Performance evaluation of a power generation unit-organic Rankine cycle system with electric energy storage

By

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This research proposes the use of electric energy storage (EES) in conjunction with a power generation unit organic Rankine cycle system (PGU-ORC). The EES is used when available so that continuous operation of the PGU is not required. The potential of the PGU-ORC-EES system's performance is evaluated in terms of operational cost, primary energy consumption (PEC), and carbon dioxide emissions (CDE) from simulations of a restaurant building in twelve U.S. locations with different climate conditions. The performance of the proposed system is compared to a conventional system. Results indicate that the EES addition to the PGU-ORC system is beneficial for most locations. Ratios between electricity and fuel cost, CDE conversion factors, and PEC conversion factors are used to estimate potential performance benefits. The effect of the EES size and the capital cost available are also analyzed.

DEDICATION

To my parents, *Randy and Vicky*, and to my best friend, *Anastasia*, and the many other *family*, *friends*, *faculty*, *staff*, and *colleagues* who've supported my academic journey.

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NOMENCLATURE

CHP	Combined Heat and Power
CCHP	Combined Cooling, Heating, and Power
PGU	Power Generation Unit
SHP	Separate Heating and Power
PEC	Primary Energy Consumption
CDE	Carbon Dioxide Emissions
ORC	Organic Rankine Cycle
TES	Thermal Energy Storage
EES	Electric Energy Storage
FEL	Following the Electric Load
FTL	Following the Thermal Load
BL	Base-Loaded
E_b	Building Electric Demand
E_{batMAX}	Nominal Battery Capacity
ξ_{bat}	Battery Efficiency Factor
E_{bat}	Battery Capacity
t	Time
Δt	Time Step
E_{PGU}	Electric Output of the PGU

F_{PGU}	Fuel energy required to operate PGU
E_{PGUnom}	Nominal Size of the PGU
Q_{PGU}	Waste energy available from the PGU operation
HRS	Heat Recovery System
Q_{rec}	Recovered Heat from PGU
ξ	PGU Loss Factor
η_{HRS}	Efficiency of HRS
η_{ORC}	Efficiency of ORC
E_{ORC}	Electrical Energy Output of ORC
$Cost_{PGU-ORC-ES}$	Operational Cost of the PGU-ORC-ES System
$Cost_{conv}$	Operational Cost of the Reference SHP System
$CDE_{PGU-ORC-ES}$	CDE of the PGU-ORC-ES system
CDE_{conv}	CDE of the Reference SHP system
$PEC_{PGU-ORC-ES}$	PEC of the PGU-ORC-ES system
PEC_{conv}	PEC of the Reference SHP system
$Cost_f$	Cost of Fuel (natural gas)
$Cost_e$	Cost of Electricity
$CF_{CDE,f}$	CDE Conversion Factor for Natural Gas
$CF_{CDE,e}$	CDE Conversion Factor for Electricity
$CF_{PEC,f}$	PEC Conversion Factor for Natural Gas
$CF_{PEC,e}$	PEC Conversion Factor for Electricity
R_{cost}	Ratio of the cost of electricity to cost of fuel

R_{CDE}	Ratio of the CDE Conversion Factor for electricity to fuel
R_{PEC}	Ratio of the PEC Conversion Factor for electricity to fuel

CHAPTER I

INTRODUCTION

1.1 CHP Systems

A combined heat and power (CHP) system simultaneously generates on-site electricity and provides useful heat by recovering waste heat from a power generation unit (PGU). CHP systems have been shown to provide 25-45% increases in efficiency over conventional systems [1]. CHP systems can be operated using different strategies: following the electric load (FEL), following the thermal load (FTL), base loaded (BL), or using a combination of these load strategies. When the system is operated FEL, the PGU provides all of the building's electric demand while the waste heat is used to satisfy the building's thermal demand. Since the recovered waste heat may not be enough to satisfy all of the building's thermal demand, a boiler is used to supplement the waste heat recovered by the PGU. When the CHP system is operated FTL, it provides all of the building's thermal demand, and the electricity generated is used to satisfy the building's electric demand. Since the electricity generated by the CHP system may not be enough to satisfy the building's electric demand, electricity imported from the utility grid may be used to supply the additional electricity needed. When the CHP system operates BL, the PGU supplies part of the building's electric demand at a constant rate, and the waste heat is used to satisfy part of the building's thermal demand. Results have been reported for FEL and FTL operation by Mago et al. [2], Wang et al. [3], Mago and Chamra [4], Mago et al. [5], Fumo et al. [6], Caliano at al [7], and Somma et al. [8]. Most of the studies mentioned above analyzed the performance of combined cooling, heating, and power (CCHP) and CHP systems operating FEL and FTL based on primary energy consumption (PEC), operational cost, carbon dioxide emissions (CDE), and exergy efficiency for buildings located in different climate conditions. In general, they concluded that the selection of CHP and CCHP systems operational strategies depend on the building's electric and thermal loads as well as the geographical location where the system is installed. Caliano et al. [7] optimized a micro-CHP system, for a multi-apartment housing situated in Italy using two heat-led operational strategies to reduce the cost compared to separate generation systems. Similarly, Somma et al. [8] determined that a distributed energy system optimized with respect to cost can significantly improve the results as compared with the conventional system. Results for BL operation have been presented by Mago and Luck [9] and Mago et al. [10]. They evaluated the performance of a BL CHP system for a small office building located in different climate zones. Similar to FEL and FTL operation, the system performance was evaluated based on PEC, operational cost, and CDE reductions. In addition to the operational strategy of the system, the size of the PGU also affects the overall performance of the system. Hueffed and Mago [11] studied the influence of the PGU size and operational strategy on the performance of CCHP systems under different electric rate structures in Chicago, IL and Hartford, CT. They showed that the size of the PGU has an impact on the performance of the CCHP system and that smaller engine sizes showed better performance for their evaluated CHP and CHP with thermal energy storage (CHP-TES) systems.

1.2 ORC Systems

Another technology that could be used to recover low to medium temperature waste heat to generate electricity is the organic Rankine cycle (ORC), which is similar to a typical Rankine cycle but uses an organic fluid as the working fluid. The selection of the organic working fluid is fundamental for the cycle thermal efficiency and for the availability to recover waste heat from multiple sources. A large selection of organic working fluids could be selected for different applications. Maizza and Maizza [12-13], Vijayaraghavan and Goswami [14], Gao et al. [15], and Yu et al. [16] are some of the investigators who have performed analyses on different organic working fluids for different applications. ORCs could be employed in geothermal plants, solar applications, CHP plants, and general heat recovery applications from many potential sources [17]. Several researchers have investigated the ORC for solar applications. Some of them include: Delgado-Torres and García-Rodríguez [18], Kumar and Shukla [19], Spayde and Mago [20], and Quoilin et al. [21], among others. Delgado-Torres and García-Rodríguez [18] studied the combined use of a solar powered ORC with a desalination technology and reported that the combination could allow for less energy consumption during reverse osmosis. Kumar and Shukla [19] studied the performance of a solar powered ORC using benzene as the working fluid, and they concluded that their system could achieve improved efficiency and better economy compared to an ORC using other organic fluids. Spayde and Mago [20] developed a model to evaluate the performance of a solar-powered ORC for a system located in Jackson, MS and Tucson, AZ using different dry organic working fluids: R218, R227ea, R236ea, R236fa, and RC318. Quoilin et al. [21] presented the design of a solar ORC installed in a rural area for electrification purposes.

In addition to solar, the implementation of an ORC into a CHP system has also been shown to have the potential to reduce operational cost, PEC, and CDE [22-26]. Knizley et al. [22] evaluated the potential of a PGU-ORC system to reduce the operational cost, PEC, and CDE in different locations in the U.S. They established a parameter, R_{min}, based on system efficiencies that could be used to estimate when the PGU–ORC system would potentially provide savings with respect to the conventional system. If the methodology proposed by Knizley et al. [22] predicts potential reductions of operational cost, PEC, and CDE, then the PGU–ORC system should be carefully and further explored using the information about the facility where the system will be installed. Mago et al. [23] analyzed and optimized the use of CHP–ORC systems for small commercial buildings in several locations. They also found that the addition of an ORC system to a CHP system reduces the cost, PEC, and CDE for the cities simulated in their study. For 24-hour operation, they found that with the addition of an ORC system the average cost, PEC, and CDE were reduced by 25.9%, 26.1%, and 26.5%, respectively. In a similar study, Fang et al. [24] examined the effect of adding an ORC to a CHP system and found this combination to be an economically beneficial choice for several applications. Anvari et al. [25] performed a detailed energy-exergy analysis for a CHP plant with a regeneration ORC and determined that the regeneration cycle can increase first and second law thermodynamic efficiencies. Lecompte et al. [26] presented a thermo-economic design methodology to study the part load behavior of an ORC combined with a CHP system.

1.3 Energy Storage Systems

1.3.1 TES

Thermal storage is another component that has also shown to be an effective way to improve CHP system performance [27-30]. Smith et al. [27] presented a methodology to estimate the benefits of TES on CHP systems for different commercial building types. They determined that, in general, the use of TES with a CHP system reduces operational cost, PEC, and CDE. In another study, the effect of the addition of TES for a dual PGU-CHP configuration (D-CHP) was analyzed by Mago et al. [28] for a reference building in four different locations using two different operating strategies. In the first operating strategy, the first PGU operated BL while the second PGU operated FEL. In the second operating strategy, the second PGU operated FTL. In order to maximize the benefits of the addition of TES, the second PGU was operated FEL to meet the building's electric demand. They reported that the addition of TES further enhances the potential benefits of D-CHP systems to reduce operational cost and CDE, and that cities with high cost and emission ratios achieved the best cost and emission reductions, respectively. In addition to cost and emission savings, the addition of thermal storage to CHP systems could also reduce the PEC [30]. In another study Mago and Luck [9] evaluated the effect of TES on the performance of the BL CHP system. They reported that, in general, the use of thermal storage is beneficial because it reduces cost, PEC, and CDE compared to a CHP system without thermal storage.

1.3.2 EES

In addition to TES, other authors have investigated the use and benefits of electric energy storage (EES) on CHP system applications or other distributed generation technologies. Chen et al. [31] investigated the use of an EES system on a domestic CHP system operated FEL. In their system, they used the EES to reduce the amount of electricity purchased from the grid during peak charge hours, and they indicated that the overall system energy efficiency was improved by 47.86% compared to the efficiency of a CHP without the energy storage. Bianchi et al. [32] studied the performance of a CHP system with both thermal (TES) and electric energy storage (EES) for residential applications. They showed that if the appropriate size of EES and TES is selected, significant savings in PEC with respect to the conventional case could be achieved. Dusonchet et al. [33] evaluated the performance of combined generators, using renewable energy sources, and electric storage systems for small to medium scale facilities. They investigated a strategy to use their proposed system in load shifting applications, in order to reduce the cost of electricity by charging the energy storage during off–peak time periods and discharging the energy storage during on–peak periods, when electricity cost is high. In a more general study, Telaretti et al. [34] investigated the economic feasibility of stationary electrochemical storages as an option to reduce the electric bill for some customers in the Italian market. They found that the use of some electrochemical technologies could benefit customers only if there is a significant difference between maximum and minimum electricity prices or when high peak demand charges are applied to customers. Jenkins et al. [35] analyzed the efficiency of lead-acid batteries in storing electric energy generated from photovoltaic (PV) cells, wind turbines, and CHP systems. Their battery model results indicated an overall battery efficiency of 70-72%. Balcombe et al. [36] simulated an integrated PV, Stirling engine CHP (SECHP), and battery system for 30 households with different energy demands. Results showed that with a 6 kWh battery households were able to obtain an electricity self-sufficiency of 72% (28% imported from grid). Aghaei et al. [37] modeled a CHP-based microgrid (MG) with a lithium ion battery energy storage system (ESS), three types of thermal PGUs, and demand response programs (DRPs). The results showed that a 1.5% reduction of the daily operation cost and no change in the emission cost could be obtained when implementing the ESS with the MG (without DRPs). Shah et al. [38] simulated a PV-battery-CHP system for a residence in three representative locations in the U.S (hot, moderate, and cold climate). It was concluded that the PV-battery-CHP system was able to satisfy the load demand in all three regions. During a 48 hour period, Majic et al. [39] analyzed a CHP system with thermal and electric energy storage for a hospital building with a large thermal load by examining cost reduction versus the reference case where the thermal load was provided by a boiler, and the electric load was supplied by the grid. Compared to the reference case, the results showed 8.60% savings for the CHP system with thermal and electric energy storage. Gu et al. [40] simulated a CHP hybrid system with wind power, PV cells, a battery, a fuel cell, and a heat recovery boiler for a 24 hour period. When compared to the first operation mode (without battery), the second operation mode (with battery) was able to reduce the amount of power purchased from the grid and therefore reduce operational costs. Warren et al. [41] implemented EES into a PGU-ORC system and simulated a benchmark restaurant building in twelve different locations in the U.S. Their findings showed that the addition of EES to the PGU-ORC system was beneficial for most locations in terms of operational cost, CDE, and PEC reductions. This paper, in addition to a conference paper on the same subject [42], is a summary of the research completed for this thesis.

1.4 Objective

The main objective of this thesis is to evaluate the effect of using EES on the performance of a PGU-ORC system in which the waste heat from a PGU is used to generate and to store electricity using an ORC coupled with EES. Then, the electricity that is stored in the EES (battery) could be used during system operation at different times of the day so that the PGU does not have to continuously operate. This PGU-ORC-EES was modeled as presented in the methodology and was evaluated by comparing it to a conventional system in terms of operational cost, PEC, and CDE reductions. The effect of climate conditions on the proposed PGU-ORC-EES system was also evaluated by simulating a building in different climate zones in the US and comparing the resulting operational cost, PEC, and CDE reductions between locations.

CHAPTER II

METHODOLOGY

2.1 PGU-ORC-EES System Configuration and Modeling Equations

The mathematical model for the PGU-ORC-EES system, illustrated in Fig. 2.1, is presented in this chapter. In this hourly model, EES (a battery) is implemented to meet the building electric demand, E_b, for as long its capacity allows while the PGU is nonoperational. Then, the PGU, which is modeled as a natural gas generator, is operated to meet the building electric demand, while the waste heat from the PGU is recovered to operate an ORC, which is used to re-charge the EES device. Hourly building electric demand is obtained from EnergyPlus [43] software simulated for a full-service restaurant benchmark building for different locations in different climate zones in the US. The PGU is operated FEL so it always satisfies the building electric demand. When the PGU is not operating, the battery is used to meet building electric demand, and no supplemental electricity needs to be imported from the utility grid.

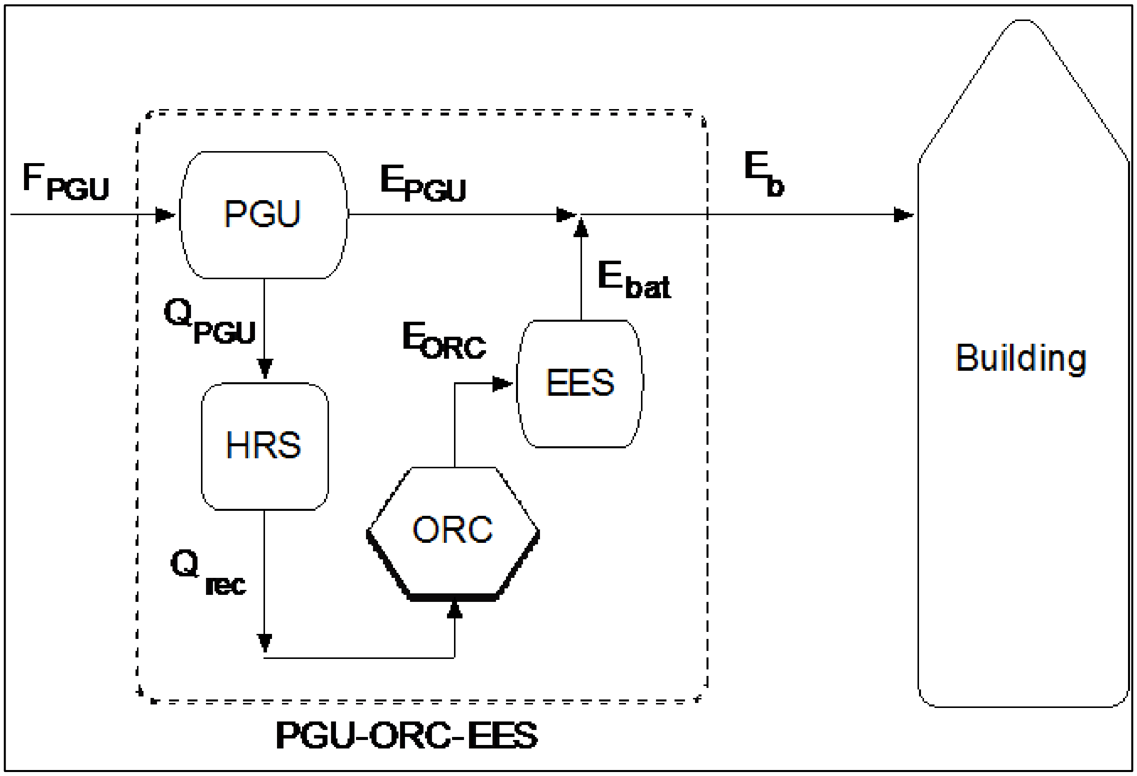


Figure 2.1 Schematic of proposed PGU-ORC-EES system

For the battery, a nominal capacity, E_{batMAX}, is assumed. The battery is assumed to be initially charged, and the PGU-ORC-EES system is first operated using the stored electric energy. Battery energy losses occur during charging, discharging, and self-discharging; however, all battery energy losses are lumped at the discharge side of the battery to simplify the simulations. An efficiency factor for the battery, ξ_{bat}, is assumed to account for this hourly energy loss. Thus, the energy required from the building and the energy discharged from the battery follow the following relationship

$$E_{discharge} = \frac{E_b}{\xi_{bat}} \tag{2.1}$$

where $E_{discharge}$ represents the electricity discharged from the battery. The remaining battery capacity is then

$$E_{bat,t} = E_{bat,t-\Delta t} - E_{discharge,t} \tag{2.2}$$

where $E_{bat,t}$ is the capacity of the battery at a given time, *t*, and Δt is the hourly time step.

Once the battery reaches its minimum recommended storage threshold, i.e., its minimum capacity, the PGU turns on and follows the electric load to meet the building's electric demand, and the ORC is employed to re-charge the battery to its maximum capacity.

The hourly electric output of the PGU, E_{PGU}, is prescribed to fully meet the hourly building electric demand at any time *t* as follows:

$$E_{PGU,t} = E_{b,t} \tag{2.3}$$

The fuel energy required to operate the PGU is modeled as a function of energy output as follows

$$F_{PGU,t} = A \cdot E_{PGU,t} + B \cdot E_{PGUnom} \tag{2.4}$$

where *A* and *B* are constants derived from curve-fitting engine performance data and E_{PGUnom} is the nominal PGU capacity [28]. The waste energy available from the PGU operation is

$$Q_{PGU} = F_{PGU} - E_{PGU} \tag{2.5}$$

The heat that can be recovered by the heat recovery system (HRS) and used to operate the ORC can be estimated as

$$Q_{rec} = Q_{PGU} \cdot \xi \cdot \eta_{HRS} \tag{2.6}$$

where ξ is a factor accounting for energy losses from the PGU, and η_{HRS} is the efficiency of the HRS. The electrical output of the ORC, E_{ORC}, is modeled by assuming an ORC efficiency, η_{ORC}, such that:

$$E_{ORC} = \eta_{ORC} \cdot Q_{rec} \tag{2.7}$$

The electrical output of the ORC is used to charge the battery while the PGU is operating, and the battery is allowed to charge to maximum capacity before the PGU stops operating and again allows the battery to discharge. The charging battery is modeled as follows, up to the maximum battery capacity:

$$E_{bat,t} = E_{bat,t-\Delta t} + E_{ORC,t} \tag{2.8}$$

2.2 PGU-ORC-EES System Performance Calculations

The performance of the PGU-ORC-EES system is determined according to the fuel energy required to operate the PGU, while the performance of a comparative conventional system, where electricity is purchased exclusively from the utility grid, is determined according to the amount of electricity that would have to be purchased from the grid. Therefore, the operational cost of the PGU-ORC-EES system, $Cost_{PGU-ORC-EES}$, and the conventional case, $Cost_{conv}$, to provide all the electricity needed by the facility can be estimated as:

$$Cost_{PGU-ORC-EES} = Cost_f \cdot F_{PGU} \tag{2.9}$$

$$Cost_{conv} = Cost_e \cdot E_b \tag{2.10}$$

where $Cost_f$ and $Cost_e$ are the cost of fuel and electricity, respectively.

The reduction of operational cost of the PGU-ORC-EES system over the conventional system can be determined as follows

$$Red_{Cost} = \frac{Cost_{conv} - Cost_{PGU-ORC-EES}}{Cost_{conv}} \quad (2.11)$$

It is important to highlight that the cost associated with satisfying the thermal load of the building is not described here since it is the same for both cases (PGU-ORC-EES system and conventional) and therefore will cancel out while determining the cost reduction using Eq. 2.11.

The CDE of the PGU-ORC-EES system, $CDE_{PGU-ORC-EES}$, and the conventional case, CDE_{conv}, to provide all the electricity needed by the facility can be estimated as:

$$CDE_{PGU-ORC-EES} = CF_{CDE,f} \cdot F_{PGU} \quad (2.12)$$

$$CDE_{conv} = CF_{CDE,e} \cdot E_b \quad (2.13)$$

where $CF_{CDE,f}$ and $CF_{CDE,e}$ are the CDE conversion factors for fuel and electricity, respectively. The reduction of CDE of the PGU-ORC-EES system over the conventional system can be determined as

$$Red_{CDE} = \frac{CDE_{conv} - CDE_{PGU-ORC-EES}}{CDE_{conv}} \quad (2.14)$$

Finally, the PEC of the PGU-ORC-EES system, $PEC_{PGU-ORC-EES}$, and the conventional case, PEC_{conv}, to provide all the electricity needed by the facility can be estimated as:

$$PEC_{ORC} = CF_{PEC,f} \cdot F_{PGU} \quad (2.15)$$

$$PEC_{conv} = CF_{PEC,e} \cdot E_b \quad (2.16)$$

The reduction of PEC of the PGU-ORC-EES system over the conventional system can be determined as follows

$$Red_{PEC} = \frac{PEC_{conv} - PEC_{PGU-ORC-EES}}{PEC_{conv}} \quad (2.17)$$

where $CF_{PEC,f}$ and $CF_{PEC,e}$ are the PEC conversion factors for fuel and electricity, respectively. Note that in Eqs. (2.11), (2.14), and (2.17) a positive reduction value indicates savings of PGU-ORC-EES over the conventional reference case.

CHAPTER III

RESULTS

3.1 System Performance Analysis

To evaluate the potential of the proposed PGU-ORC-EES system, in terms of operational cost, PEC, and CDE reduction, using the model described in Chapter 2, the electricity requirements of the facility need to be known. The performance of a PGU-ORC-EES system was analyzed for a full-service restaurant benchmark building located in different climate zones of the U.S. [44]. This building is presented in Figs. 3.1 and 3.2 along with some important information about the building in Table 3.1 [45]. The selected benchmark building was simulated over a year with Energy Plus software [43] for the selected locations. The climate zones for these selected locations, and other locations in the U.S., can be seen in Fig. 3.3 [44]. The hourly results from the simulations (hourly electric loads) were used as inputs to the model described in Chapter 2. The yearly electricity requirement, the maximum and minimum hourly requirement, and the hourly average requirement for the evaluated building for all the selected locations are presented in Table 3.2. The maximum electricity requirement was 382,421 kWh/year for Miami, and the minimum electricity requirement was 294,519 kWh/year for Fairbanks. Since the maximum hourly electricity requirement is different for the selected locations, the PGU size used in the simulations varied with the location and was sized to be equal to the maximum load required for each location. The selected PGU sizes for each climate zone are presented in Table 3.3. The PGU sizes ranged between 55 kW to 80 kW. The values used for the simulation of the PGU-ORC-EES system such as the PGU efficiency constants, the efficiencies of the heat recovery system and of the ORC system, the battery capacity, the factor that accounts for PGU energy losses before moving through the heat recovery system, and the battery efficiency factor are presented in Table 3.4. These values have been assumed on the basis of typical performance parameters, manufacturer data [46], and engineering judgment. The cost, CDE conversion factors, and the PEC factors for electricity and fuel (natural gas) for the different climate zones are presented in Table 3.5. Table 3.6 presents the values of $R_{cost} = \frac{Cost_e}{Cost_f}$, $R_{CDE} = \frac{CF_{CDE,e}}{CF_{CDE,f}}$, and $R_{PEC} = \frac{CF_{PEC,e}}{CF_{PEC,f}}$ for the different climate zones.

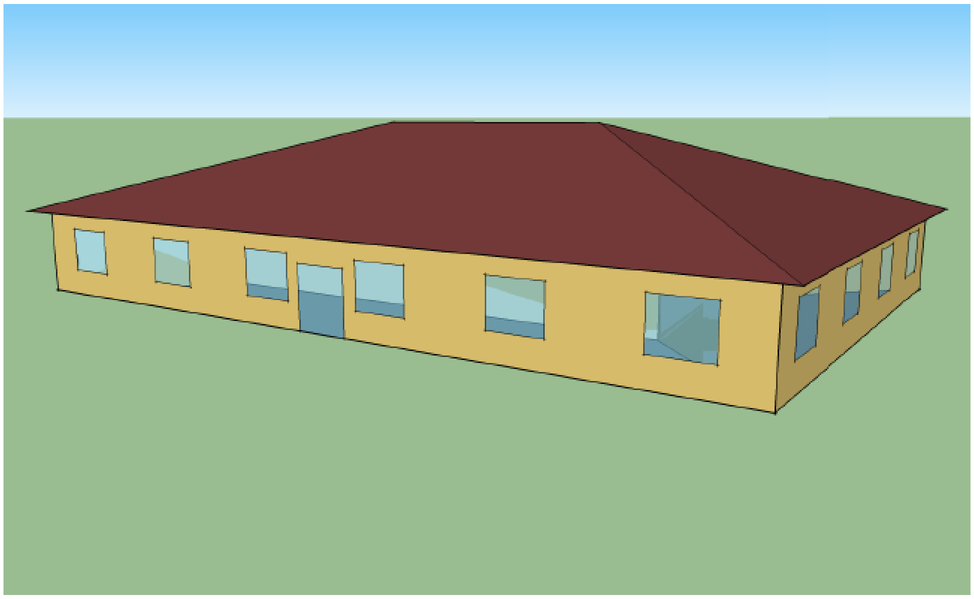


Figure 3.1 Front view of full-service restaurant benchmark building [45]

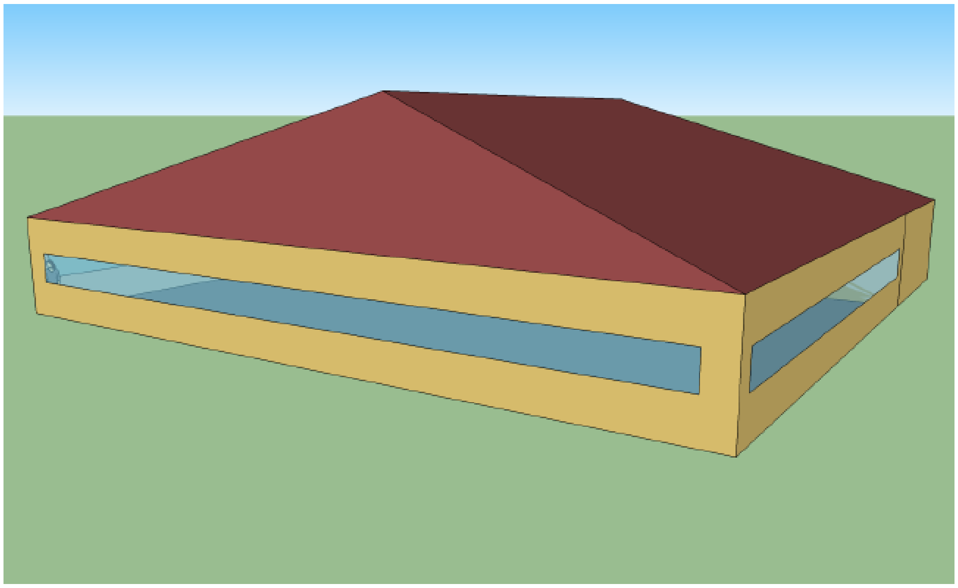
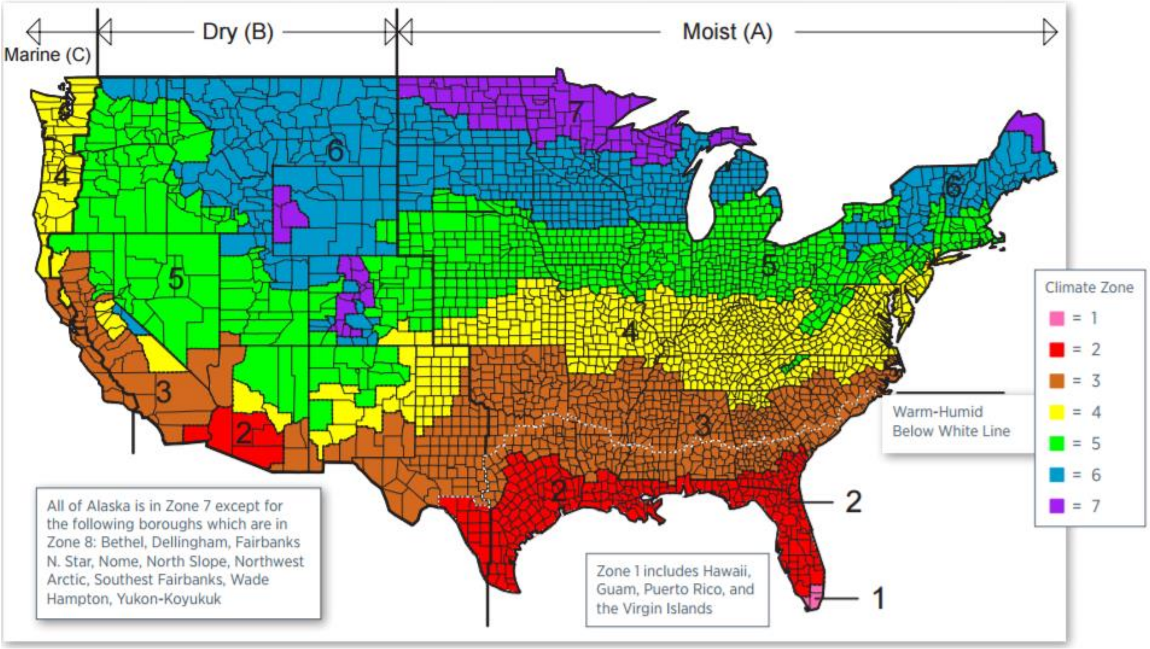


Figure 3.2 Back view of full-service restaurant benchmark building [45]

Table 3.1 Full-service restaurant benchmark building information [45]

Floor Area (ft^2)	5500
Stories	1
Zones	2
Window to Wall Ratio (%)	17.1
HVAC System	Packaged Single Zone (PSZ) AC with Gas Furnace and Economizer



All of Alaska is in Zone 7 except for the following boroughs which are in Zone 8: Bethel, Dellingham, Fairbanks N. Star, Nome, North Slope, Northwest Arctic, Southest Fairbanks, Wade Hampton, Yukon-Koyukuk

Zone 1 includes Hawaii, Guam, Puerto Rico, and the Virgin Islands

Figure 3.3 Climate zones of the U.S. [44]

Table 3.2 Electricity requirements for the restaurant building for different locations [43]

Location	E_{total} (kWh/year)	E_{max} (kWh)	E_{min} (kWh)	$E_{average}$ (kWh)
1A-Miami	382,421	70.2	14.8	43.7
2A-Houston	357,911	71.8	14.6	40.9
2B-Phoenix	361,424	80.0	14.6	41.3
3A-Atlanta	329,281	71.5	14.6	37.6
3B-Las Vegas	344,056	77.2	14.6	39.3
3C-San Francisco	297,190	59.2	14.7	33.9
4A-Baltimore	320,404	70.6	14.6	36.6
4B-Albuquerque	321,125	69.1	14.6	36.7
5A-Chicago	311,883	68.8	14.6	35.6
6A-Minneapolis	310,039	67.7	14.6	35.4
7A-Duluth	298,561	57.5	14.6	34.1
8A-Fairbanks	294,519	54.6	10.7	33.6

Table 3.3 PGU size for each location

Location	PGU Size (kW)
Miami	70
Houston	71
Phoenix	80
Atlanta	71
Las Vegas	78
San Francisco	60
Baltimore	70
Albuquerque	70
Chicago	69
Minneapolis	68
Duluth	58
Fairbanks	55

Table 3.4 Parameters used in the simulations for all locations

HRS Efficiency, η_{HRS}	0.8
PGU Energy Loss Factor, ξ	0.95
ORC Efficiency, η_{ORC}	0.2
Heating System Efficiency, η_h	0.9
PGU Efficiency constant A [46]	2.3698
PGU Efficiency constant B [46]	1.0322
Initial Battery charge (kWh)	250
Battery efficiency factor, ξ_{bat}	0.95

Table 3.5 Cost [47, 48], emissions conversion factors [49], and primary energy conversion for electricity [50] and natural gas [51] by location

	1A- Miami	2A- Houston	2B- Phoenix	3A- Atlanta	3B-Las Vegas	3C- San Francisco	4A- Baltimore	4B- Albuquerque	5A- Chicago	6A- Minneapolis	7A- Duluth	8A- Fairbanks
$Cost_f$ (\$/kWh)	0.0338	0.0215	0.0304	0.0316	0.0241	0.0229	0.0325	0.0205	0.0252	0.0207	0.0207	0.0263
$Cost_e$ (\$/kWh)	0.0981	0.082	0.1076	0.1044	0.1014	0.1789	0.1105	0.1147	0.0877	0.101	0.101	0.1796
$F_{CDE,f}$ (kg/kWh)	0.181	0.181	0.181	0.181	0.181	0.181	0.181	0.181	0.181	0.181	0.181	0.181
$F_{CDE,e}$ (kg/kWh)	0.543	0.553	0.534	0.614	0.534	0.277	0.454	0.534	0.682	0.697	0.697	0.57
$F_{PEC,f}$	1.047	1.047	1.047	1.047	1.047	1.047	1.047	1.047	1.047	1.047	1.047	1.047
$F_{PEC,e}$	3.05	3.16	3.06	3.2	2.92	2.45	3.25	3.27	3.5	3.53	3.53	2.9

Table 3.6 R_{cost}, R_{CDE}, and R_{PEC} for all locations

	1A- Miami	2A- Houston	2B- Phoenix	3A- Atlanta	3B- Las Vegas	3C- San Francisco	4A- Baltimore	4B- Albuquerque	5A- Chicago	6A- Minneapolis	7A- Duluth	8A- Fairbanks
R_{cost}	2.90	3.81	3.54	3.30	4.21	7.81	3.40	5.60	3.48	4.88	4.88	6.83
R_{CDE}	3.00	3.06	2.95	3.39	2.95	1.53	2.51	2.95	3.77	3.85	3.85	3.15
R_{PEC}	2.91	3.02	2.92	3.06	2.79	2.34	3.10	3.12	3.34	3.37	3.37	2.77

As shown in Table 3.4, the battery was initially charged to its full capacity of 250 kWh. The simulation started using the battery until it was discharged beyond capacity to meet building demand after several hours. The PGU then generates the power required for the facility. During this process, the waste heat from the PGU is used to generate electricity through the ORC, and the electricity from the ORC recharges the battery.

Figure 3.4 illustrates the yearly percentage of the cost reduction for each location. This figure shows that the PGU-ORC-EES system is able to reduce operational cost for all the selected locations with respect to the conventional case. The highest reduction was obtained for San Francisco, 63.8%, while the lowest reduction was obtained for Miami, 2.7%. In addition, it can be clearly seen that with higher values of R_{cost}, better cost savings can be achieved from the PGU-ORC-EES system operation. San Francisco has an R_{cost} value of 7.8 while Miami has an R_{cost} value of 2.9. Results also indicate that an R_{cost} value lower than 2.9 may or may not give any potential cost savings for the evaluated system.

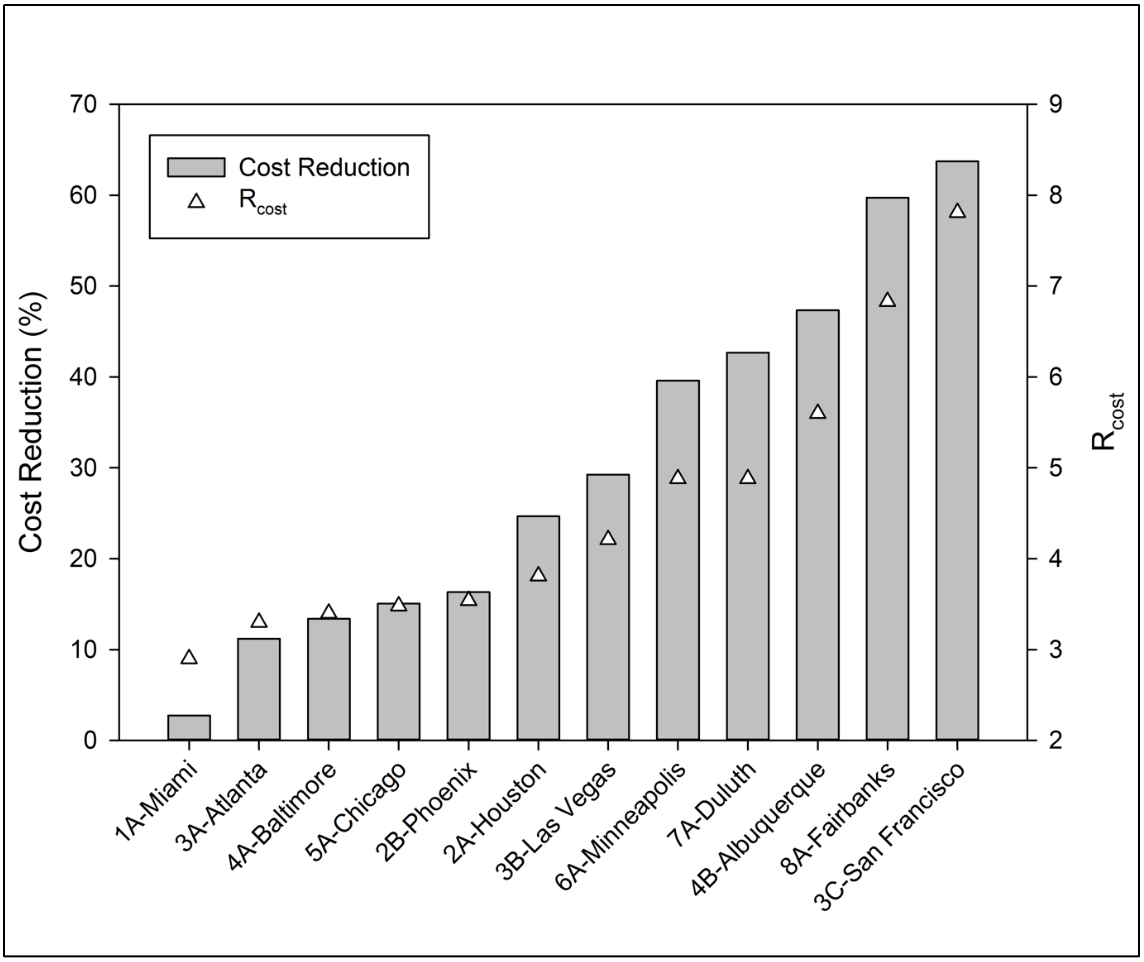


Figure 3.4 Yearly percentage operational cost reduction for each location

Figure 3.5 shows the yearly percentage of the CDE reduction for each location. This figure illustrates that the PGU-ORC-EES system is not able to reduce CDE for all the selected locations with respect to the conventional case. For San Francisco and Baltimore, the PGU-ORC-EES system generates more CDE than the conventional case. For San Francisco, the proposed system increases the CDE by about 85% and, for Baltimore, by about 17.4%. For Phoenix, Las Vegas, and Albuquerque, system performance is almost the same as the conventional case. The highest reduction in CDE was obtained from Duluth, 27.4%. Similar to the previous case, there is a strong correlation between the value of R_{CDE} and the potential CDE savings. The lowest R_{CDE} was 1.5 for San Francisco, which is the location with the worst performance. On the other hand, the highest R_{CDE} was 3.9 for Duluth, which is the city with the highest CDE reduction. Results also indicate that an R_{CDE} value lower than 2.9 may or may not give any potential cost savings for the evaluated system. This is supported by the fact that Albuquerque has an R_{CDE} value of 2.95 and only provides 0.2% of CDE reduction.

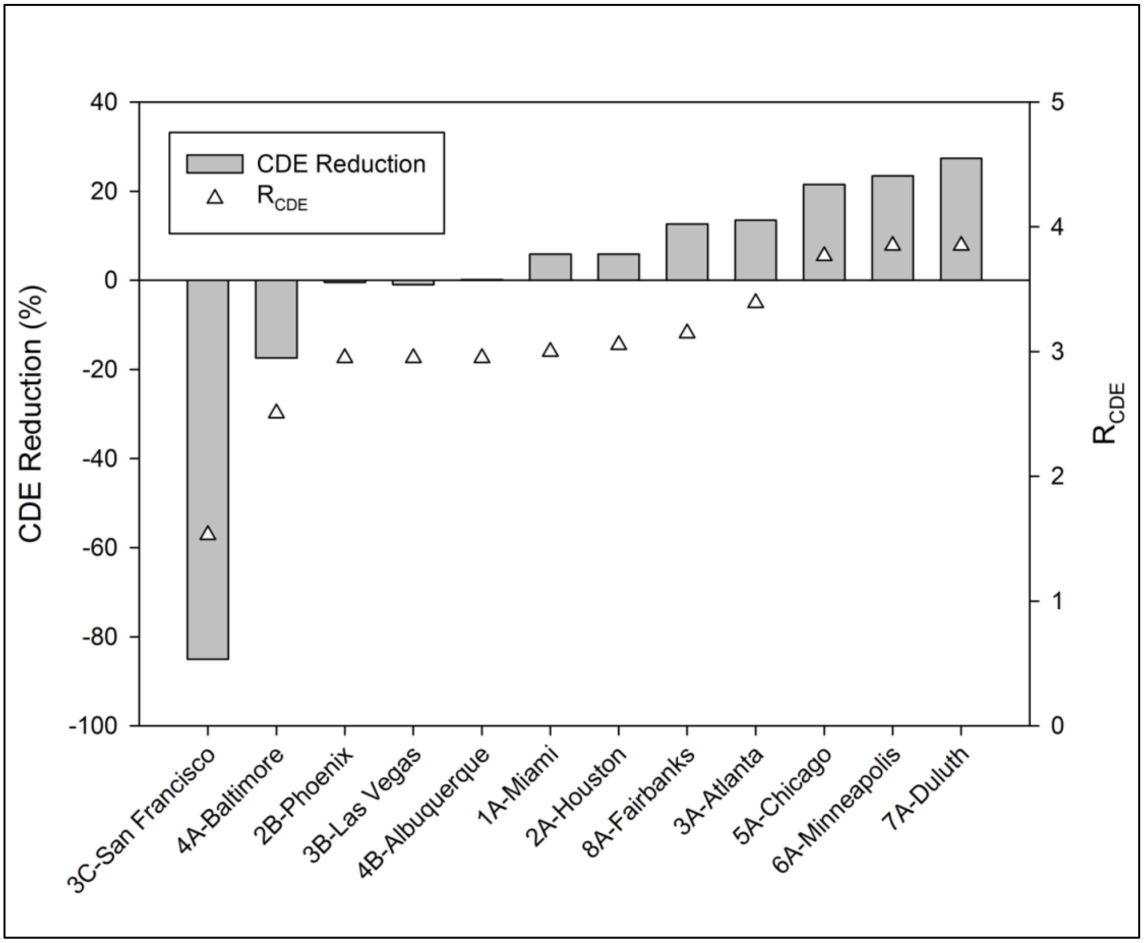


Figure 3.5 Yearly percentage CDE reduction for each location

Figure 3.6 illustrates the yearly percentage of the PEC reduction for each location. This figure shows that, except for San Francisco, the PGU-ORC-EES system is able to reduce PEC for all selected locations with respect to the conventional case. For San Francisco the proposed system increases the PEC by about 21%. For Fairbanks and Las Vegas, the system performance is almost the same as the conventional case. The highest reduction in PEC was obtained from Duluth, 17%. Similar to the previous case, there is a strong correlation between the value of R_{PEC} and the potential PEC savings. The lowest R_{PEC} was 2.3 for San Francisco, which is the location with the worst performance. On the other hand, the highest R_{PEC} was 3.4 for Duluth, which is the city with the highest PEC reduction. Results also indicate that an R_{PEC} value lower than 2.9 may or may not give any potential PEC savings for the evaluated system. Las Vegas and Fairbanks have R_{PEC} values of 2.8 and 2.7, respectively, and the system performance is the same as the reference case.

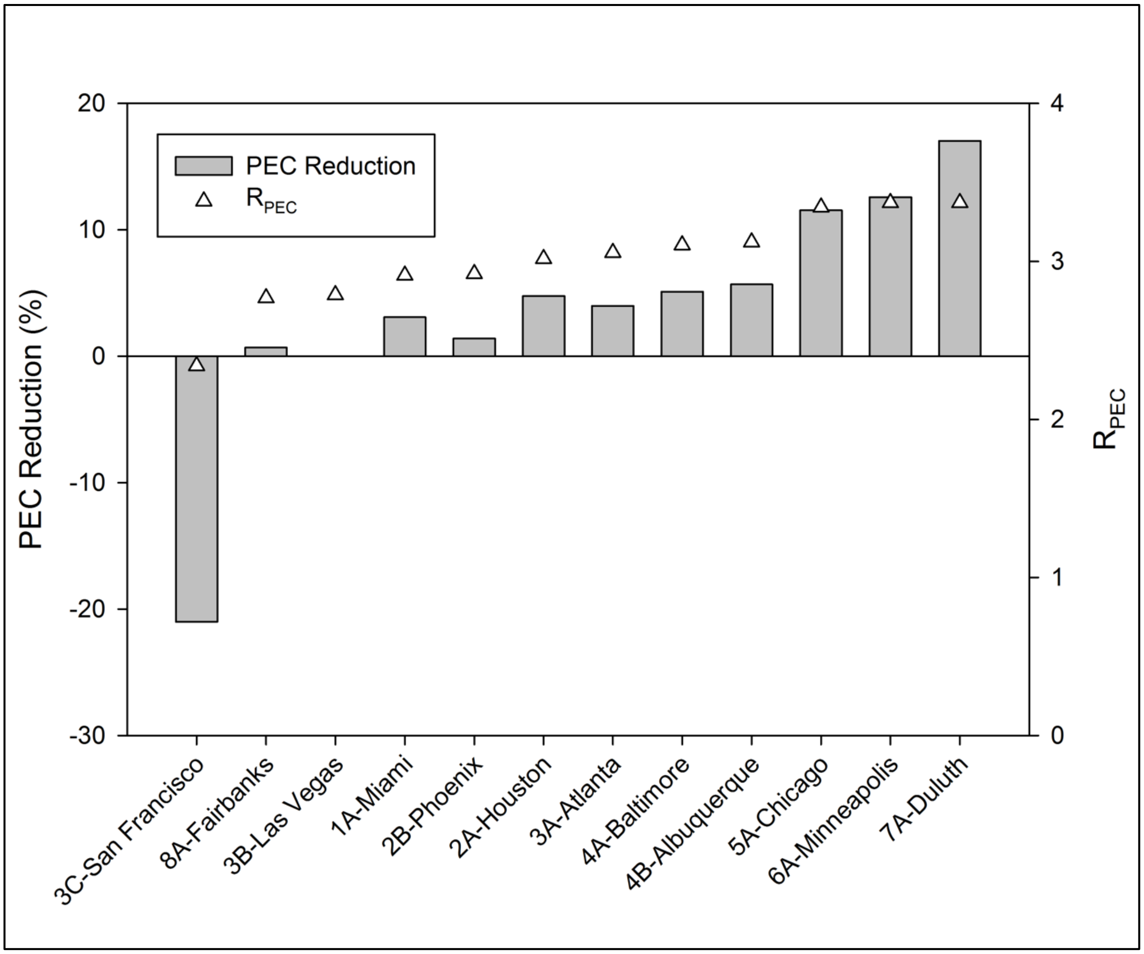


Figure 3.6 Yearly percentage PEC reduction for each location

3.2 System Parametric Analysis

To illustrate the performance of the system each month, the results from the facility simulated in Chicago were used. Figure 3.7 illustrates the number of hours per month that the battery was able to operate to supply electricity to the facility. On average the battery ran for about 246 hours per month with the highest number of hours of operation at 260 hours, for the month of January, while the lowest was for February at 224 hours. Overall, the battery operates about 2,948 hours/year, which represents about

33.6% of the total yearly operational time. Dependent on the usage demands, the 250 kWh battery was able to supply about 4-10 hours of electric demand before discharging beyond usage capability where the battery's electricity level at a given hour is less than the building's electric demand.

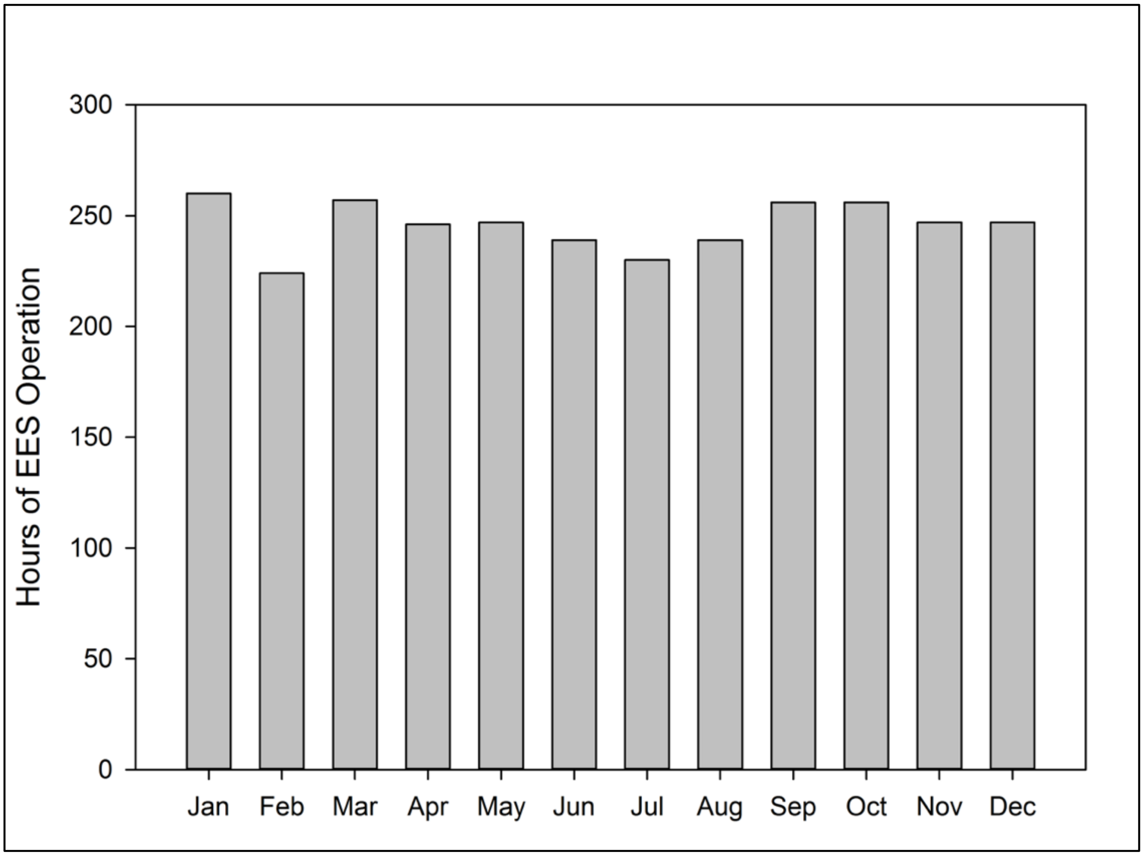


Figure 3.7 Battery usage per month (250 kWh battery capacity) in Chicago, IL

Figure 3.8 shows the reduction of the operational cost, CDE, and PEC (over the conventional case) for each month for Chicago, IL. Results indicate that the proposed PGU-ORC-EES system is able to reduce the three parameters for the whole year. In terms of cost, the proposed system was able to reduce the yearly operational cost by an average of 15%. The maximum reduction in cost was obtained for the month of July, 17.9%, while the lowest reduction was obtained for the month of February, 13.1%. Similarly, the proposed system was able to reduce the yearly CDE by an average of 21.5%. The maximum CDE reduction was obtained during July, 24.1%, while the lowest was obtained for the month of February, 19.7%. Finally, the proposed system was able to reduce the yearly PEC by an average of 11.6%. The maximum reduction of PEC was obtained for the month of July, 14.5%, while the lowest reduction was obtained for the month of February, 9.5%.

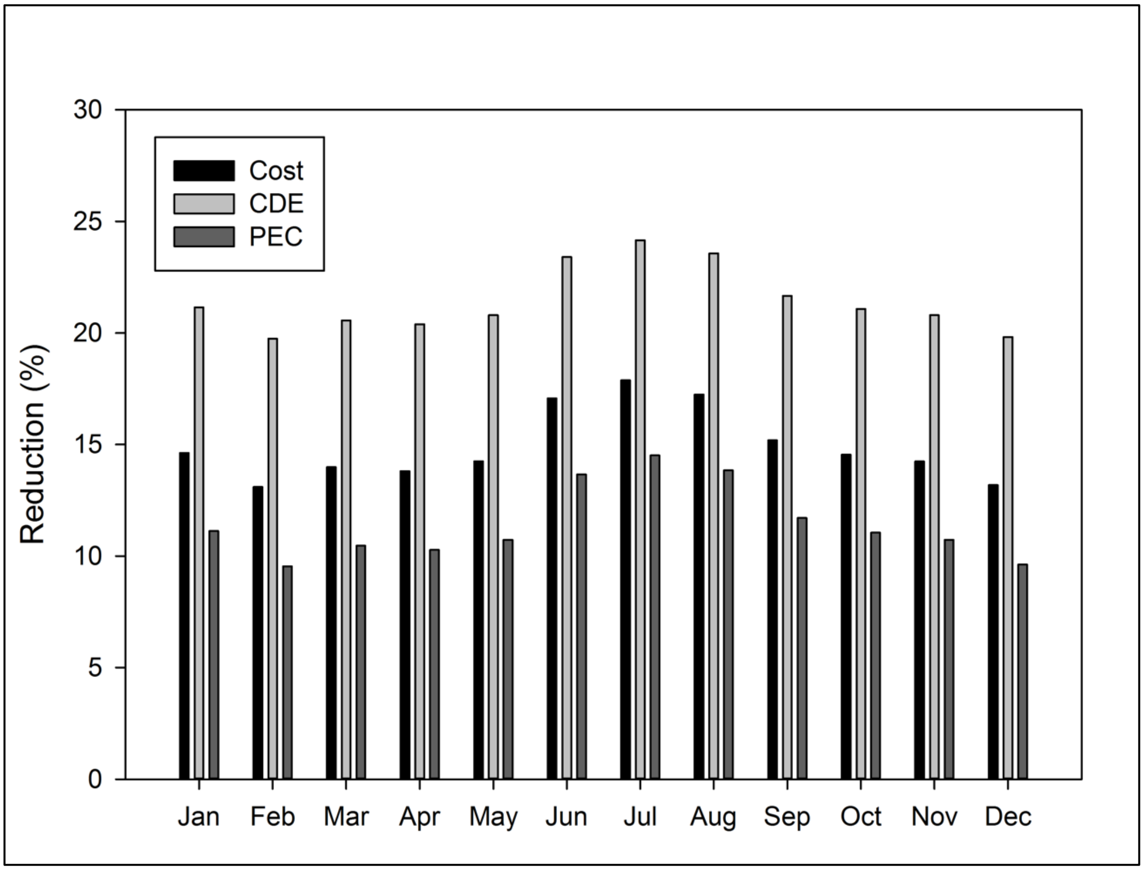


Figure 3.8 Monthly percentage operational cost, CDE, and PEC reduction in Chicago, IL

Figure 3.9 illustrates the effects of R_{cost}, R_{CDE}, and R_{PEC} on the reduction of the yearly operational cost, CDE, and PEC, respectively, for the system evaluated in Chicago. As can be seen in the figure, higher R values indicate better potential of the proposed system to achieve more reductions as compared with the conventional case. For any R values below 2.90 the system may not be able to provide any cost, CDE, or PEC savings. These results could be used to estimate if the system would be able to potentially provide savings for the evaluated locations.

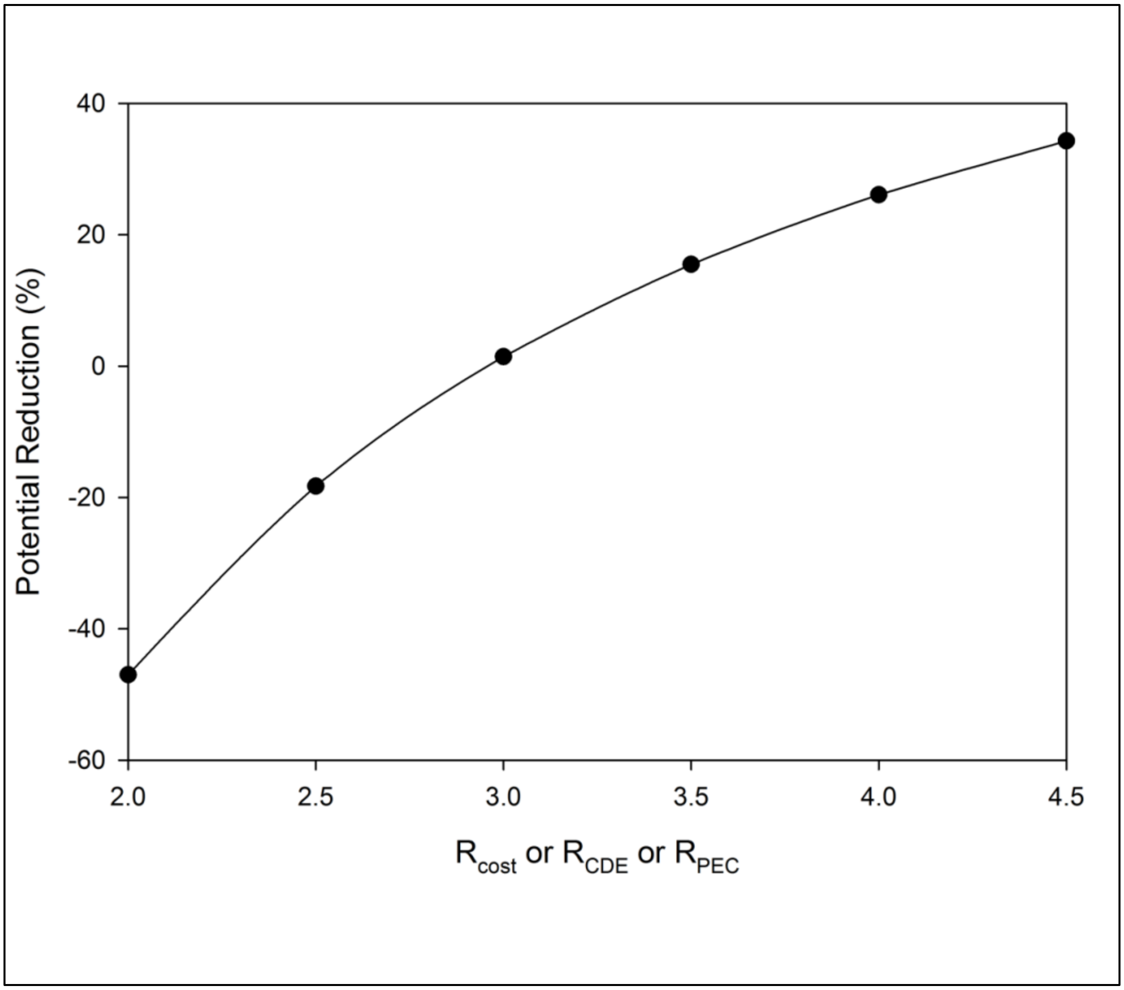


Figure 3.9 Variation effect of R_{cost}, R_{CDE}, and R_{PEC} on potential operational cost, CDE, and PEC reductions, respectively, in Chicago, IL

Figure 3.10 shows the effect of the battery capacity on the reduction of cost over the conventional system. For all the parameters it is clear that increasing the battery capacity will provide more benefits. However, the capital cost needed for the increased capacity battery may negate the operational cost reductions. The reduction in operational cost ranges from 8.2% for a 50 kWh battery to 15.4% for a 500 kWh battery. In terms of the percent of battery usage, a 50 kWh battery is able to provide power to the facility for about 28.5% of the time while a larger 500kWh battery would be able to provide electricity 33.3% of the time.

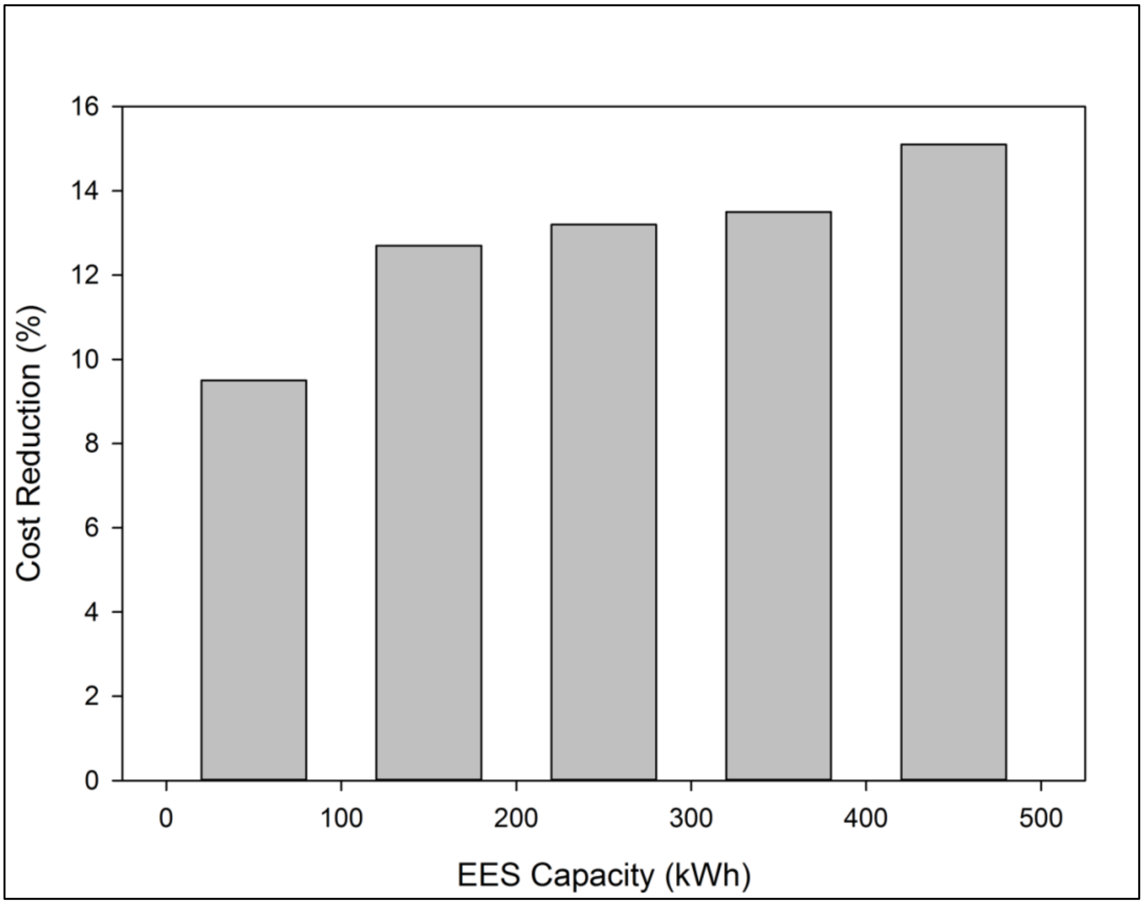


Figure 3.10 Battery capacity effect on operational cost reduction in Chicago, IL

Figure 3.11 illustrates the capital cost available for different payback periods for the 50kWh and 250 kWh battery capacities. This figure shows that for the 250 kWh capacity with a desired payback period of 1 year, the capital cost available would be about $4,133, while for a 5-year payback period, the capital cost available would be about $20,665. On the other hand, for the 50 kWh capacity for a desired payback period of 1 year, the capital cost available would be about $2,722, while for a 5-year payback period, the capital cost available would be about $13,620. In addition to capital cost, designers and engineers need to carefully consider all of the financial incentives available for the installation of these types of systems for different locations [52].

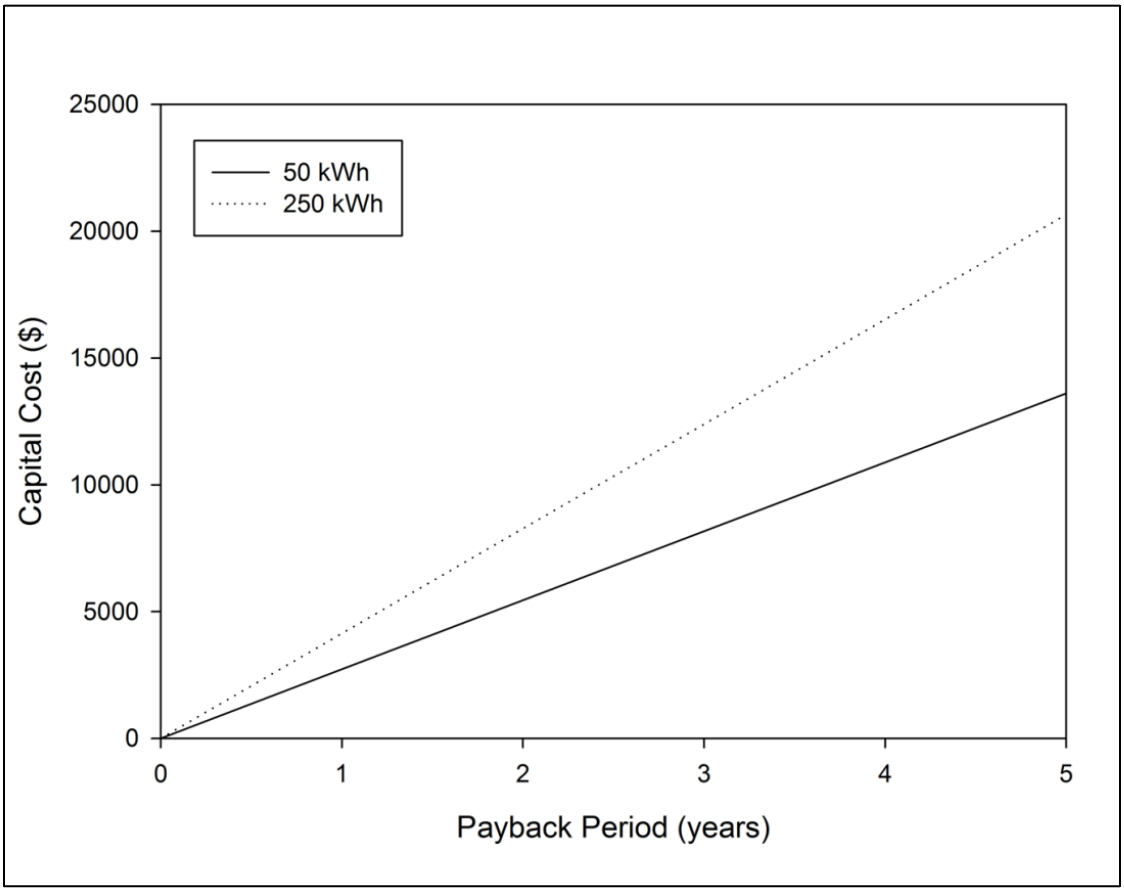


Figure 3.11 Capital cost available for different payback periods

CHAPTER IV

CONCLUSIONS

This research evaluated the potential of a PGU-ORC-EES system to reduce the operational cost, CDE, and PEC compared with a conventional system. The potential of the proposed PGU-ORC-EES system was assessed by evaluating the performance of simulations of a restaurant facility in twelve different geographical locations reflecting a variety of climate conditions. Results indicated that the addition of EES is beneficial to the PGU-ORC system for most locations in terms of the three evaluated parameters.

In terms of operational cost, the PGU-ORC-EES system was able to reduce this cost for all of the selected locations with respect to the conventional case. In terms of CDE, the PGU-ORC-EES system was not able to reduce the CDE for all the selected locations with respect to the conventional case. For some locations, such as San Francisco and Baltimore, the PGU-ORC-EES system generated more CDE than the conventional case. In terms of PEC, the PGU-ORC-EES system was able to reduce PEC for all selected locations with respect to the conventional case, except for the city of San Francisco. On the other hand, for Fairbanks and Las Vegas, the system performance was almost the same as the conventional case.

Furthermore, results indicated that higher values of R_{cost}, R_{PEC}, and R_{CDE} indicated better reductions in cost, PEC and CDE, respectively, from the PGU-ORC-EES system operation. For the evaluated case in Chicago, results show that a value of R_{cost},

R_{PEC}, or R_{CDE} greater than 2.9 indicates that the proposed PGU-ORC-ES may be able to reduce the cost, PEC, and CDE with respect to the conventional system. Further investigation would have to be performed to confirm this indication.

The monthly performance of the PGU-ORC-EES restaurant facility simulations in Chicago showed that the battery operated about a third of the total operation time with the highest monthly operation hours during January and March at around 260 hours and the lowest monthly operation hours in February at 224 hours. The maximum monthly cost, CDE, and PEC reductions in Chicago occurred during July with reductions of 17.9%, 24.1%, and 14.5% respectively. While the minimum monthly cost, CDE, and PEC reductions in Chicago occurred during February with reductions of 13.1%, 19.7%, and 9.5% respectively. For this city, the reduction in operational cost was between 8.2% for a 50 kWh battery and 15.4% for a 500 kWh battery. A payback period analysis showed that for a 250 kWh capacity battery and a 5-year payback period, the capital cost available would be about \$20,665. On the other hand, for a smaller capacity battery of 50 kWh, the capital cost available would be around \$13,620.

REFERENCES

[1] Rosen, M. A., Le, M. N., and Dincer, I., 2005. Efficiency Analysis of a Cogeneration and District Energy System. *Applied Thermal Engineering,* 25(1), pp. 147-159.

[2] Mago, P. J., Fumo, N., and Chamra, L. M., 2009. Performance Analysis of CCHP and CHP Systems Operating Following the Thermal and Electric Load. *International Journal of Energy Research*, 33(9), pp. 852-864.

[3] Wang, J-J., Jing, Y-Y., Zhang, C-F., and Zhai, Z-J., 2011. Performance Comparison of Combined Cooling Heating and Power System in Different Operation Modes. *Applied Energy,* 88(12), pp. 4621-4631.

[4] Mago, P.J., and Chamra, L.M., 2009. Analysis and Optimization of CCHP Systems Based on Energy, Economical, and Environmental Considerations. *Energy and Buildings,* 41(10), pp. 1099-1106.

[5] Mago, P. J., Chamra, L. M., and Hueffed, A., 2009. A Review on Energy, Economical, and Environmental Benefits of the Use of CHP Systems for Small Commercial Buildings for the North American Climate. *Internal Journal of Energy Research,* 33, pp. 1252-1265.

[6] Fumo, N., Mago, P. J., and Smith, A. D., 2011. Analysis of Combined Cooling, Heating, and Power Systems Operating Following the Electric Load and Following the Thermal Load Strategies with No Electricity Export. *Proceedings of the Institution of Mechanical Engineers,* Part A: Journal of Power and Energy, 25(8), pp. 1016-1025.

[7] Caliano, M., Bianco, N., Graditi, G., and Mongibello, L., 2016. Economic optimization of a residential micro-CHP system considering different operation strategies. *Applied Thermal Engineering*, 101, pp. 592-600.

[8] Somma, M. Di., Yan, B., Bianco, N., Graditi, G., Luh, P.B., Mongibello, L., and Naso, V., 2015. Operation optimization of a distributed energy system considering energy costs and exergy efficiency. *Energy Conversion and Management*, 103, pp. 739-751.

[9] Mago, P. J., and Luck, R., 2013. Evaluation of a Base-Loaded Combined Heating and Power System with Thermal Storage for Different Small Building Applications. *International Journal of Energy Research*, 37, pp. 179-188.

[10] Mago, P.J., Luck, R., and Smith A.D., 2011. Environmental evaluation of base-loaded CHP systems for different climate conditions in the US. *International Journal of Ambient Energy,* 32(4), pp. 203-214.

[11] Hueffed, A.K., and Mago, P.J., 2010. Influence of prime mover size and operational strategy on the performance of combined cooling, heating, and power systems under different cost structures. *Energy and Buildings,* 42(10), pp. 1628-1636.

[12] Maizza, V., and Maizza, A., 1996. Working Fluids in Non-Steady Flows for Waste Energy Recovery Systems. *Applied Thermal Engineering*, 16 (7) pp. 579-590.

[13] Maizza, V., and Maizza, A., 2001. Unconventional Working Fluids in Organic Rankine-Cycles for Waste Energy Recovery Systems, *Applied Thermal Engineering*, 21 (3), pp. 381-390.

[14] Vijayaraghavan, S., and Goswami, D. Y., 2005. Organic Working Fluids for a Combined Power and Cooling Cycle. *ASME Journal of Energy Resources Technology,* 127, pp. 125-130.

[15] Gao, H., Liu, C., He, C., Xu, X., Wu, S., and Li, Y., 2012. Performance Analysis and Working Fluid Selection of a Supercritical Organic Rankine Cycle for Low Grade Waste Heat Recovery. *Energies*, 5, pp. 3233-3247.

[16] Yu, Z., Tan, G., He, T., and Guo, X. et al., 2016. The Selection of Working Fluid Used in the Organic Rankine Cycle System for Hydraulic Retarder. *SAE Technical Paper 2016-01-0187,* doi:10.4271/2016-01-0187.

[17] Mago, P.J., Chamra, L.M., Srinivasan, K., and Somayaji, C., 2008. An examination of regenerative organic Rankine cycles using dry fluids. *Applied Thermal Engineering,* 28(8-9), pp. 998-1007.

[18] Delgado-Torres, A.M., and García-Rodríguez, L., 2010. Analysis and optimization of the low-temperature solar organic Rankine cycle (ORC). *Energy Conversion and Management,* 51(12) pp. 2846-2856.

[19] Kumar, A., and Shukla, S.K., 2016. Analysis and Performance of ORC Based Solar Thermal Power Plant Using Benzene as a Working Fluid. *Procedia Technology,* 23, pp. 454-463.

[20] Spayde, E., & Mago, P. J., 2015. Evaluation of a solar-powered organic Rankine cycle using dry organic working fluids. *Cogent Engineering*, *2*(1), 1085300.

[21] Quoilin, S., Orosz, M., Hemond, H., and Lemort, V., 2011. Performance and design optimization of a low-cost solar organic Rankine cycle for remote power generation. *Solar Energy,* 85(5), pp. 955-966.

[22] Knizley, A., Mago, P. J., Tobermann, J., and Warren, H. R., 2015. Performance Characterization of a Power Generation Unit-Organic Rankine Cycle System Based on the Efficiencies of the System Components. *Energy Conversion and Management,* 105, pp. 480-487.

[23] Mago, P. J., Hueffed, A., & Chamra, L., 2010. Analysis and Optimization of the Use of CHP-ORC Systems for Small Commercial Buildings. *Energy & Buildings,* 42 (9), pp. 1491-1498.

[24] Fang, F., Wei, L., Liu, J., Zhang, J., and Hou, G., 2012. Complementary configuration and operation of a CCHP-ORC system. *Energy,* 46(1), pp. 211-220.

[25] Anvari, S., Jafarmadar, S., and Khalilarya, S., 2016. Proposal of a combined heat and power plant with regeneration organic Rankine cycle: Energy-Exergy evaluation. *Energy Conversion and Management,* 122, pp. 357-365.

[26] Lecompte, S., Huisseune, H., van den Broek, M., De Schampheleire, S., and De Paepe, M., 2013. Part load based thermo-economic optimization of the Organic Rankine Cycle (ORC) applied to a combined heat and power (CHP) system. *Applied Energy,* 111, pp. 871-881.

[27] Smith, A. D., Mago, P. J., Fumo, N., 2013. Benefits of Thermal Energy Storage Option Combined with CHP System for Different Commercial Building Types. *Sustainable Energy Technologies and Assessments*, 1, pp. 3-12.

[28] Mago, P. J., Luck, R., and Knizley, A., 2014. Combined Heat and Power Systems with Dual Power Generation Units and Thermal Storage. *International Journal of Energy Research,* 38, pp. 896-907.

[29] Verda, V., and Colella, F., 2011. Primary energy savings through thermal storage in district heating networks. *Energy,* 36(7), pp. 4278-4286.

[30] Kostowski, W. and Skorek, J., 2005. Thermodynamic and economic analysis of heat storage application in co-generation systems. *International Journal of Energy Research,* 29(2), pp. 177-188.

[31] Chen, X.P., Wang, Y.D., Yu, H.D., Wu, D.W., Li, Y. and Roskilly, A.P., 2012. A domestic CHP system with hybrid electrical energy storage. *Energy and Buildings,* 55, pp. 361-368.

[32] Bianchi, M., De Pascale, A., and Melino, F., 2013. Performance analysis of an integrated CHP system with thermal and Electric Energy Storage for residential application. *Applied Energy,* 112, pp. 928-93.

[33] Dusonchet, L., Ippolito, M.G., Telaretti, E., Zizzo, G., and Graditi, G., 2013. An optimal operating strategy for combined RES– based Generators and Electric Storage Systems for load shifting applications. *4th international Conference on Power Engineering, Energy, and Electrical Drives,* Istanbul, Turkey, 13-17 May 2013.

[34] Telaretti, E., Graditi, G., Ippolito, M.G., and Zizzo, G., 2016. Economic feasibility of stationary electrochemical storages for electric bill management applications: The Italian scenario, *Energy Policy,* 94, pp. 126-137.

[35] Jenkins, D.P., Fletcher, J., and Kane, D., 2008. Model for evaluating impact of battery storage on microgeneration systems in dwellings. *Energy Conversion and Management,* 49(8), pp. 2413-2424.

[36] Balcombe, P., Rigby, D., and Azapagic, A., 2015. Environmental impacts of microgeneration: integrating solar PV, Stirling engine CHP, and battery storage. *Applied Energy,* 139, pp.245-259.

[37] Aghaei, J., and Alizadeh, M. I., 2013. Multi-objective self-scheduling of CHP (combined heat and power)-based microgrids considering demand response programs and ESSs (Energy Storage Systems), *Energy*, 55, pp. 1044-1054.

[38] Shah, K. K., Aishwarya, S. M., and Pearce, J. M., 2015. Perfmance of U.S. hybrid distributed energy systems: solar photovoltaic, battery, and combined heat and power. *Energy Conversion and Management,* 105, pp. 71-80.

[39] Majjic, L., Krelj, I., and Delimar, M., 2013. Optimal scheduling of a CHP system with energy storage. *Information & Communication Technology Electronics & Microelectronics (MIPRO) 36th International Convention,* Opatija, Croatia, pp. 1253-1257.

[40] Gu, W., Wu, Z., and Yuan, X., 2010. Microgrid economic optimal operation of the combined heat and power system with renewable energy. *IEEE PES General Meeting,* Minneapolis, MN, pp. 1-6.

[41] Warren, H., Mago, P. J., Knizley, A., and Luck, R., 2017. Performance enhancement of a power generation unit-organic Rankine cycle system through the addition of electric energy storage. *Journal of Energy Storage,* 10, pp. 28-38.

[42] Warren, H., Knizley, A., and Mago, P. J., 2016. Effect of electric energy storage on the performance of a power generation unit-organic Rankine cycle system. Proceedings of the ASME 2016 International Mechanical Engineering Congress and Exposition. CD ROM. (Phoenix, Arizona, Nov. 11-17).

[43] U.S. Department of Energy. EnergyPlus Energy Simulation Software. Available at https://energyplus.net.

[44] Guide to Determining Climate Regions by County, PREPARED BY Pacific Northwest National Laboratory. Michael C. Baechler, Theresa L. Gilbride, Pam C. Cole, Marye G. Hefty, and Kathi Ruiz , August 2015. Available at http://www.energy.gov/sites/prod/files/2015/10/f27/ba_climate_region_guide_7.3.pdf.

[45] "Commercial Reference Buildings," https://energy.gov/eere/buildings/commercial-reference-buildings.

[46] Gas generators. Kholer, 2012. Available at: http://www.kohlerpower.com.

[47] U.S. Energy Information Administration – EIA. Available at https://www.eia.gov.

[48] "Average Commercial Price," http://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PCS_DMcf_a.htm.

[49] "eGRID 9th edition Version 1.0 Summary Tables for year 2010 data - eGRID_9th_edition_V1-0_year_2010_Summary_Tables.pdf," http://www.epa.gov/cleanenergy/documents/egridzips/eGRID_9th_edition_V1-0_year_2010_Summary_Tables.pdf.

[50] "Final Report v1 -0008ENERGYEMISSIONFACTORSRESCONSUMPTION.pdf," http://www.aga.org/SiteCollectionDocuments/KnowledgeCenter/OpsEng/CodesStandards/0008ENERGYEMISSIONFACTORSRESCONSUMPTION.pdf.

[51] "Methodology for Incorporating Source Energy Use - site_source.pdf," http://www.energystar.gov/ia/business/evaluate_performance/site_source.pdf.

[52] Zhang, J., Cho, H., and Knizley, A., 2016. Evaluation of financial incentives for combined heat and power (CHP) systems in U.S. regions, *Renewable and Sustainable Energy Reviews,* 59, pp. 738-762.