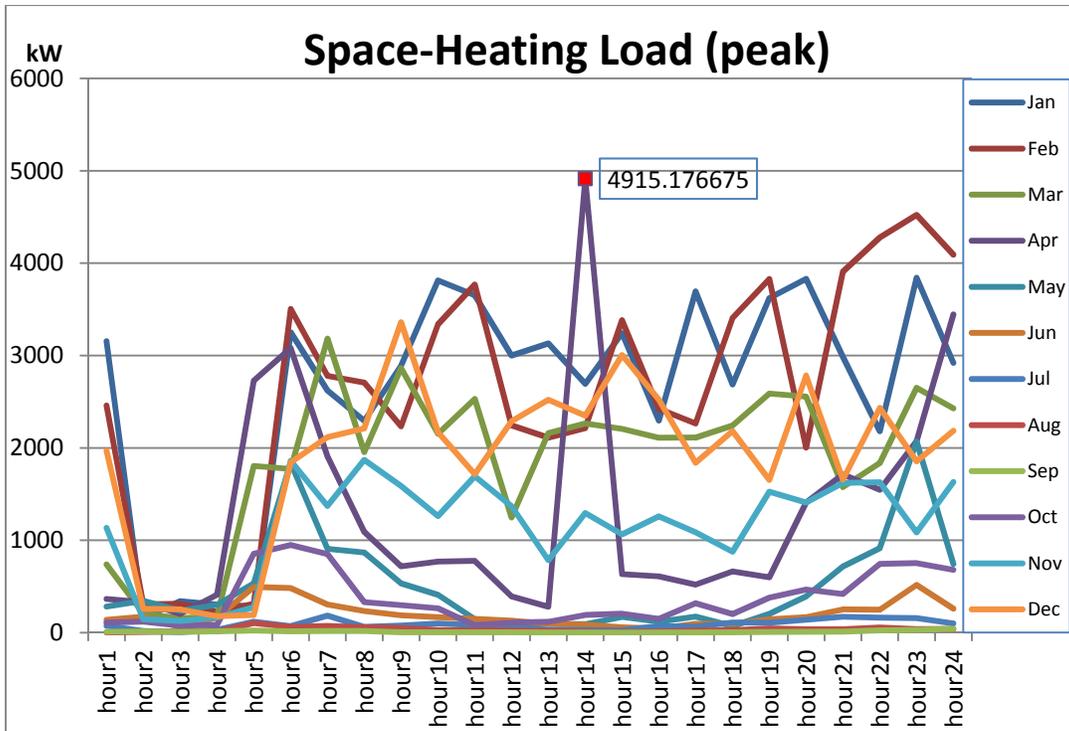


FIGURE 3.5 IIT Microgrid Space-Heating Load (peak)

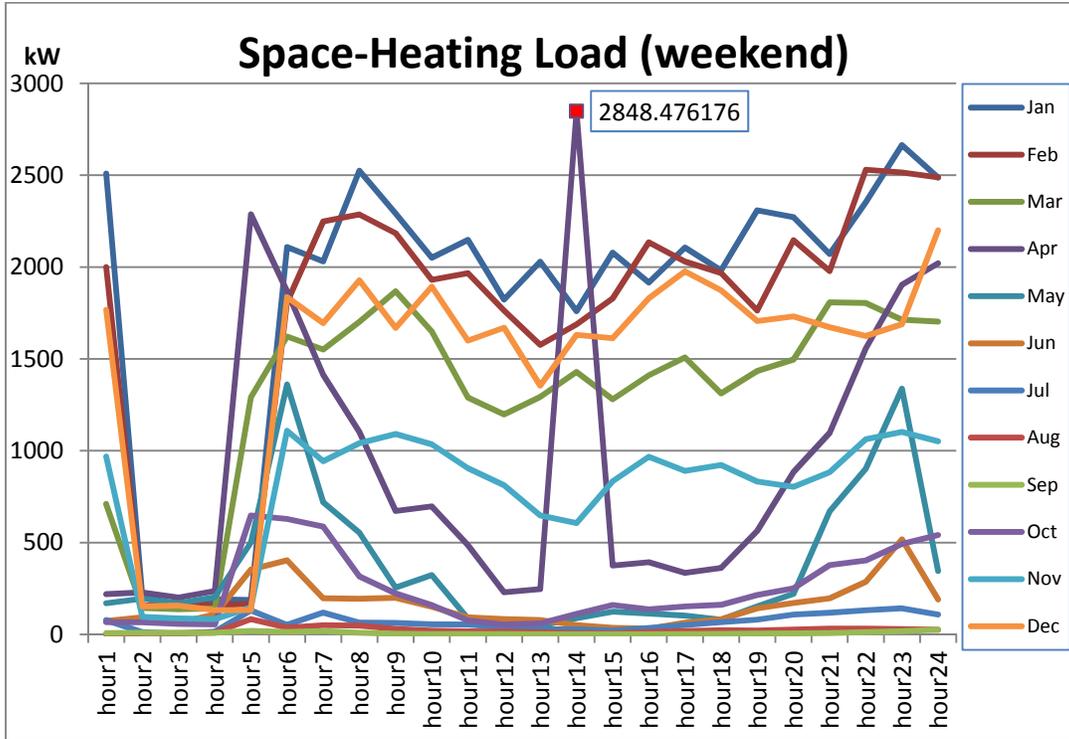


FIGURE 3.6 IIT Microgrid Space-Heating Load (weekend)

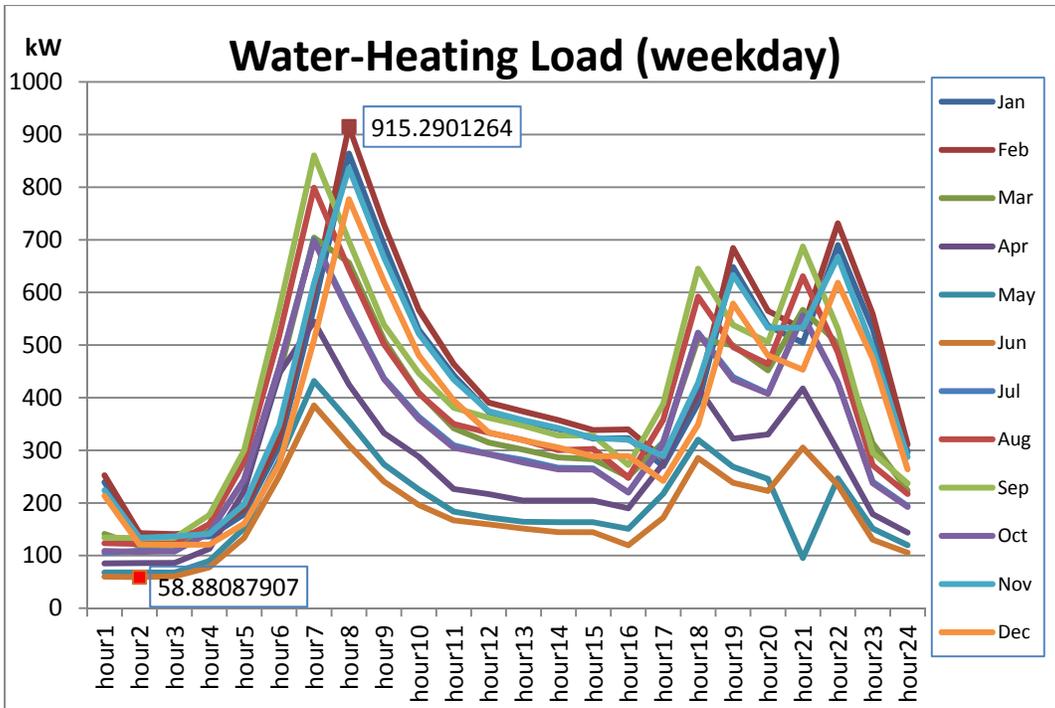


FIGURE 3.7 IIT Microgrid Water-Heating Load (weekday)

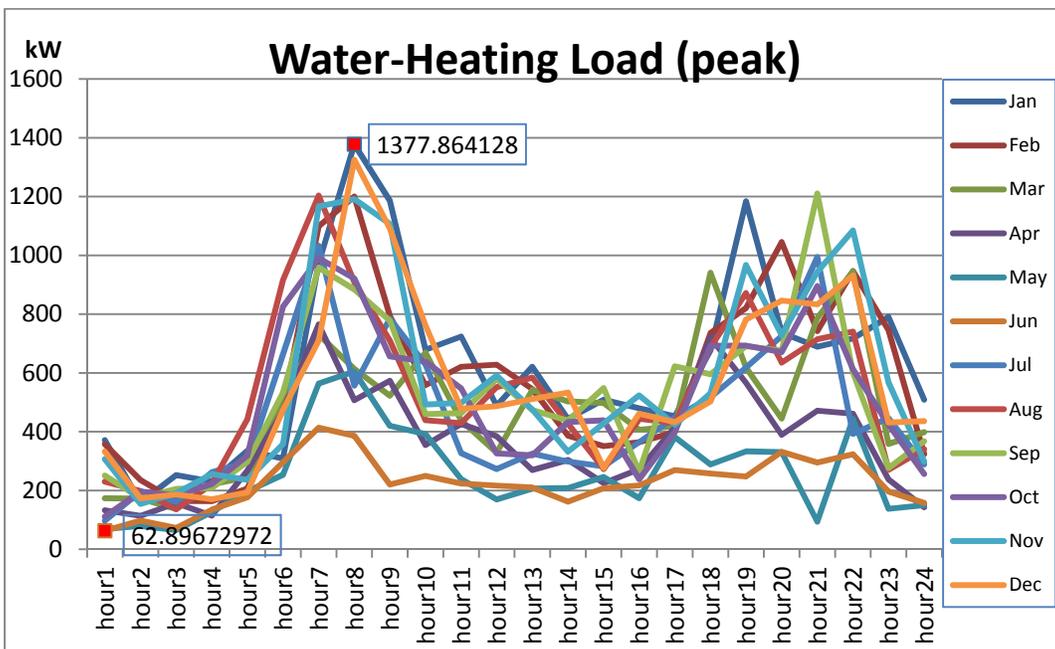


FIGURE 3.8 IIT Microgrid Water-Heating Load (peak)

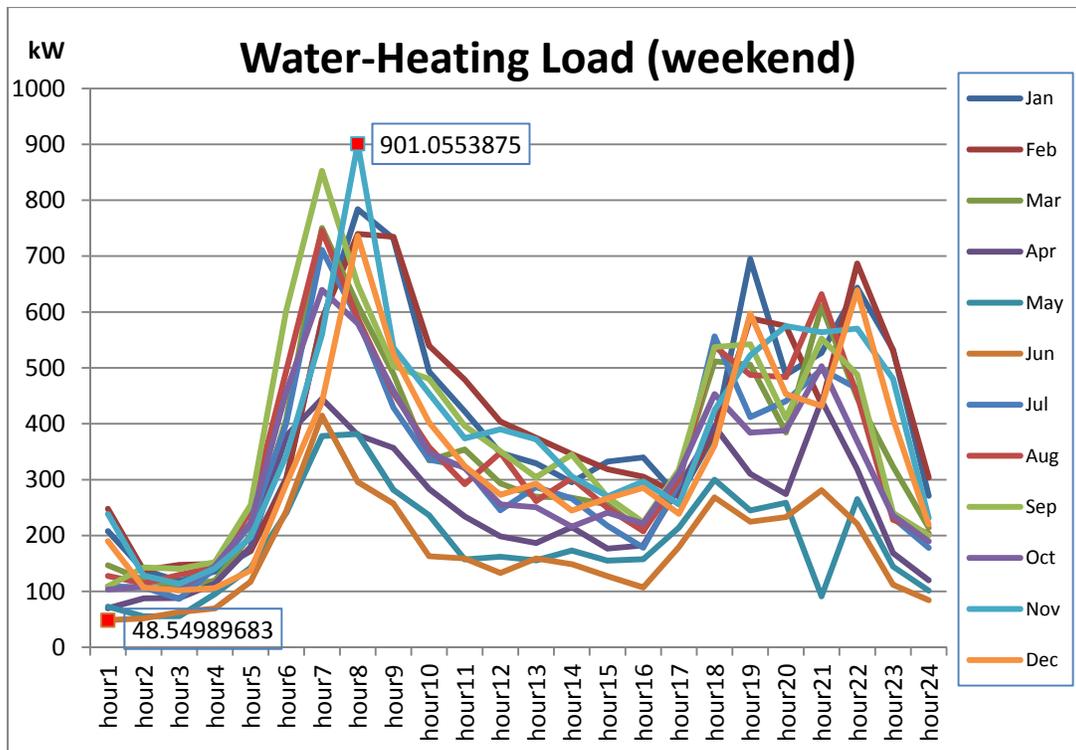


FIGURE 3.9 IIT Microgrid Water-Heating Load (weekend)

Beside electrical and thermal loads, DER-CAM also requires the customer to set up cooling, refrigeration, and gas-only loads. Currently, IIT does not have a central chiller plant. Instead, multiple electric chillers are scattered through the campus (none of these electric chillers are interconnected). Several buildings also use window AC units to meet cooling requirements. So both cooling and refrigeration loads have been aggregated into electricity load. Similarly, most dormitories and student service centers are equipped with electric stoves to meet cooking requirements. So the remaining three categories of load are set to zero in this project.

3.1.2 Environmental Conditions

A. Microgrid Boundaries

The IIT Microgrid is located 2.5 miles south of downtown Chicago (Figure 3.10, left) and is bounded by major streets, highways, and railroads (Figure 3.10, right). The total area of the IIT campus is 120 acres (485,622.8 m²). It is assumed that all the buildings without rooftop facilities can accommodate the installation of PV panels, and thus the current potential PV space in DER-CAM is set as 8000 m². Extra wind turbine investment is rejected on the basis of current campus design.



FIGURE 3.10 IIT Microgrid Boundaries

B. Solar Insolation

Solar Insolation is used as an input to calculate the power generation by PV panels. Figure 3.11 shows the solar insolation profiles at Chicago Midway International Airport [2], which is 7 miles away from the IIT Microgrid. These profiles are obtained by averaging historical data. It is assumed that one daily profile with hourly time steps represents the solar profile for the entire month.

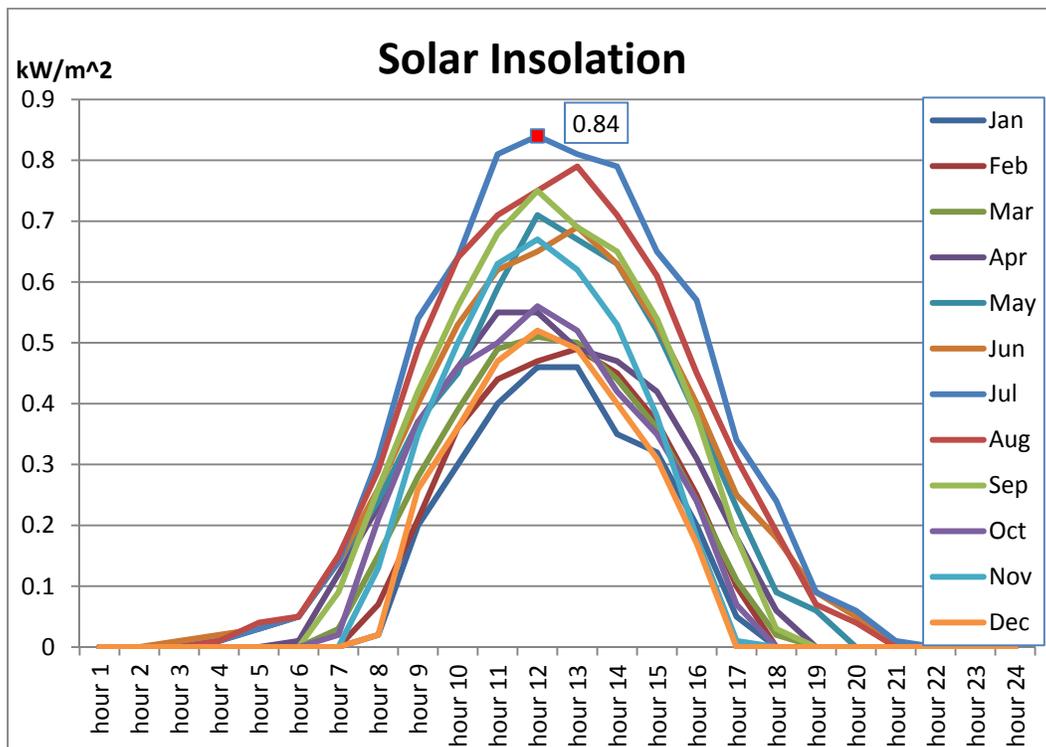


FIGURE 3.11 Solar Insolation in the Vicinity of the IIT Campus

C. Ambient Temperature

The Ambient Hourly Temperature defines the average hourly ambient dry-bulb temperature over each month. In DER-CAM, this information is used to estimate losses and efficiency of thermal devices such as heat storage. It also impacts the efficiency of PV and solar thermal panels. Figure 3.12 reports the ambient temperature. The data are provided by the National Weather Service [3].

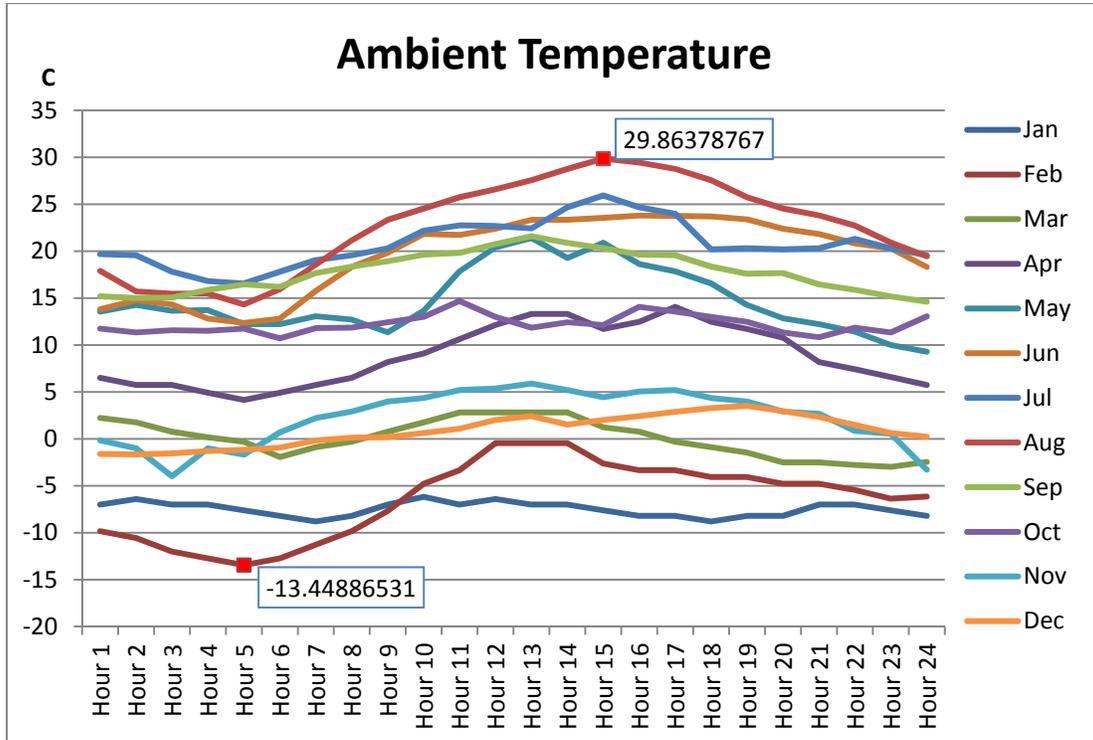


FIGURE 3.12 Ambient Temperature in the Vicinity of the IIT Campus

In addition, the average annual wind speed is 4.61 m/s in Chicago. This parameter also has an impact on the efficiency of the PV and solar thermal panels. It should be noted that this parameter does not relate to wind power in DER-CAM.

3.1.3 Utility Information

The utility segment in DER-CAM requires defining information regarding the utility tariffs for both electricity and fuels. Marginal CO₂ emissions of macro grid may also be defined within this segment.

A. Macro Grid Marginal CO₂ Emission

Macro Grid Marginal CO₂ emissions correspond to the added CO₂ emissions when purchasing one additional kWh of electricity from the macro grid. They are defined in metric tons of CO₂/MWh (or kg of CO₂ per kWh). PJM Interconnection, which is a regional transmission organization where the IIT Microgrid is located, plays the role of macro grid. Figure 3.13 reports the PJM marginal CO₂ emission.

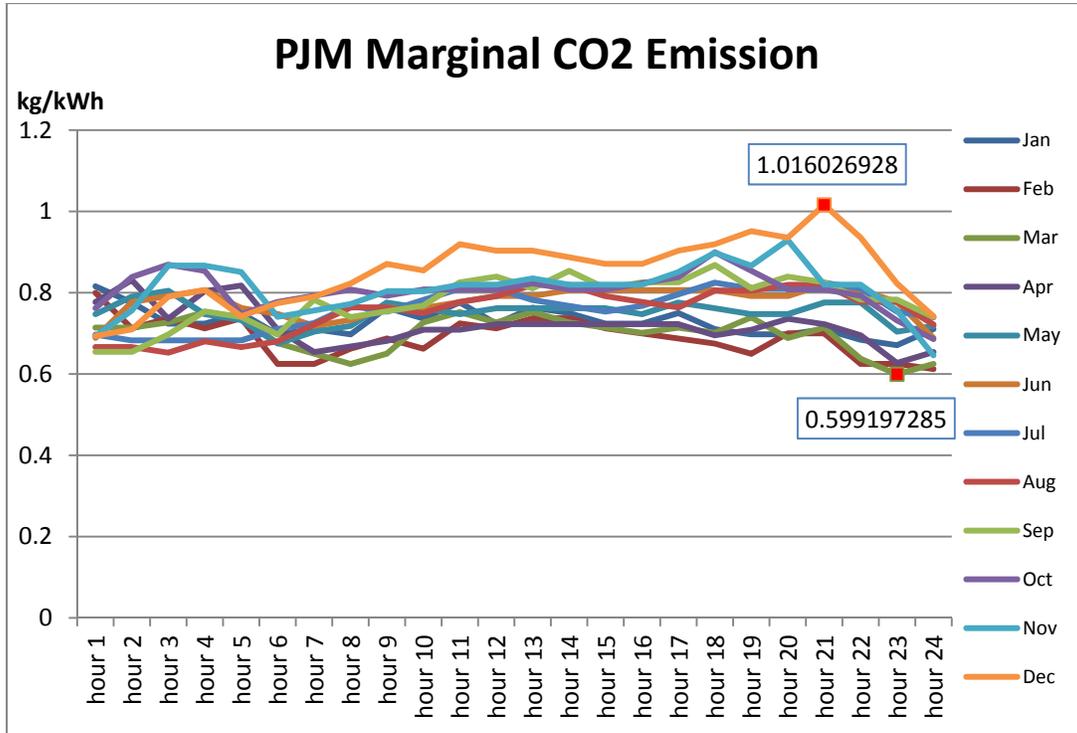


FIGURE 3.13 PJM Marginal CO₂ Emission

B. Electricity and Gas Rates

For electricity, the IIT Microgrid is connected to the ComEd utility grid through two substations and three 12.47-kV circuits, as shown in Figure 2.8. For fuel sources, the IIT Microgrid has access to uninterrupted fuel sources via two natural gas pipelines from CenterPoint Energy Services. The utility rates are summarized in Table 3.1. The rates are based on one summer- and one winter-month bill from Year 2013-14.

TABLE 3.1 Utility Rates (fixed)

Utility	Rate
Natural Gas	0.650 \$/therm (0.02218 \$/kWh)
Diesel	0.0912 \$/kWh
Electricity	0.07 \$/kWh

In this project, we also consider the case of **real-time utility rates**. Like the utilities' fixed-price electric supply rate reflected in the Price to Compare (the price per kilowatt-hour electric distribution company will charge to provide generation) table, utilities also charge residential real-time pricing customers for the costs of purchasing the electric supply without any markup or profit. Unlike the utilities' fixed-priced electric supply rate, the utilities charge residential real-time pricing customers for the electricity they consume each hour on the basis of the corresponding wholesale hourly market price of electricity.

With ComEd's residential real-time pricing program, prices are based on the actual real-time hourly market price of electricity during the day and customers are notified when real-time prices are high or are expected to be high so they can respond in real time and shift the use of major appliances to lower-priced hours. While savings are not guaranteed, customers can manage electricity costs under real-time pricing by shifting use of electricity from hours when prices are higher to hours when prices are lower.

In DER-CAM, the hourly real-time prices are simplified to three levels: peak, mid-peak, and off-peak-hour prices. Each month has different peak, mid-peak, and off-peak-hour patterns based on the season. Table 3.2 reports the hourly real-time prices used in this project. They are collected from PJM real-time local marginal prices for the load of ComEd [4]. It should be noted that these profiles are multiplied by a factor to keep the average price equal to 0.07 \$/kWh, since delivery charges and taxes still apply.

TABLE 3.2 Utility Rates (real-time, \$/kWh)

	Peak	Mid-Peak	Off-Peak
Jan	0.0812	0.0618	0.0482
Feb	0.0959	0.0719	0.0517
Mar	0.1747	0.0791	0.0379
Apr	0.1645	0.0678	0.0506
May	0.1686	0.0740	0.0479
Jun	0.2110	0.0817	0.0512
Jul	0.0650	0.0474	0.0245
Aug	0.1044	0.0536	0.0403
Sep	0.1448	0.0818	0.0273
Oct	0.0982	0.0556	0.0327
Nov	0.0745	0.0391	0.0201
Dec	0.1098	0.0662	0.0511

3.1.4 DER Technologies

DER-CAM requires all relevant techno-economical information regarding the available generation and storage technologies. All technologies are divided into two categories: discrete and continuous. This distinction stems from the way their capacities are modeled. The optimal capacity of discrete technologies is determined as a discrete number of units, whereas the capacity of continuous technologies is determined by a continuous variable.

A. Discrete Technology

Discrete technology includes gas and micro turbines, fuel cells, and internal combustion engines, all of which have the capability to operate in CHP mode by enabling heat recovery. Table 3.3 reports the major parameters for discrete technologies in DER-CAM for this project.

TABLE 3.3 Discrete Technologies in DER-CAM

Technology	MaxP	CapCost	OMVar	Efficiency	HTPr
ICE	250	1143	0.015	0.3	
GT	1000	2039	0.011	0.22	
MT	150	1723	0.017	0.29	
ICE-HX	250	2377	0.015	0.2	1.48
GT-HX	3970	2794	0.011	0.22	1.96
MT-HX	150	1935	0.017	0.29	1.4
ICE-DIESEL	200	300	0.018	0.34	

MaxP: NamePlate capacity of technology [kW]; CapCost: Investment costs of technology [\$/kW];
 OMVar: Variable operation costs [\$/kWh]; Efficiency: NamePlate efficiency;
 HTPr: Heat-to-Power ratio of CHP technologies; ICE: Internal combustion engine; GT: Gas turbine;
 MT: Micro turbine; HX: Heat exchanger that enables waste heat recovery

B. Continuous Technology

Continuous technology in DER-CAM includes technologies where the existing market sizes and the economies of scale allow modeling the optimal capacity using a continuous variable and defining the investment cost by a fixed and variable cost. Fixed costs are incurred regardless of the installed capacity, and can describe installation costs. Variable costs are capacity-dependent, and are described per unit of capacity. Table 3.4 reports the major parameters for continuous technologies in DER-CAM for this project.

TABLE 3.4 Continuous Technologies in DER-CAM

Technology	Fixed Cost	Variable Cost	Maintenance Cost
Electric Storage	295	300	0
Heat Storage	10000	50	0
Flow Battery	0	2125	0
Absorb Chiller	93912	685.2	1.88
Absorb Refrigeration	93912	753.74	2.07
PV	3850	3237	0.25
Solar Thermal	0	500	0.5
Air Source Heat Pump	0	70	0.52
Ground Source Heat Pump	0	79.74	0.32

Fixed Cost: Basic investment costs of technology [\$]; Variable Cost: Unit costs of technology [\$/kW];

Maintenance Cost: Costs of maintenance [\$/kW]

3.1.5 Critical Outage Event

The Master Controller for the IIT Microgrid will start and stop generators and storage devices; control local loads on the basis of predetermined sequences of operation and load reduction priority schemes; automatically switch loads to alternate transformers, campus feeds and substation as required by conditions; and place a building or the entire campus in island mode when necessary. If an island is formed on the IIT campus, an anti-islanding element detects the island and disconnects the IIT Microgrid from the ComEd utility network within the required time specified by IEEE Std 1547.

So in addition to the base case where we assume the service from the ComEd utility is available throughout the whole year (8760 hours), we consider the case of one emergency week in each of four months (January, February, July, and August), when IIT operates in island mode and no loads are curtailed.

3.2 DER-CAM OUTPUTS

On the basis of the input information we collected above, DER-CAM has been applied to three cases, as shown in Table 3.5.

TABLE 3.5 Cases Considered in DER-CAM for IIT Microgrid Planning

Case No.	Objective	Utility Rates	Electric Utility Availability
Case 1	Cost minimization	Fixed	100%
Case 2	Cost minimization	Real-time	4 emergency weeks without access to electric utility grid
Case 3	Multi-objective	Fixed	100%

For all three cases, we assume the maximum payback period is 15 years and the interest rate is 5%.

3.2.1 Case 1

In Case 1, we consider the objective of minimizing energy costs (the most economical plan). The utility rates are fixed and the electric utility availability is 100% (i.e., the utility grid is always available).

DER-CAM is applied to find DER investments that minimize energy and investment costs. The investment decisions are shown in Figure 3.14. The new investments suggested by DER-CAM include 3,000 kW of internal combustion engines (1,500 kW of which are equipped with heat exchange systems), 600 kW of gas-fired micro turbines (450 kW of which are equipped with heat exchange systems), an air source heat pump of 345 kW, and a ground source heat pump of 77 kW (as shown in Figure 3.14, middle). The total capital costs for new investments are 5,396.5 k\$. Of all installed technologies, the investment in internal combustion engines with heat exchange systems is the most capital-intensive (as shown in Figure 3.14, right).

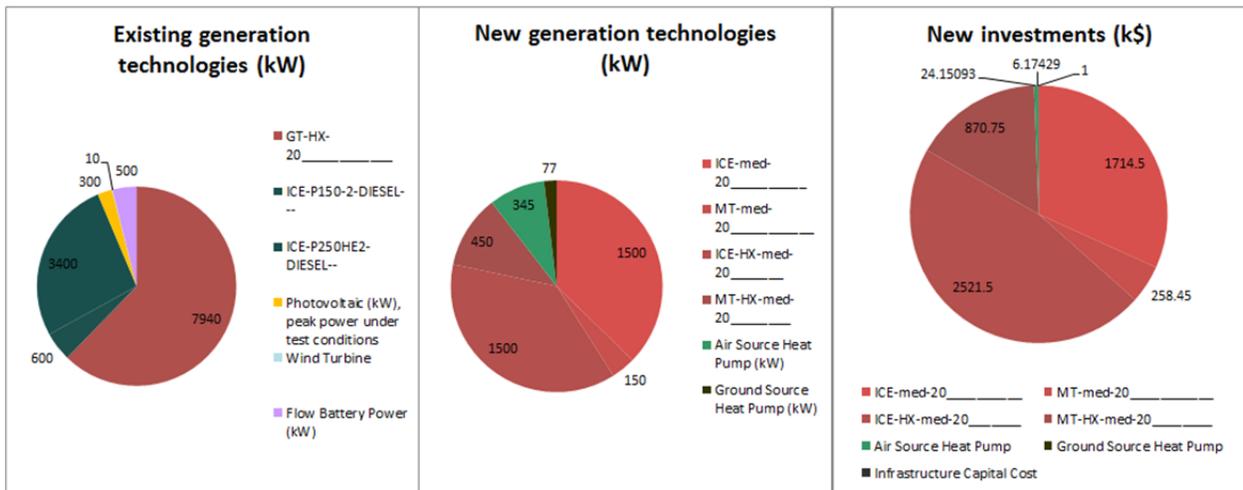


FIGURE 3.14 Investment Capacities and Upfront Capital Costs (Case 1)

The current annual energy costs for IIT are 6,495.1 k\$. The annual CO₂ emissions are 39,838.5 metric tons. These two values are set as a reference here and in the following analysis. With the plan from DER-CAM, the annual energy cost, which includes annual investment in new installed technologies and annual operation costs, is decreased to 5,428.9 k\$ (as reported in Table 3.6). In case 1, we only consider the minimization of costs to be the objective, so there is only 5.29% reduction in annual CO₂ emissions with this plan.

TABLE 3.6 Annual Energy Costs and CO₂ Emissions (Case 1)

	Annual Energy Costs (k\$)	Annual CO ₂ Emissions (metric tons)
Reference	6,495.1	39,838.5
Case 1	5,428.9	37,733.9

The annual energy costs consist of annual operation costs and annual investment costs (as shown in Figure 3.15, left). The operational savings obtained are 16.41%. This is because less electricity is bought from the grid and the on-site cheaper generation is used instead (as shown in Figure 3.15, right).

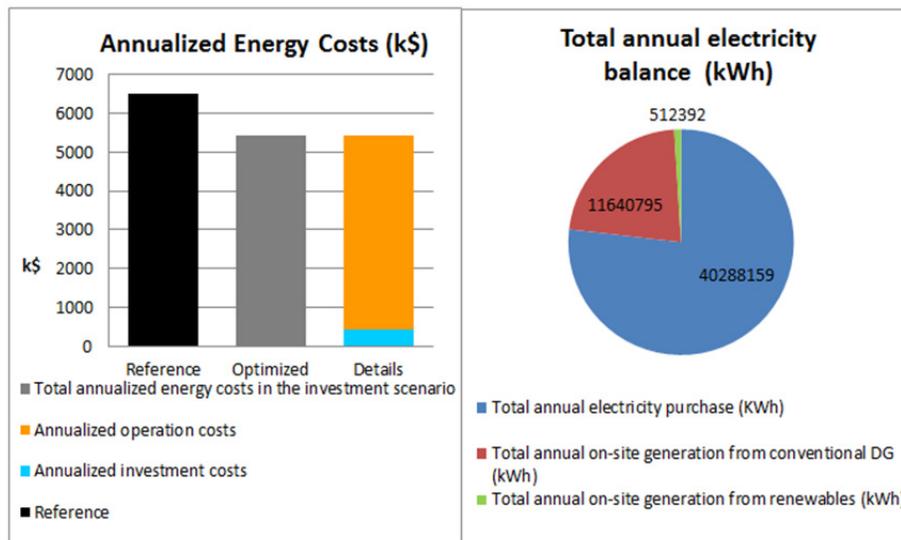


FIGURE 3.15 Detailed Annual Energy Costs and Energy Balance (Case 1)

Figure 3.16 shows the dispatch for electricity on a peak day in August. Similar profiles can be found in the Appendix for other day types during different months. It can be seen that the utility purchase (green) is now lower in terms of power consumption when compared to the base case (black dashed line), which significantly contributes to lower power demand charges.

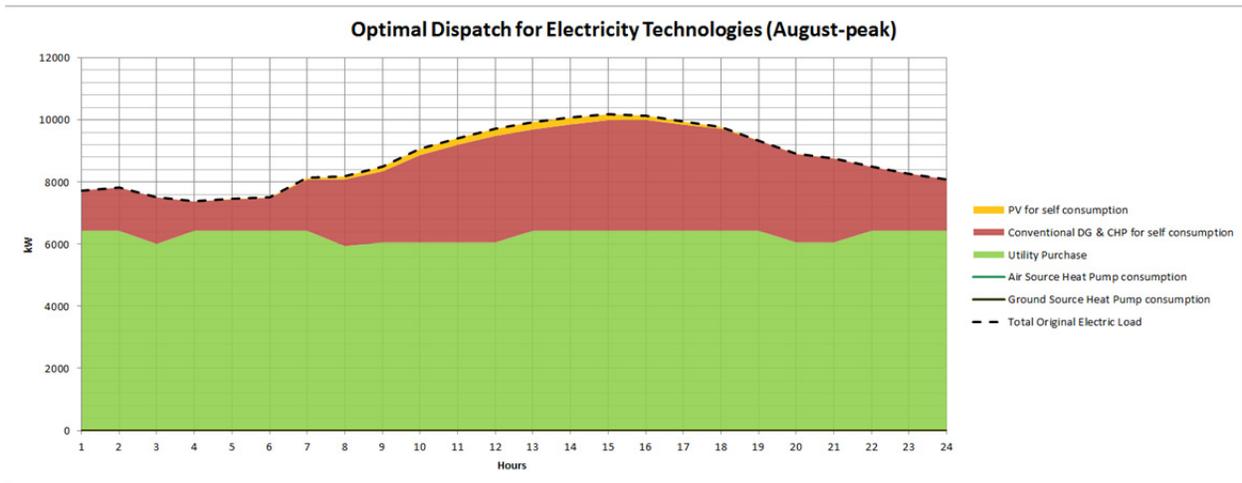


FIGURE 3.16 Electricity Dispatch on a Peak Day in August (Case 1)

Figure 3.17 shows the dispatch for heating resources on a peak day in January. Similar profiles can be found in the appendix for other day types during different months. It can be seen that the newly installed air source heat pump (green) and ground source heat pump (black) mainly dispatch during peak hours to meet the heat load requirements, which can help the CHP (red) dispatch to flatten.

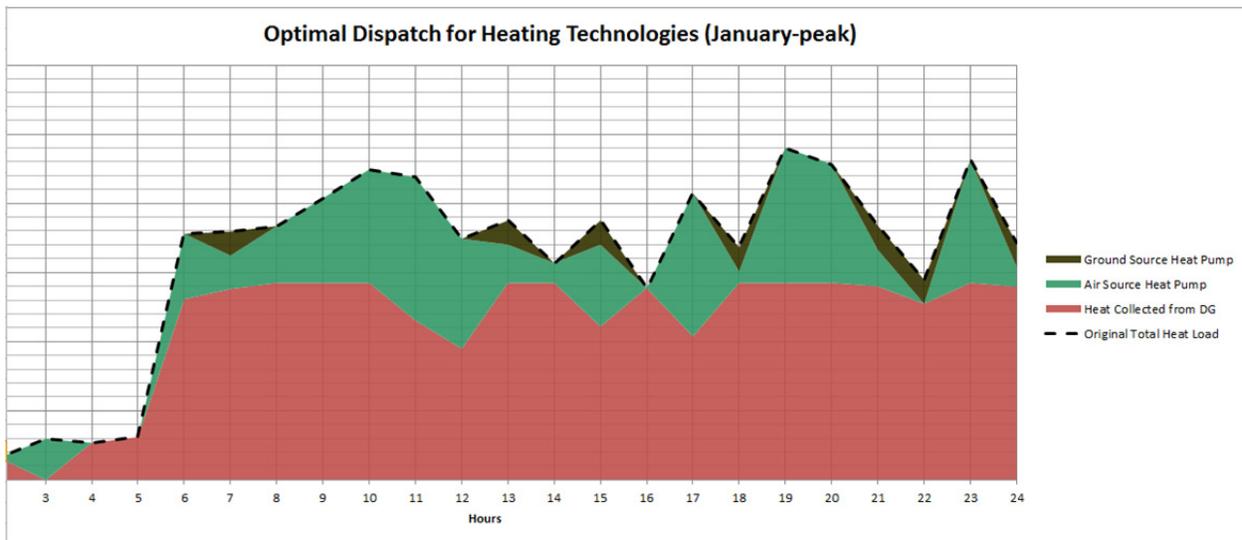


FIGURE 3.17 Heating Dispatch on a Peak Day in January (Case 1)

3.2.2 Case 2

In Case 2, the objective is still to minimize energy costs. However, we consider that the utility charges real-time prices, as shown in Table 3.2. We also consider the case where there are 7 emergency days (3 emergency weekdays, 2 emergency peak days, and 2 emergency weekend days) in each of four months (January, February, July, and August), when IIT operates in island mode and no loads are curtailed.

In this case, DER-CAM suggests investing in 3,000 kW of internal combustion engines (1,500 kW of them equipped with heat exchange systems), 1,000 kW of gas turbines, 1,800 kW of gas-fired micro turbines (900 kW of them equipped with heat exchange systems), 514 kW of PV panels, 3 kW of solar thermal, an air source heat pump with 332 kW of capacity, and a ground source heat pump with 18 kW of capacity (as shown in Figure 3.18, middle). There are also two types of storage investment recommended by DER-CAM in this case: 206 kWh of stationary battery capacity and 778 kWh of heat storage capacity (as shown in Figure 3.18, right). The total capital costs for new investments are 11,368.65 k\$. Of all installed technologies, the investment in internal combustion engines with heat exchange systems is the most capital-intensive (as shown in Figure 3.19).

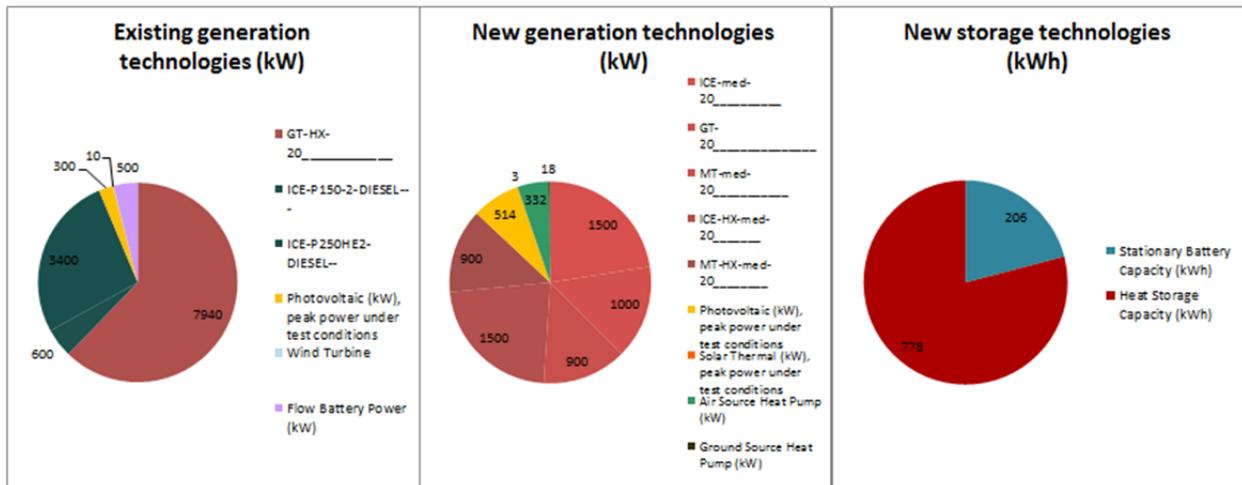


FIGURE 3.18 Investment Capacities (Case 2)

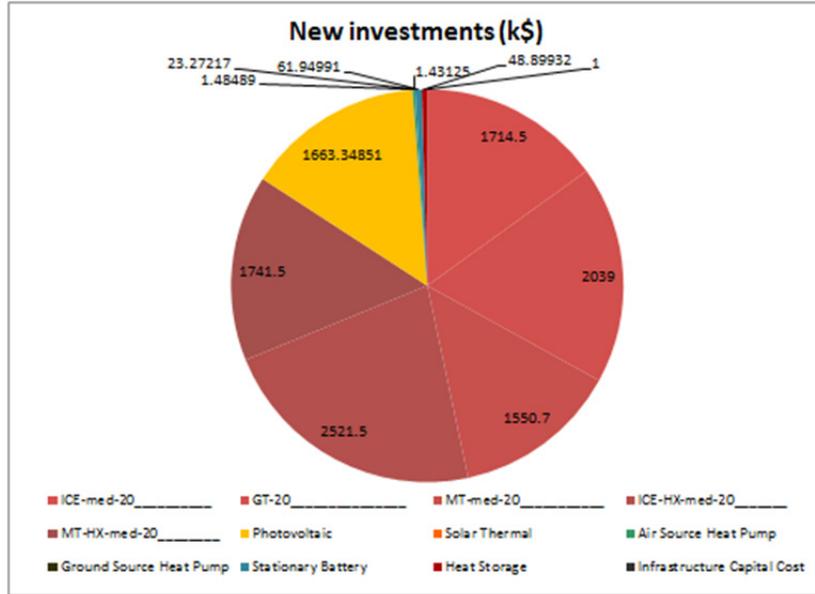


FIGURE 3.19 Upfront Capital Costs (Case 2)

With the plan from DER-CAM, the annual energy costs decrease to 5,360.9 k\$, and the total annual CO₂ emissions decrease to 36,668.9 metric tons (as reported in Table 3.7).

If we use 6,495.1 k\$ and 39,838.5 metric tons, which are the current IIT annual energy costs and CO₂ emissions, as the reference, the total cost savings are 17.46% and the reduction in CO₂ emissions are 7.96%. Figure 3.20 shows the detailed annual energy costs and energy balance with this plan.

TABLE 3.7 Annual Energy Costs and CO₂ Emissions (Case 2)

	Annual Energy Costs (k\$)	Annual CO ₂ Emissions (metric tons)
Reference	6,495.1	39,838.5
Case 2	5,360.9	36,668.9

Figure 3.21 shows the dispatch for electricity on an emergency peak day in August. Figure 3.22 shows the dispatch for heating technologies on an emergency peak day in January. It can be seen that the on-site generators are dispatched to meet all electricity load requirements when the microgrid operates in the island mode. Since most of the on-site generators are equipped with heat exchange systems, they can provide adequate heating capacity to meet all heating load requirements during the emergency days.

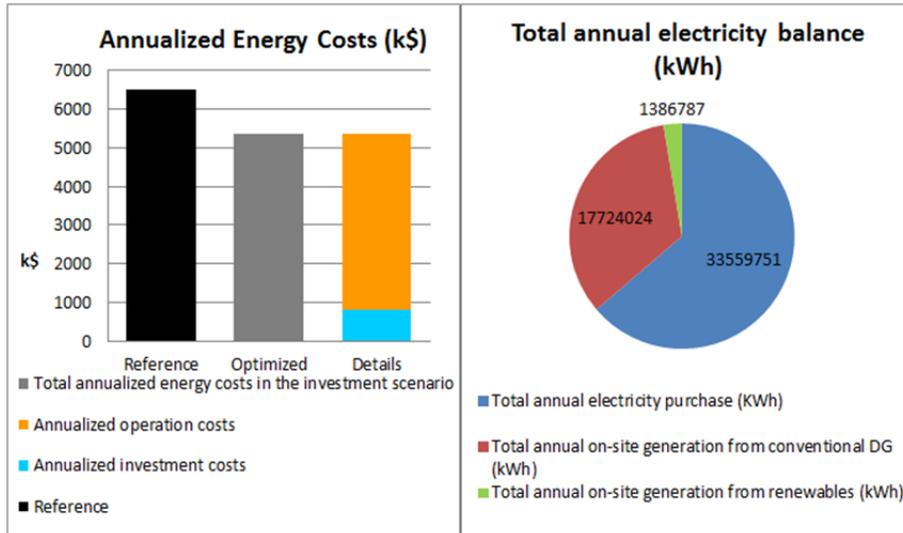


FIGURE 3.20 Detailed Annual Energy Costs and Energy Balance (Case 2)

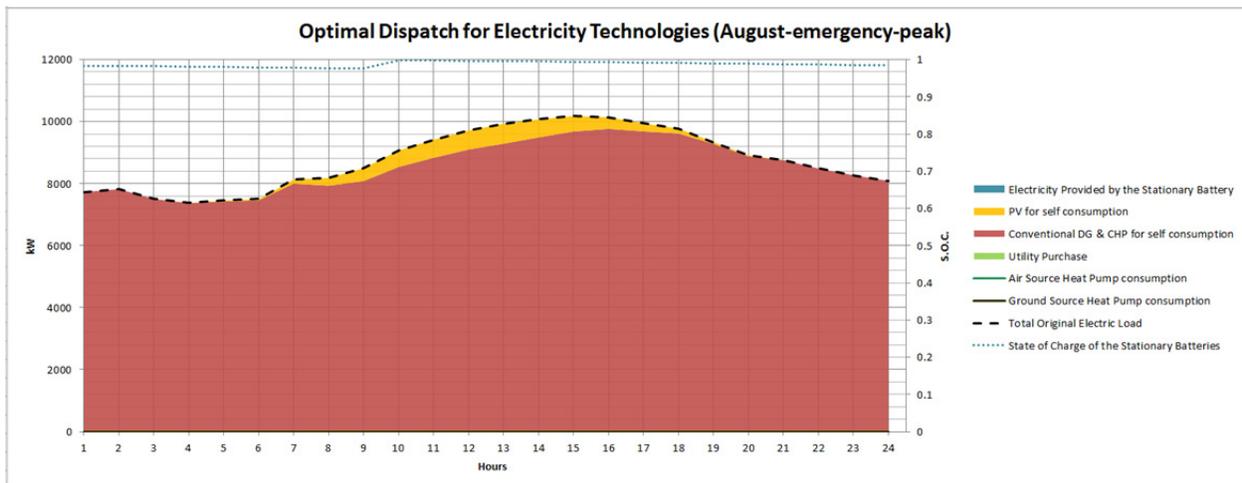


FIGURE 3.21 Electricity Dispatch on an Emergency Peak Day in August (Case 2)

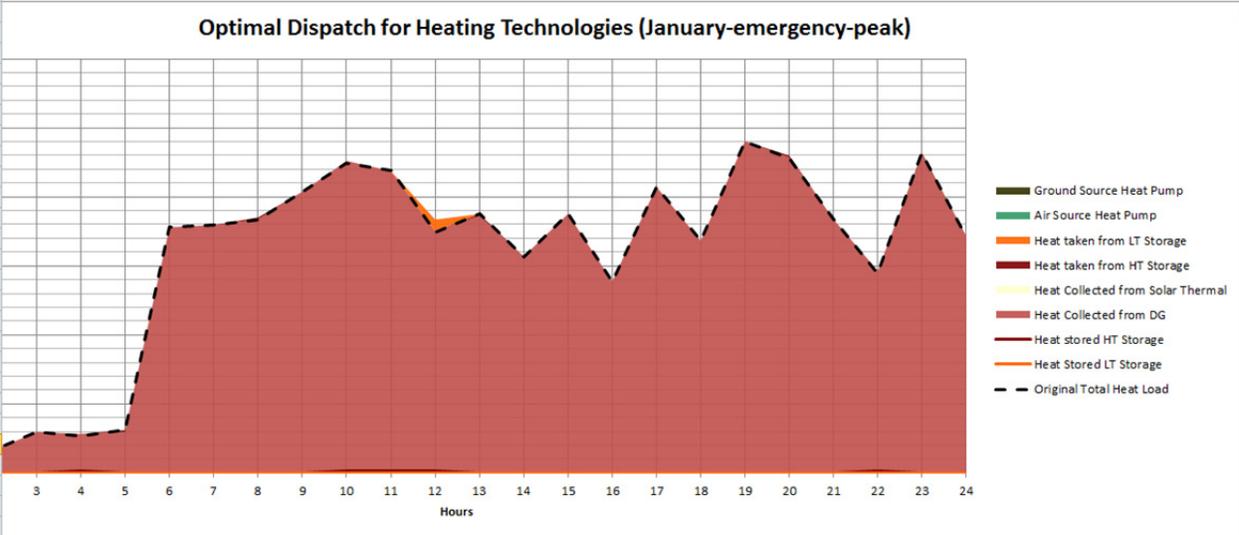


FIGURE 3.22 Heating Dispatch on an Emergency Peak Day in January (Case 2)

3.2.3 Case 3

In Case 3, the utility rates are restored to fixed values and the electric utility availability is 100%. We utilized a multi-objective that simultaneously considers both energy costs and CO₂ emissions. In DER-CAM, the multi-objective is realized by applying a weighted objective function:

$$\text{Obj} = a \times \text{costs} + b \times \text{CO}_2 \text{ emissions},$$

where *a* and *b* are weights for cost and CO₂ emissions, respectively. DER-CAM allows the customer to set how each of the cost and CO₂ emissions objectives is weighted. In this study, Case 3 is expanded into 4 subcases representing different DER-CAM objectives (reported in Table 3.8).

TABLE 3.8 Subcases under Case 3 with Weighted Objectives

Subcase No.	Weight of Cost Minimization	Weight of CO ₂ Emission Minimization
Subcase 3.1	0.75	0.25
Subcase 3.2	0.5	0.5
Subcase 3.3	0.25	0.75
Subcase 3.4	0	1

Note that Case 1 can also be viewed as an extra subcase under Case 3, where we set a weight of 1 for cost minimization and 0 for CO₂ emissions minimization.

A. Subcase 3.1: Multi-Objective Optimization (weight of 0.75 for cost minimization)

In this subcase, DER-CAM is applied to find DER investments with a multi objective considering both energy cost minimization and CO₂ emissions minimization. In this run, we assign a higher weight for cost minimization (a weight of 0.75 for cost minimization and 0.25 for CO₂ emissions minimization).

In this subcase, DER-CAM suggests investing in 3,000 kW of internal combustion engines (1,500 kW of them equipped with heat exchange systems), 1,000 kW of gas turbines, 1,800 kW of gas-fired micro turbines (900 kW of them equipped with heat exchange systems), 515 kW of PV panels, an air source heat pump with 542 kW of capacity, and a ground source heat pump with 989 kW of capacity (as shown in Figure 3.23, middle). Compared to Case 1, DER-CAM suggests investing in extra solar PVs, since we are starting to consider environmental impacts by reducing CO₂ emissions. The total capital costs for new investments are 11,350.5 k\$. Of all installed technologies, the investment in the internal combustion engines with heat exchange systems is the most capital-intensive (as shown in Figure 3.23, right).

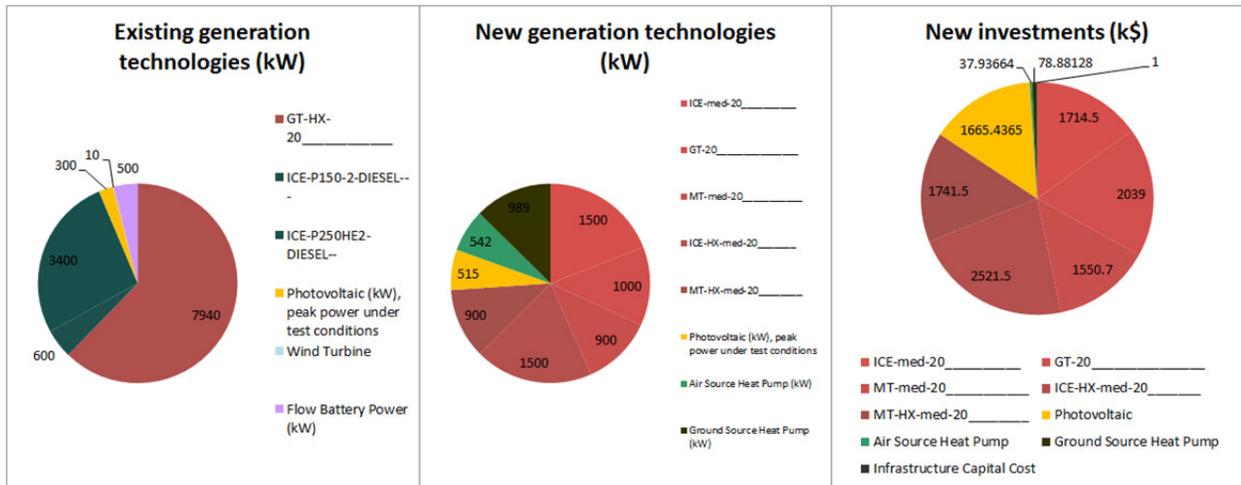


FIGURE 3.23 Investment Capacities and Upfront Capital Costs (Subcase 3.1)

With the plan from DER-CAM, the annual energy costs decrease to 5,877.4 k\$. In this subcase, the annual costs are higher than those in Case 1. This is mainly due to the investment in extra solar PVs. In return, the total annual CO₂ emissions decrease to 34,701.0 metric tons (as reported in Table 3.9).

TABLE 3.9 Annual Energy Costs and CO₂ Emissions (Subcase 3.1)

	Annual Energy Costs (k\$)	Annual CO ₂ Emissions (metric tons)
Reference	6,495.1	39,838.5
Subcase 3.1	5,877.4	34,701.0

With this plan, the total cost savings are 9.46% and the reduction in CO₂ emissions are 12.90%. Figure 3.24 shows the detailed annual energy costs and energy balance with this plan. One shall note that the electricity usage from on-site renewable generation increases to 1,406,589 kWh.

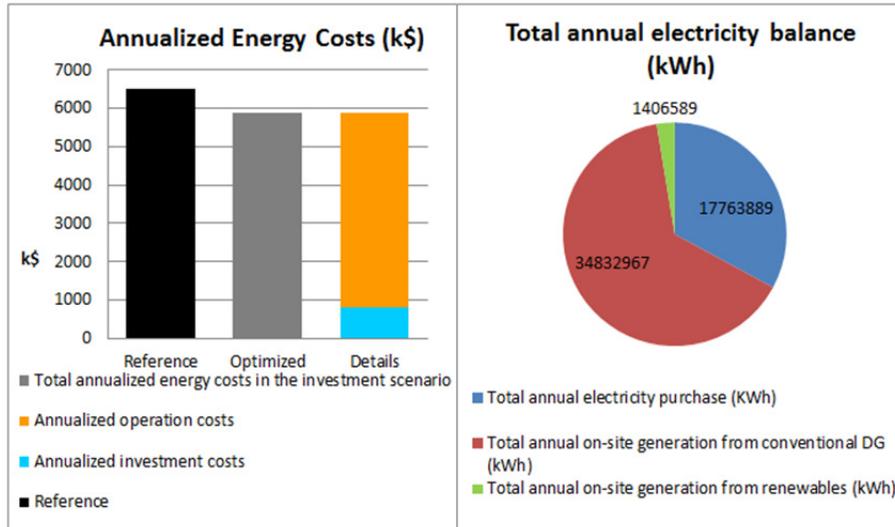


FIGURE 3.24 Detailed Annual Energy Costs and Energy Balance (Subcase 3.1)

Figure 3.25 shows the dispatch for electricity on a peak day in August. It is similar to that for Case 1, but this time it can be seen that the utility purchase (green) is much lower in terms of power consumption when compared to the base case (black dashed line); and the electricity usage from solar energy (yellow) obviously increases.

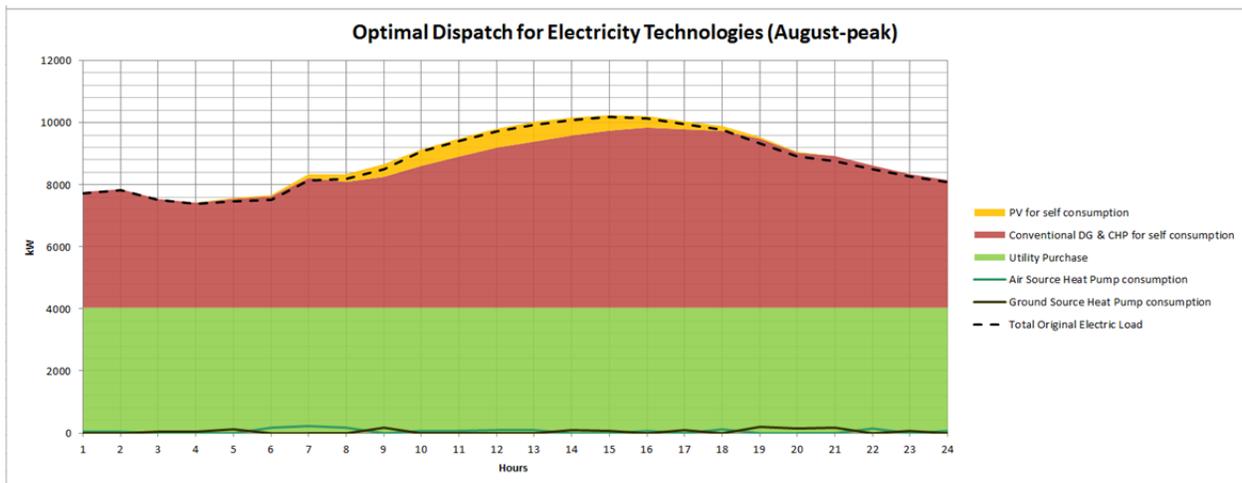


FIGURE 3.25 Electricity Dispatch on a Peak Day in August (Subcase 3.1)

Figure 3.26 shows the dispatch for heating resources on a peak day in January. In this run, it can be seen that the installed air-source heat pump and ground source heat pump are mainly dispatched to meet the heating load requirements.

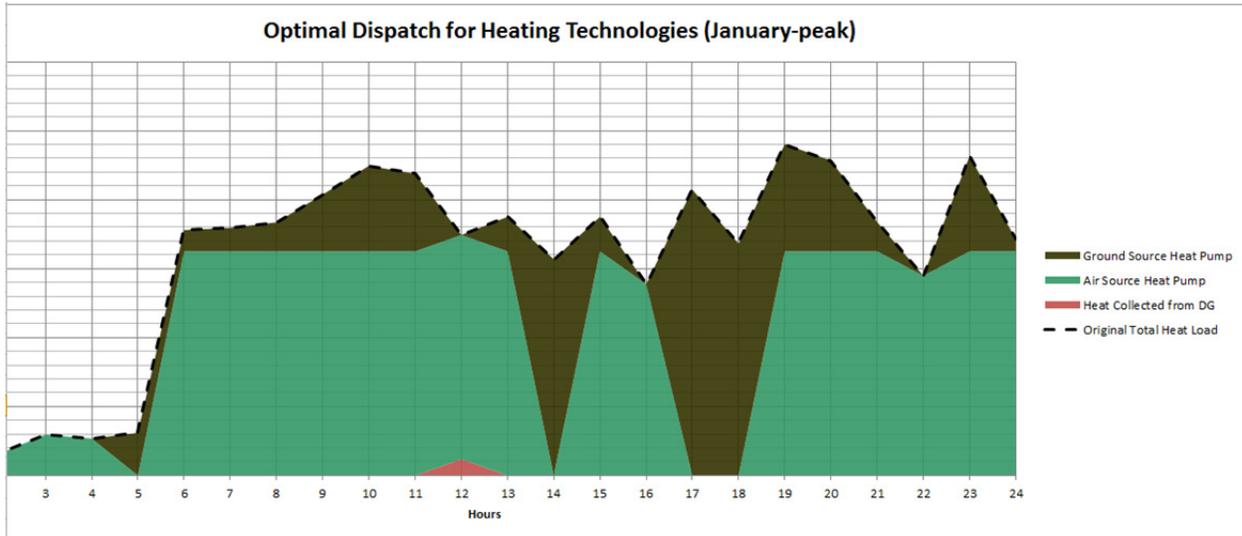


FIGURE 3.26 Heating Dispatch on a Peak Day in January (Subcase 3.1)

B. Subcase 3.2: Multi Objective Optimization (even weights)

In this subcase, DER-CAM is applied to find DER investments with a multi-objective considering both energy cost minimization and CO₂ emissions minimization. Here we assign equal weights for both criteria (i.e., a weight of 0.5 for cost minimization and 0.5 for CO₂ emissions minimization).

In this subcase, DER-CAM suggests investing in 3,000 kW of internal combustion engines (1,500 kW of them equipped with heat exchange systems), 2,000 kW of gas turbines, 1,800 kW of gas-fired micro turbines (900 kW of them equipped with heat exchange systems), 515 kW of PV panels, an air source heat pump with 272 kW of capacity, and a ground source heat pump with 19 kW of capacity (as shown in Figure 3.27, middle). In addition, two types of storage technologies are recommended by DER-CAM in this subcase: 427 kWh of stationary battery capacity and 427 kWh of heat storage capacity (as shown in Figure 3.27, right). The total capital costs for new investments are 13,453.01 k\$. Of all installed technologies, the investment in gas turbines is the most capital-intensive (as shown in Figure 3.28).

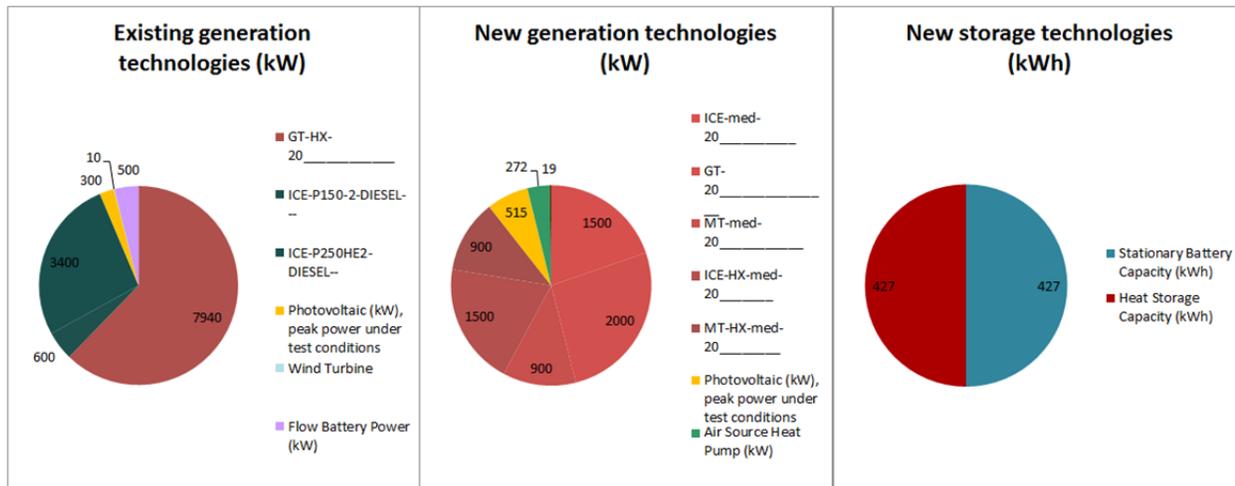


FIGURE 3.27 Investment Capacities (Subcase 3.2)

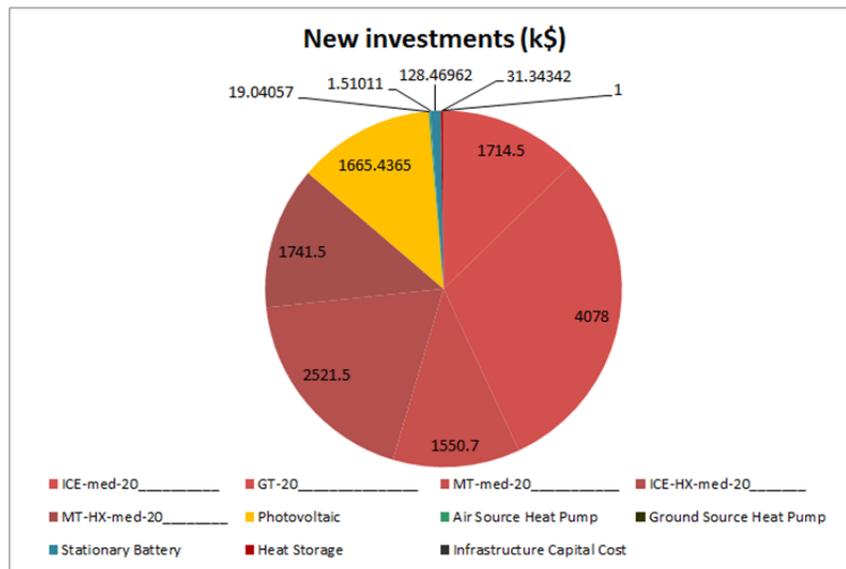


FIGURE 3.28 Upfront Capital Costs (Subcase 3.2)

With the plan from DER-CAM, the annual energy costs decrease to 5,911.2 k\$. Owing to the new investments in solar PVs and storage technologies, the total annual CO₂ emissions further decrease to 32,537.4 metric tons (as reported in Table 3.10).

With this plan, the total cost savings are 8.99% and the reduction in CO₂ emissions are 18.33%.

Figure 3.29 shows the detailed annual energy costs and energy balance with this plan.

TABLE 3.10 Annual Energy Costs and CO₂ Emissions (Subcase 3.2)

	Annual Energy Costs (k\$)	Annual CO ₂ Emissions (metric tons)
Reference	6,495.1	39,838.5
Subcase 3.2	5,911.2	32,537.4

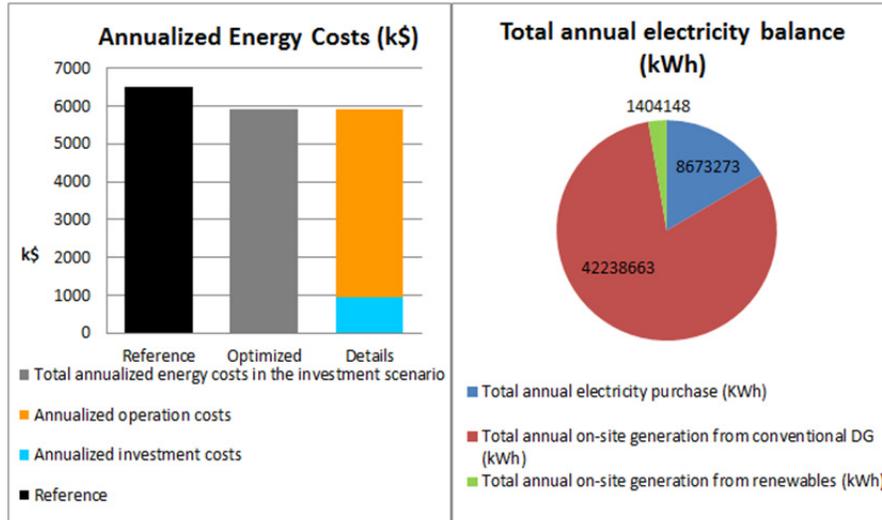


FIGURE 3.29 Detailed Annual Energy Costs and Energy Balance (Subcase 3.2)

Figure 3.30 shows the dispatch for electricity on a peak day in May. It can be seen that the stationary battery reaches its maximum charging speed during early morning and late night (blue dashed line). The stationary battery discharges during the afternoon to reduce a small part of the peak load (blue). Also, the utility purchase (green) is now much lower than those in previous subcases, since we encouraged more DER investment by reducing the weight of cost minimization.

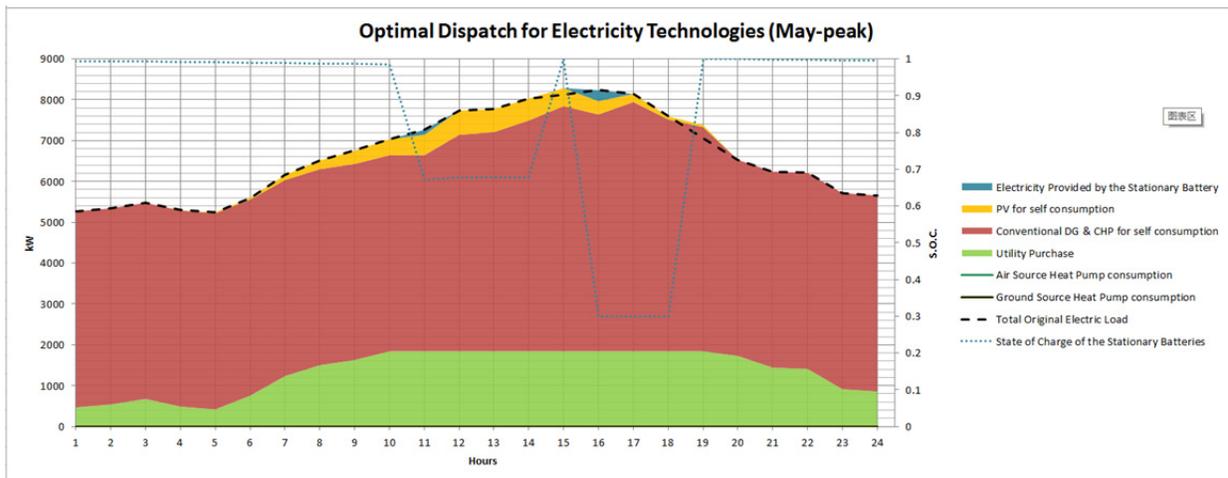


FIGURE 3.30 Electricity Dispatch on a Peak Day in May (Subcase 3.2)

Figure 3.31 shows the dispatch for heating resources on a peak day in November. It can be seen that the newly installed heat storage device mainly stores heating resources in the early morning (orange line) and dispatches these resources to meet heating load requirements during the remaining hours (orange line).

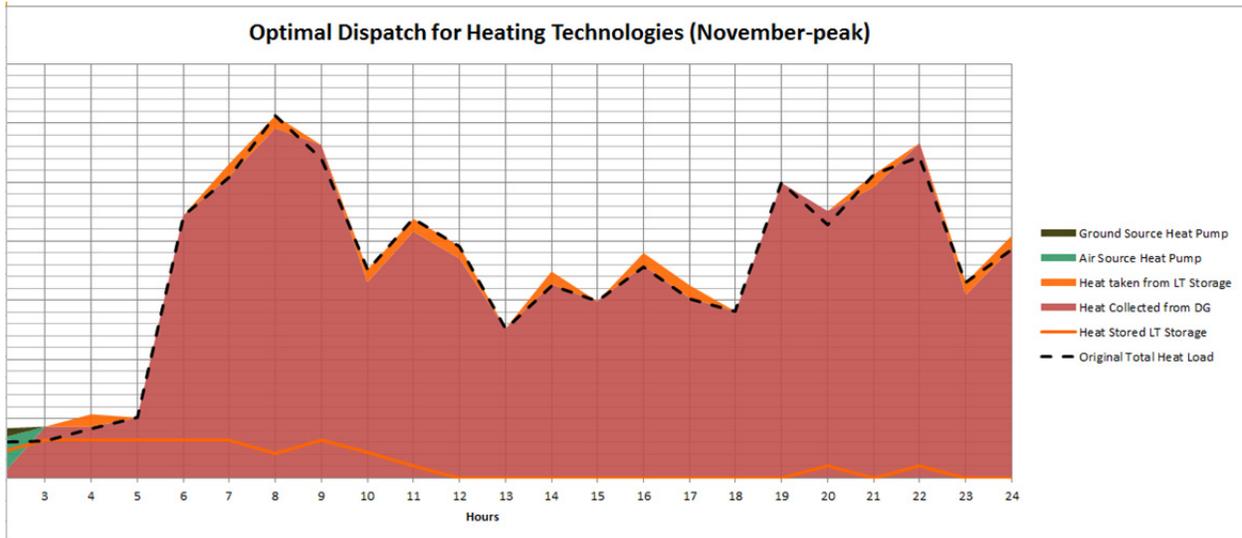


FIGURE 3.31 Heating Dispatch on a Peak Day in November (Subcase 3.2)

C. Subcase 3.3: Multi Objective Optimization (weight of 0.75 for CO₂ emission minimization)

In this subcase, DER-CAM is applied to find DER investments with a multi objective considering both cost minimization and CO₂ emissions minimization. Here, we assign a higher weight to CO₂ emissions minimization (weight of 0.25 for cost minimization and 0.75 for CO₂ emissions minimization).

In this subcase, DER-CAM suggests investing in 3,000 kW of internal combustion engines (1,500 kW of them equipped with heat exchange systems), 2,000 kW of gas turbines, 1,800 kW of gas-fired micro turbines (900 kW of them equipped with heat exchange systems), 840 kW of PV panels, an air source heat pump with 446 kW of capacity, and a ground source heat pump with 998 kW of capacity (as shown in Figure 3.32, middle). In addition, two types of storage technologies are recommended by DER-CAM in this subcase: 8,657 kWh of heat storage capacity and 10,912 kWh of cold storage capacity (as shown in Figure 3.32, right). The total capital costs for new investments are 15,502.9 k\$. Of all installed technologies, the investment in gas turbines is the most capital-intensive (as shown in Figure 3.33).

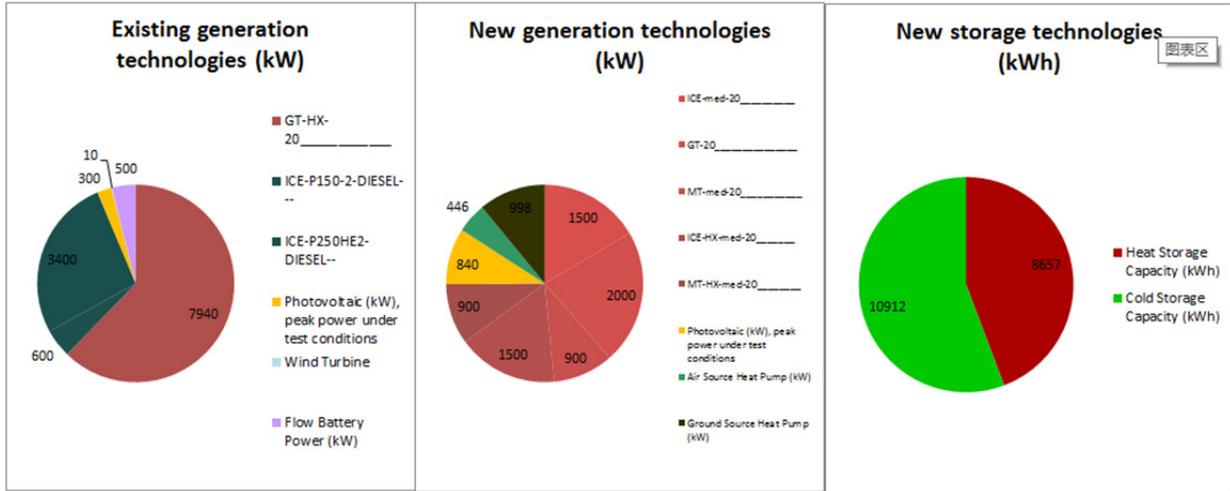


FIGURE 3.32 Investment Capacities (Subcase 3.3)

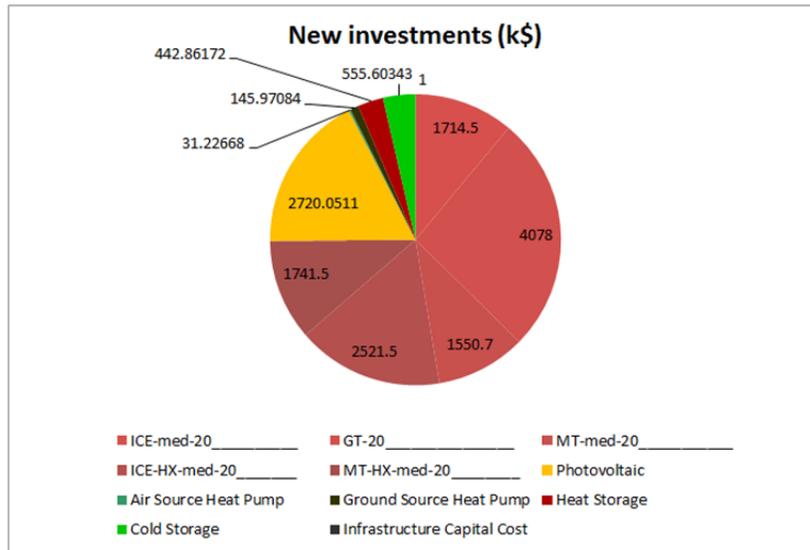


FIGURE 3.33 Upfront Capital Costs (Subcase 3.3)

With this plan from DER-CAM, the annual energy costs decrease to 6,265.6 k\$, and the total annual CO₂ emissions further decrease to 32,166.9 metric tons (as reported in Table 3.11).

In this subcase, the total cost savings are 3.53% and the reduction in CO₂ emissions is 19.26%. Figure 3.34 shows the detailed annual energy costs and energy balance with this plan.

The electricity usage from on-site renewable generation increases to 1,968,077 kWh

TABLE 3.11 Annual Energy Costs and CO₂ Emissions (Subcase 3.3)

	Annual Energy Costs (k\$)	Annual CO ₂ Emissions (metric tons)
Reference	6,495.1	39,838.5
Subcase 3.3	6,265.6	32,166.9

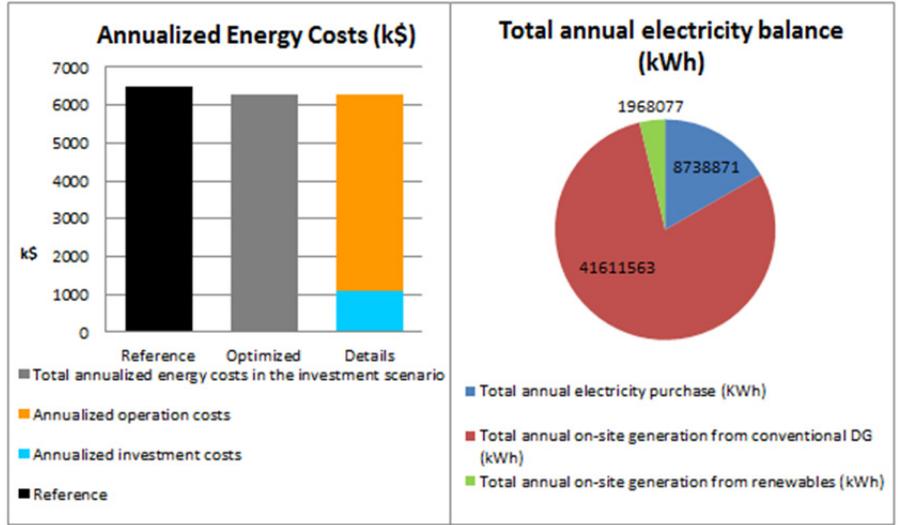


FIGURE 3.34 Detailed Annual Energy Costs and Energy Balance (Subcase 3.3)

Figure 3.35 shows the dispatch for electricity on a peak day in June. In this subcase, more solar PV investments are made and the electricity usage from PV generation also increases (yellow).

Figure 3.36 shows the dispatch for heating resources on a peak day in December. Similarly to subcase 3.2, the newly installed heat storage device mainly stores heating resources in the early morning (orange line) and dispatches these resources to meet heating load requirements during the remaining hours (orange).

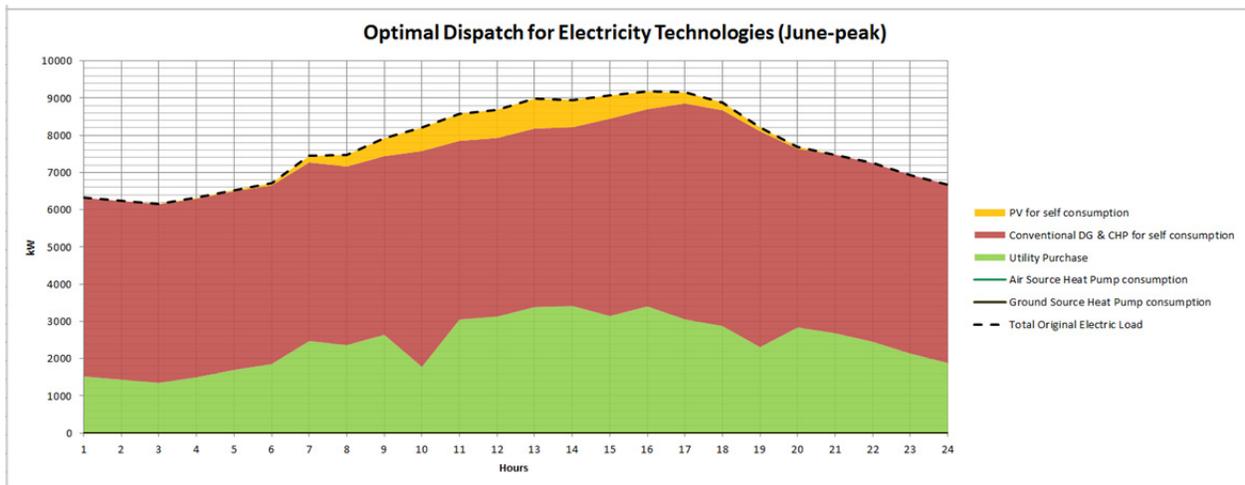


FIGURE 3.35 Electricity Dispatch on a Peak Day in June (Subcase 3.3)

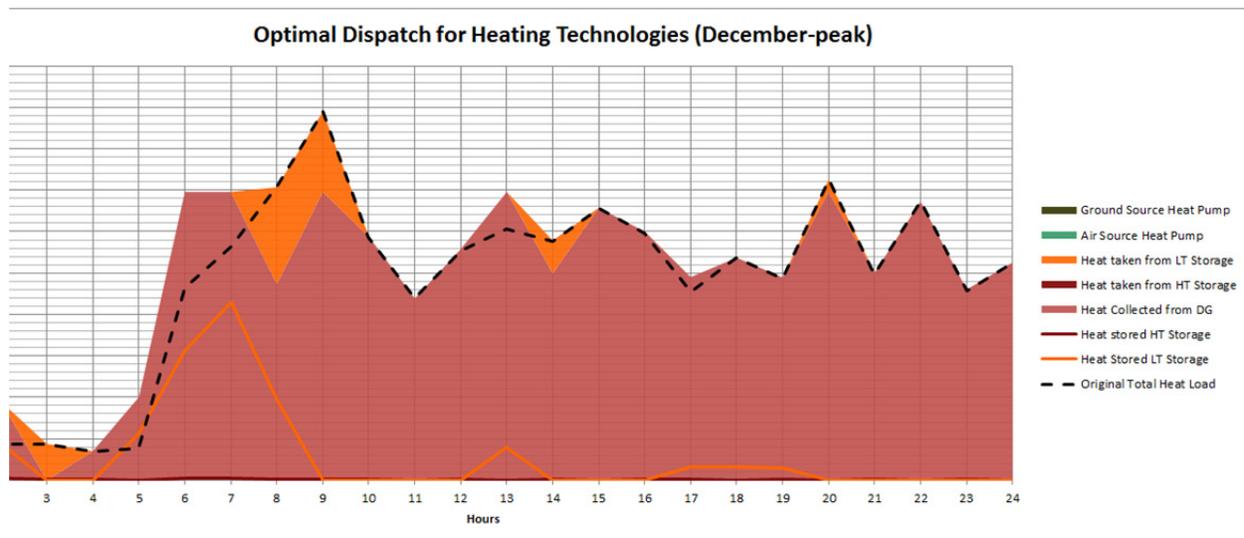


FIGURE 3.36 Heating Dispatch on a Peak Day in December (Subcase 3.3)

D. Subcase 3.4: Carbon Dioxide Emissions Minimization

In this subcase, DER-CAM is applied to find DER investments that will minimize carbon dioxide emissions.

In this subcase, DER-CAM suggests investing in 3,000 kW of internal combustion engines (1,500 kW of them equipped with heat exchange systems), 3,000 kW of gas turbines, 1,800 kW of gas-fired micro turbines (900 kW of them equipped with heat exchange systems), 1,117 kW of PV panels, and 976 kW of solar thermal facilities. The air source and ground source heat pumps are not recommended anymore and are replaced by solar thermal technologies (as shown in Figure 3.37, middle). DER-CAM also suggests investing in 12,196 kWh of heat storage (as shown in Figure 3.37, right). Compared to previous subcases, we can see that a large amount of renewable storage technology is suggested in this CO₂ minimization case; the total capital costs for new investments are 18,990.5 k\$. Of all installed technologies, the investment in gas turbines is the most capital-intensive (as shown in Figure 3.38).

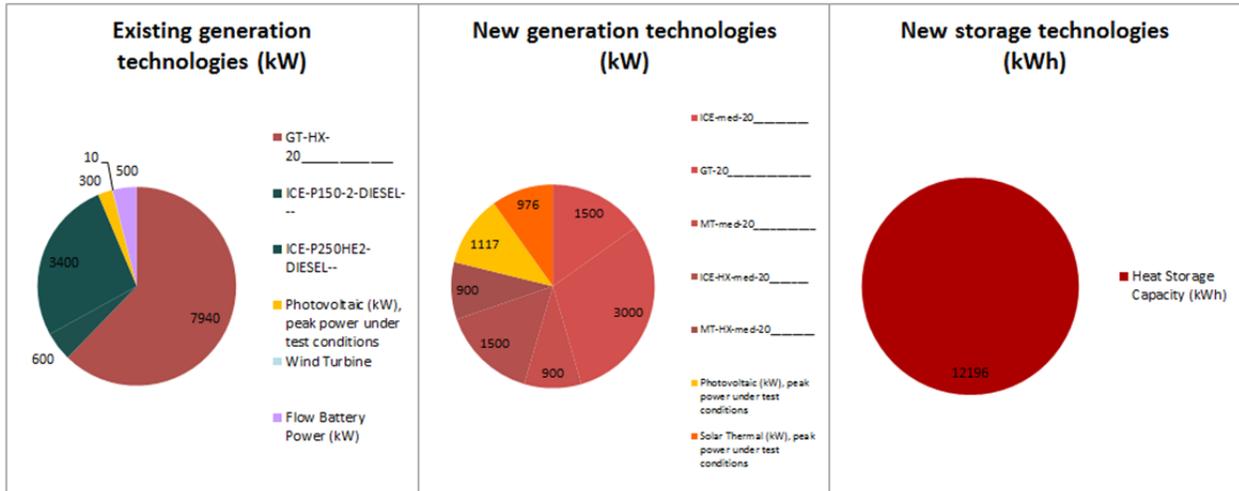


FIGURE 3.37 Investment Capacities (Subcase 3.4)

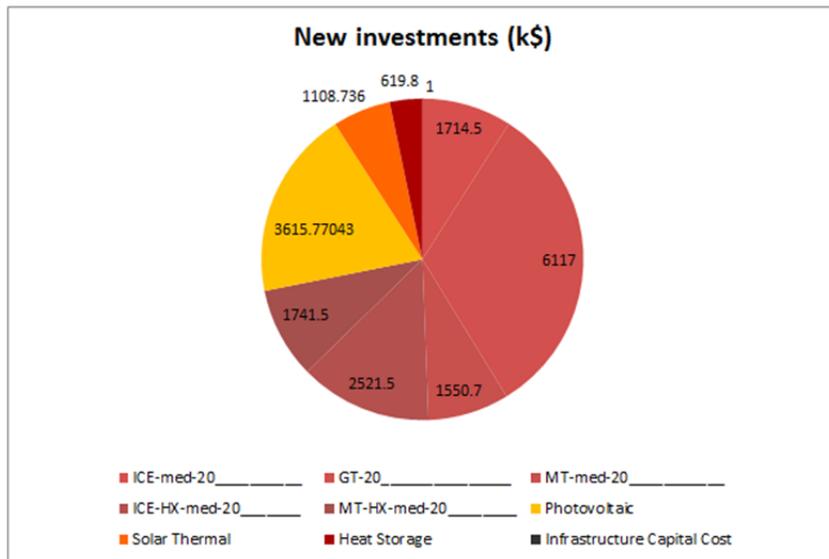


FIGURE 3.38 Upfront Capital Costs (Subcase 3.4)

With this plan from DER-CAM, the annual energy costs increase to 6,501.3 k\$ because of the large amount of renewable storage technology. The annual CO₂ emissions now decrease to 31,725.5 metric tons (as reported in Table 3.12).

In this subcase, the annual energy costs are higher than current IIT case. As a return, there is a reduction of 20.36% in CO₂ emissions.

TABLE 3.12 Annual Energy Costs and CO₂ Emissions (Subcase 3.4)

	Annual Energy Costs (k\$)	Annual CO ₂ Emissions (metric tons)
Reference	6,495.1	39,838.5
Subcase 3.4	6,501.3	31,725.5

Compared to all previous cases, much less electricity is bought from the grid, and the on-site generation is used instead. The electricity usage from on-site renewable generation increases to 2,447,091 kWh. Figure 3.39 shows the detailed annual energy costs and energy balance with this plan.

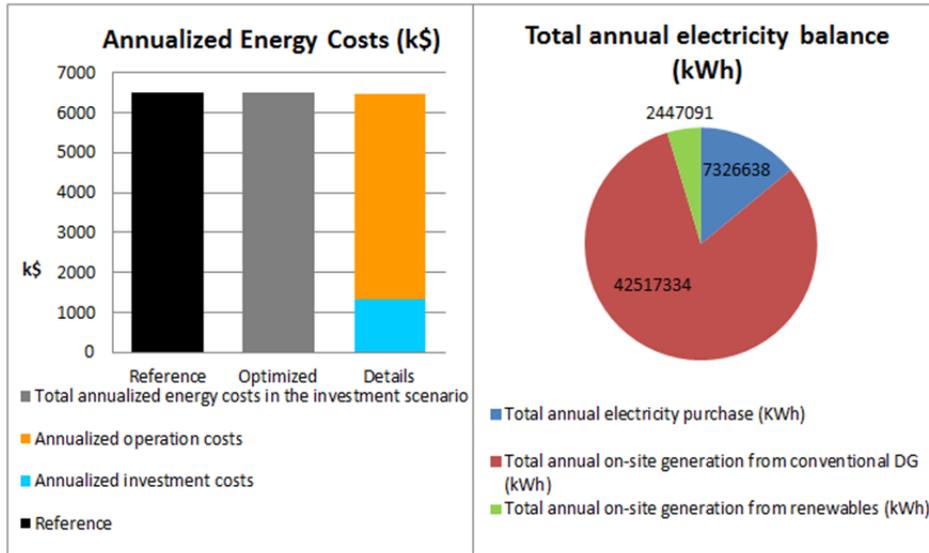


FIGURE 3.39 Detailed Annual Energy Costs and Energy Balance (Subcase 3.4)

Figure 3.40 shows the dispatch for electricity on a peak day in June. Figure 3.41 shows the dispatch for heating resources on a peak day in December.

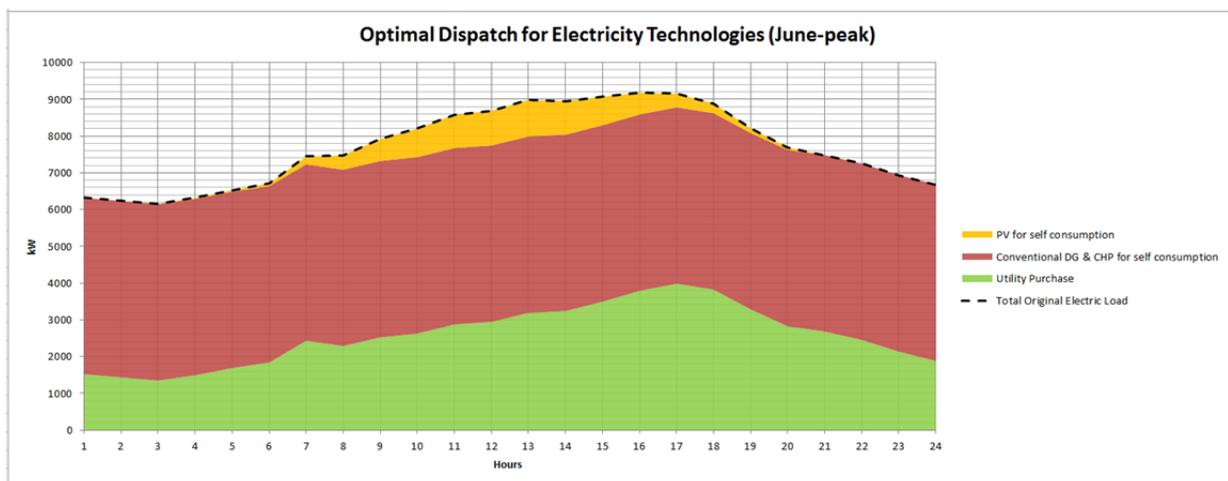


FIGURE 3.40 Electricity Dispatch on a Peak Day in June (Subcase 3.4)

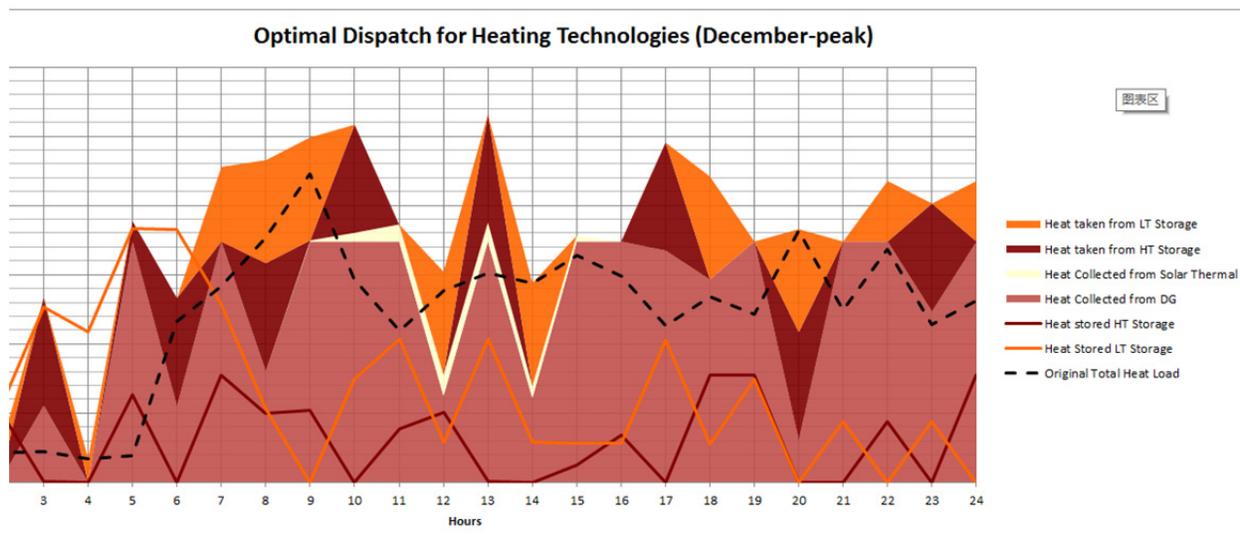


FIGURE 3.41 Heating Dispatch on a Peak Day in December (Subcase 3.4)

3.2.4 Comparison and Analysis of Test Results

A. Comparison between Case 1 and Case 2

In Table 3.13, we compare the results from Case 1 and Case 2. In both cases, we utilized the same objective, which is to minimize the energy costs (including investment costs and operation costs). We can see that the plan from Case 2 leads to lower annual energy costs and CO₂ emissions than Case 1. Although it is hard to judge that the plan from case 2 is better, as the utility conditions in the two cases are different, we can see that the more “flexible” utility conditions (real-time prices) can allow DER-CAM to consider a wider range of DER investments, which might bring greater economic and environmental benefits.

TABLE 3.13 Comparison between Case 1 and Case 2

	Current IIT Microgrid	Case 1	Case 2
Annual energy costs (k\$)	6,495.1	5,428.9	5,360.9
Annual CO ₂ emissions (metric tons)	39,838.5	37,733.9	36,668.9
Energy cost reduction		16.41%	17.46%
CO ₂ emissions reduction		5.29%	7.96%
Conventional DER units (kW)	11,940	15,540	17,740
Renewable DERs (kW)	310	310	827
Storage technologies (kWh)	500	500	1,484
Annual electricity purchase (kWh)	51,914,235	40,288,159	33,559,751
Annual generation from conventional DERs (kWh)	0	11,640,795	17,724,024
Annual generation from renewable DERs (kWh)	512,268	512,392	1,386,787

B. Comparison between Case 1 and Case 3

For both Case 1 and Case 3, we assumed the current fixed utility rates and 100% electric utility availability. Regarding the objectives, Case 1 and the 4 subcases under Case 3 reflect different settings of weights (Obj: $a \times \text{costs} + b \times \text{CO}_2 \text{ emissions}$, where a and b are weights for cost minimization and CO_2 emissions minimization, respectively). Case 1 ($a = 1$ and $b = 0$) involves cost minimization only, subcase 3.4 ($a = 0$ and $b = 1$) involves CO_2 emissions minimization only, and the subcases 3.1 to 3.3 are in between. The results are summarized in Figure 3.42.

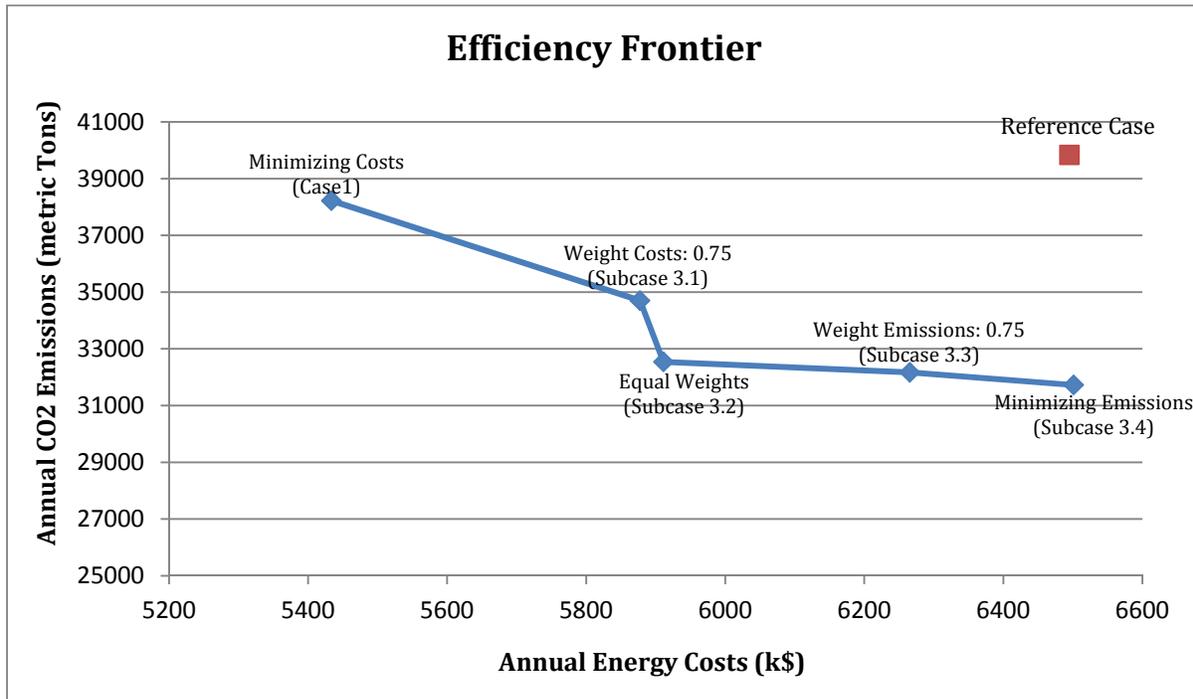


FIGURE 3.42 Case 1 and Case 3 Efficiency Frontier

There is a clear trade-off between energy cost minimization and CO_2 emissions minimization. It is very interesting to look at the point representing equal weights (subcase 3.2). For only a small increase of 0.52% (9.51%-8.99%) in the annual energy costs, the CO_2 emissions are lowered by 5.43% (18.33%-12.90%) compared to subcase 3.1. Table 3.14 compares each subcase in detail. If we simply add up the percentage energy costs reduction and percentage CO_2 emissions reduction, subcase 3.2, which can bring about a total reduction of 27.32%, is very appealing.

TABLE 3.14 Comparison between Case 1 and Case 3

	Current IIT	Case 1	Subcase 3.1	Subcase 3.2	Subcase 3.3	Subcase 3.4
Annual energy costs (k\$)	6,495.1	5,428.9	5,877.4	5,911.2	6,265.6	6,501.3
Annual CO ₂ emissions (metric tons)	39,838.5	37,733.9	34,701.0	32,537.4	32,166.9	31,725.5
Energy cost reduction		16.41%	9.51%	8.99%	3.53%	-0.10%
CO ₂ emissions reduction		5.29%	12.90%	18.33%	19.26%	20.36%
Conventional DER units (kW)	11,940	15,540	17,740	18,740	18,740	18,740
Renewable DERs (kW)	310	310	825	825	1,150	2,242
Storage technologies (kWh)	500	500	500	1,354	20,069	13,741
Annual electricity purchase (kWh)	51,914,235	40,288,159	17,763,889	8,673,273	8,738,871	9,278,423
Annual generation from conventional DERs (kWh)	0	11,640,795	34,832,967	42,238,663	41,611,563	40,875,313
Annual generation from renewable DERs (kWh)	512,268	512,392	1,406,589	1,404,148	1,968,077	2,143,262

4 CONCLUSIONS

In this project, DER-CAM is applied to study the expansion planning of the IIT Microgrid. We first gathered the load data, environmental data, utility data, and technology data for the IIT Microgrid and organized them to follow the DER-CAM input requirements. Then, DER-CAM was applied to study the expansion planning for 3 different cases. Case 1 considers the objective of minimizing energy costs with fixed utility rates and 100% electric utility availability. Case 2 considers the objective of minimizing energy costs with real-time utility rates and 4 emergency weeks when the IIT Microgrid does not have access to the electric utility grid and has to operate in island mode. In Case 3, the utility rates are restored to fixed values and 100% electric utility availability is assumed. A weighted multi-objective (Obj: $a \times \text{costs} + b \times \text{CO}_2 \text{ emissions}$, where a and b are weights for cost minimization and CO_2 emissions minimization) is utilized to consider both energy costs and CO_2 emissions.

On the basis of the test results, the IIT Microgrid has the potential to benefit from investments in more DER technologies. In the 6 test cases/subcases considered, the investment plans varied to reflect different objectives and utility conditions. The current annual energy costs and CO_2 emissions for the IIT microgrid are 6,495.1 k\$ and 39,838.5 metric tons, respectively. This represents the baseline for this project.

- With the plan from Case 1, investments in 3,600 kW of conventional DER units are suggested. Accordingly, the annual energy costs and CO_2 emissions are reduced to 5,428.9 k\$ and 37,733.9 metric tons (16.41% reduction from current annual energy costs; 5.29% reduction from current annual CO_2 emissions).
- With the plan from Case 2, investments in 5,800 kW of conventional DER units, 517 kW of renewable DERs, and 984 kWh of storage technologies are suggested. As a result, the annual energy costs and CO_2 emissions are reduced to 5,360.9 k\$ and 36,668.9 metric tons (17.46% reduction from current annual energy costs; 7.96% reduction from current annual CO_2 emissions).
- With the plan from subcase 3.1 (weighted objective: $a = 0.75$, $b = 0.25$), investments in 5,800 kW of conventional DER units and 515 kW of renewable DERs are suggested. As a result, the annual energy costs and annual CO_2 emissions are reduced to 5,877.4 k\$ and 34,701.0 metric tons (9.51% reduction from current annual energy costs; 12.90% reduction from current annual CO_2 emissions).
- With the plan from subcase 3.2 (weighted objective: $a = b = 0.5$), investments in 6,800 kW of conventional DER units, 515 kW of renewable DERs, and 854 kWh of storage technologies are suggested. As a result, the annual energy costs and annual CO_2 emissions are reduced to 5,911.2 k\$ and 32,537.4 metric tons (8.99% reduction from current annual energy costs; 18.33% reduction from current annual CO_2 emissions).
- With the plan from subcase 3.3 (weighted objective: $a = 0.25$, $b = 0.75$), investments in 6,800 kW of conventional DER units, 840 kW of renewable DERs, and 19,569 kWh of

storage technologies are suggested. As a result, the annual energy costs and annual CO₂ emissions are reduced to 6,265.6 k\$ and 32,166.9 metric tons (3.53% reduction from current annual energy costs; 19.26% reduction from current annual CO₂ emissions).

- With the plan from subcase 3.4 (weighted objective: $a = 0$, $b = 1$), investments in 6,800 kW of conventional DER units, 1,932 kW of renewable DERs, and 13,241 kWh of storage technologies are suggested. As a result, the annual energy cost rises to 6501.3 k\$ (0.1% increment from current annual energy costs), and CO₂ emissions are reduced to 31,725.5 metric tons (20.36% reduction from current annual CO₂ emissions).

In summary, if we want to maximize economic benefits based on fixed utility rates and 100% electric utility availability (current utility conditions), the investment plan from Case 1 is the most attractive strategy; it can save the IIT Microgrid 16.41% in annual energy costs. If we want to consider economic and environmental benefits simultaneously based on fixed utility rates and 100% electric utility availability (current utility conditions), the investment plan from subcase 3.2 (equal weights) is the most attractive plan; it can lead to 8.99% reduction from current annual energy costs and 18.33% reduction from current annual CO₂ emissions for the IIT Microgrid.

5 REFERENCES

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Energy Systems Division

9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4854

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