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RESEARCH ARTICLE

DEVELOPING A COST-OPTIMAL RETROFIT CHP SYSTEM FOR MULTI-FAMILY BUILDINGS USING HISTORICAL DEMAND.

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Abstract

Combined heat and power (CHP) systems are increasingly used in conjunction with traditional grid power for industrial and residential applications. Because many multi-family residences in the US have significant energy savings potential, this study considers a CHP application for an all-electric120-unit multi-family residence in Columbus, Ohio. This building is data rich, with historical consumption of electricity and water available from unit-level meters. ACHP system is considered to meet partial loads for electricity and hot water in order to reduce overall energy cost, when considering a demand sensitive grid power cost pricing schedule. A mathematical model is developed for deploying the CHP and dispatching the generated electric power to the facility and thermal energy to a central hot water tank. This model enables optimal management of the power dispatching in order to reduce overall energy cost. The modelingresults indicate that a CHP with electrical output of 60 kweand a hot-water tank capable of storing 400 kwh of thermal energy will optimally reduce total annual energy costs for the multi-family residence. In this case, the total annual cost is reduced by 23% relative to using only conventional grid power for the building, from $114,850 to $88,336, and the CHP provides 65% of the total demand.Reduction in total carbon emissions for this best case is estimated to be 32%.

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Introduction:-

Multi-family housing energy consumption represents a significant fraction of the total residential energy consumption in the US, where one-third of the population lives in a half a million multi-family buildings[1]. In addition, these buildings are frequentlyenergy inefficient. A recent study documents that rental multi-family residences have much higher energy use intensities (EUI), measured on a per-foot basis,than other categories of housing[2]. However, this is partly due to the smaller size of multi-family apartments. When measured on a per-household basis, researchers report thatmulti-family housing uses the least amount of energy[3]. Multi-family units tend to have fewer efficiency upgrades than owner-occupied dwellings, andrenters who do not pay utilities directly use an estimated 30% more energy for heating than renters who pay their own utilities[4]. Furthermore, even when renters directly pay theirown utility costs, the building owners lack incentive to invest in efficiency improvements. This problem is referred to as the split incentive barrier, and it contributes to the efficiency gap formulti-family housing[5].

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Upgrading the multi-family building sector has the potential to improve its energy efficiency by about 30%, and reduce overall CO2 emissions in the US by 50 to 100 million tons per year[6]. Potential energy cost savings are estimated to be $3.4 billion per year, according to the American Council for Energy-Efficient Economy. There are often tax incentives for efficiency upgrades to help realize these savings. Other options, such as programs to educate building owners, are being explored to improve this problem [7].

One possibility for improving energy efficiency in and reducing carbon emissionsfrom multi-family residences is through the use of combined heat and power systems (CHP). Chps have been identified as a practical solution to reduce overall energy demand and greenhouse gas emissions, offering a nearly uninterruptible source of electricity.Somecountries, such as Japan, have already extensively incorporated CHP technology over the past 20 years,butprimarily in the manufacturing and commercial sectors. In the US, there were 43 GW of CHP capacity in the electric power sector as of 2011, mostly powered with natural gas, accounting for about 7.9% of electricity generation [8].Most of the CHP power in the US is used by large industries, although there is potential for growth of small-scale systems to power individual buildings such as hotels, campuses, and multi-family residences, where there are balanced energy requirements between year round water heating and electricity. In the US there are federal and state policies that favor CHP technology, but more research and development on their application is needed, as well as tax incentives for investing in this technology[9].

CHP technology has several significant advantages over traditional energy generation. First, it is more efficient than traditional power plants, which waste as much as 70% of their thermal energy to create electricity. CHP systems are physically located close to where the energy is being consumed so that the heat can be used. This leads to an overall efficiency of greater than 75% for chps. The second advantage is greater energy reliability, due to the fact that CHP systems can serve as an energy backup to grid electricity. Facilities that use CHP do not need to have backup power generation, and they have greater control and incentives to use the CHP efficiently for their application. A third advantage to CHP power is that they can reduce fluctuations in power that a facility needs to draw from the grid. Utility companies include this variability in their pricing structure, so a CHP has the potential to reduce the cost per kwh of grid purchased electricity.

For multi-family residence applications, the thermal energy output from a CHP can be used for directly heating the building, providing hot-water, or cooling the building if it is used in conjunction with an absorption refrigeration unit.For example, a casestudy in Edinburgh, Scotlandapplies CHP to a building with 192 apartments and eight business units [10]. Four CHP systems (each 15 kw electric power, 30 kw thermal power) were installed, providing 74% of the total heating and hot water demand and 54% of the total electricity demand. These units operate on average about 20 hours per day, and reduced the carbon footprint by an estimated 20%.

Effectively deploying a CHP in a residential building requires appropriate equipment sizing and a cost-minimizing operating strategy. Many researchers have examined this problem. For example, a mixed-integer linear programming model was applied to optimize the annual cost of energy for a given residential customer using a CHP combined with a storage tank and back-up boiler [11]. The optimal CHP size suggested by such a model can be sensitive to parameters such as fuel price, grid electricity price, taxes, and grid buyback price if excess CHP electricity is sold back to the grid. A more recent study optimizes CHP with a thermal storage tank by taking into account grid electricity prices[12]. When electricity prices are high, the CHP operates and excess thermal energy is stored in a tank. The CHP turns off and the stored thermal energy is used when prices are low.

The objective of this analysis is to develop a cost optimal CHP system for a specific multi-family building, using historical demand data for the building. The impact of the CHP on grid energy purchases is considered, in terms of offsetting purchased electricity from the grid and altering the price per kwh of grid energy.The building contains acentral water heating system, and all recovered thermal energy from the CHP is to be stored in a large water tank.

Methodology:-

A framework for developing a cost optimal CHP system for multi-family residences with known historical power and water demand is established. Two design variables are introduced: CHP electrical capacity CHP_{cap}(kwe) andcentral hot water tank capacity T_{cap}(kwh). The CHP on/off status each hour is determined by the size of the electrical load, such that the CHP is only activated when the load is greater than CHP_{cap}. This means that a larger CHP will have a lower monthly duty cycle (percentage of on-time each month).This analysis thus assumes that at times it will be more cost effective to not operate the CHP. Considered also in the framework are capital costs associated with the CHP system and central hot water tank, addressed annually through loan payments or assessed property costs whereproperty Assessed Clean Energy (PACE) financing is employed[13]. PACE provides long term, fixed cost financing to home and business owners in order to better manage the large up-front capital costs ofenergy-efficiency retrofits.

There is a certain economically beneficial limit associated with increasing the chpsize and thermal storage capacity, primarily due to increasedcapital costs and due to diminishing returns associated with use of the generally lower cost natural gas (NG) relative to electricity cost for equivalent energy in supplanting electricity at periods of time when the real-time grid power costs are lower. The unit cost of grid power is sensitive to load factor (LF), which is defined as the ratio of the average power to the peak power drawn from the grid. A large CHP operating with low duty-cycle has the potential to increase the LF and thus decrease the unit grid power cost. However, thechp capital cost is very nearly proportional to CHP capacity.A small CHP operating with high duty-cycle is likely to decrease the LF and thus increase the unit grid power cost. The idea is to choose a capacity that optimally lowers the totalannual system cost.

Table 1 contains a list of variables usedto describe the CHP system model, and Figure 1 presents a block diagram describing how the CHP could be incorporated into the apartment energy system. As shown, it will be used to provide electrical energy to meet heating/cooling, lighting, and appliance demands in addition to thermal energy to meet hot water demands. The thermal energy from the CHP can either be directed to meet immediate hot water needs or can be used for thermal storage in a hot water tank. This thermal storage tank can store thermal energy generated by the CHP, up to a maximum amountT_{cap}.

Table 1:- List of dynamic modeling variables.

Variable Name	Units	Definition
CHP_{cap}	Kwe	CHP capacity
T_{cap}	Kwh	Hot Water tank capacity
S	Kwh	Total hourly CHP output
S_E	Kwh	Hourly CHP electrical output
S_H	Kwh	Hourly CHP hot water output
S_1	Kwh	Hourly CHP hot water directly supplied to load
S_2	Kwh	Hourly CHP hot water stored in the tank
E	Kwh	Hourly amount of hot water stored in the tank
R	Kwh	Hourly hot water released from tank
L_{HW}	Kwh	Hourly aggregate hot water load for the complex
L_E	Kwh	Hourly aggregate electrical load for the complex
G_E	Kwh	Hourly grid power to supply the electrical load
η_E	-	Electrical conversion efficiency for CHP
η_H	-	Thermal conversion efficiency for CHP
G_{HW}	Kwh	Hourly grid power to supply the hot-water load
LF	-	Monthly load factor
T_{CC}	$/kwh	Tank capitol cost per kwh
CHP_{CC}	$/kwh	CHP capitol cost per kwh
T_{SYS}	Years	Lifetime of the system
I	-	Loan interest rate
G	Kwh/CCF	Energy conversion for a CCF volume of NG to kwh
C_{NG}	$/CCF	Cost of NG per unit volume
C_{Total}	$	Total annual system cost
C_{gen}	$	The monthly generation cost of grid electricity
C_{trans}	$	The monthly transmission cost
C_{grid}	$	The total grid cost

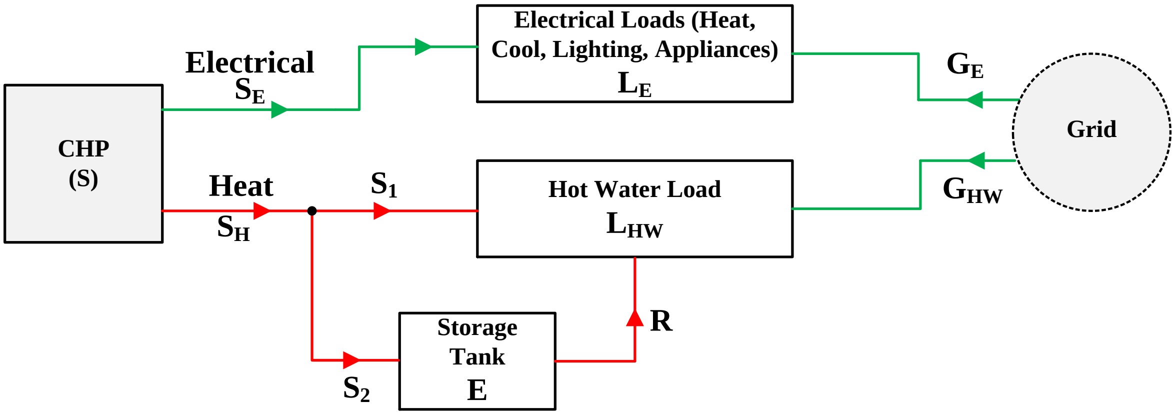


Figure 1:- Energy flow diagram of multi-family CHP system design.

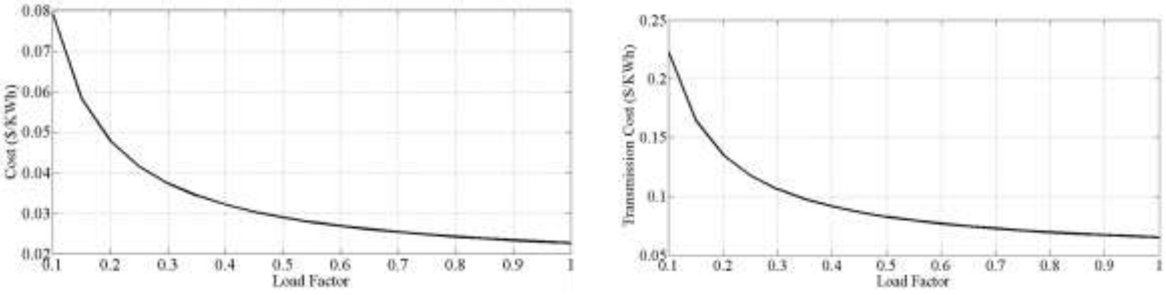
A dynamic model must be developed in order to predict the total system cost as a function of the CHP and tank capacities. This model begins with an estimation of the load profiles for heating/cooling, lighting/appliances, and water heating for the apartment complex as it now stands using historical unit level interval data for energy and water. It then considers a demand-dependent grid power pricing scenario coupled with an investment recovery strategy. An economic cost function that includes loan payback from investment, grid power purchase, and natural gas purchase is detailed. Finally, an optimization model is developed to maximize the economic benefit of the CHP given this cost function. The following describes these steps in the process.

1.1Load Profiles:-

The residential load data used for this study is from a multi-family residence in Columbus, Ohio, consisting of 120 apartments of various sizes.The heating and hot water energy supply is all electric, and each apartment has an air-source heat pump with back-up electric resistance heating. For many units, the back-up resistance heating operates for the entire heating season. Each apartment is individually metered, and hourly demand data is available for the 6-9-2013 to 6-9-2014 year, along with outdoor temperature readings. In a previous study, this total electrical demand data was separated into four categories: weather independent electricity usage, heating, cooling, and hot water [7]. As illustrated in Figure 1, the building's hot water load L_{HW} Is met each hour with the sum $S_1 + R$. The total electric load L_E For the building is the combined heating, cooling, and weather independent components, satisfied by $S_E + G_E$.

1.2Demand sensitivegrid Power Pricing Scenario:-

The optimal size of the CHP is influenced by the impact that the CHP has on the cost of the price of electricity from the grid. There are many pricing strategies used nationwide. In this study, a demand risk power pricing strategy is used,which offers a lower price for consistent loads (with a higher LF) than irregular loads (lower LF). This strategy is chosenbecause it offers the ability for grid cost savings through supply-side management. In this case, a well-designed deployment of the CHP has the potential to increase LF for the portion of the load supplied by the grid, lowering the per kwh price of grid energy.Thepricing structure considered includes separate monthly generation and transmission prices, both of which are functions of the monthly LF.Figure 3a and 3b illustrate these prices, showing the potential price advantage for increasing the LF[14].



(a) (b)

Figure 3:-(a) Monthly grid pricing generation fee and (b) transmission cost schedule versus load factor.

For a constant level of power consumption, the load factor is unity. The measuredmonthly load factorsover the time period considered in the study range from38% to 53%.At a 38% LF, the combined generation and transmission price is about 0.13 $/kwh, and this decreases to about 0.11 $/kwh for a 53% LF. In order for the CHP to increase LF for grid purchases, a large CHP would be chosen and operated during hours of peak demand, with a low duty cycle, to flatten the grid load. However, this may not be the best strategy, because of the higher cost of the CHP and because the total energy supplied by the CHP would be small due to the low duty cycle. An alternative strategy is to select a smaller CHP and operate it with a higher duty cycle. This will decrease LF, increasing the grid energy price, but this is offset by the large decrease in energy purchases from the grid.

1.3 CHP Related Investments:-

In order to upgrade the apartment complex with CHP, there are many other associated costs that must be taken into account to give a complete understanding of the economics of the upgrade. As the facility presently has stand-alone electric water heaters, in order to usethe thermal energy that the CHP produces, investments in a central hot water storage tank, additional piping to distribute the hot water to the individual apartments, and pumps to move the water are needed. Labor costs would also be incurred in installing these systems.

The electrical side of the CHP upgrade will require a control panel that monitors the real-time load and decides when to turn the CHP on. It also integrates the CHP electrical power with the grid power, so that a mix of the two can satisfy all electrical demands.

1.4Cost Function for Optimizing CHP Economic Benefit:-

In this section, the model used to evaluate the economic benefit of the chpis described. This model most importantly considers the supply-side economic impact of the CHP, through consideration of grid power reduction from employing the CHP, as well as the effect of the CHP in changing the grid power unit purchase price for the remainder of the electrical demand not supplied by the CHP.

The costs for this system includes: the capital and installation costs described in the previous section,the cost of the natural gas (NG) needed to operate the CHP, and the grid electrical power cost. The capital costs are treated as investments to be paid back via a loan or property assessment (if PACE financed). The total loan or property assessment amount is given by:

$$Capital\ Cost = (1 - Federal\ Tax\ Credit) * (CHP_{CP} * CHP_{cap} + T_{CC} * T_{cap} + Pipe_C) \quad (1)$$

Where CHP_{CP} Is the cost per kwe for the CHP, CHP_{cap} Is the rated electrical output,T_{CC}Is the capital cost per kwh for the storage tank, T_{cap} Is the tank's maximum thermal storage capacity, in kwh, and $Pipe_C$ Is re-piping costs. The federal tax credit in (1)effectively reduces the loan amount for the CHP. The total investment cost increases linearly with CHP capacity. It should be noted that many U.S. states offer additional incentives which can further reduce the capital cost outlay.

The cost of the system is spread out over the lifetimeT_{SYS} Of the CHP,assumed to be 20years[15]. The resulting annual loan payment is:

$$Annual\ Loan\ Payment = Capital\ Cost * \frac{I}{1 - \frac{1}{(1+I)^{T_{SYS}}}} \quad (2)$$

Where$I$ represents the interest rate for the loan, assumed to be 5%.

The cost of natural gas used to fuel the CHP considers both the displacement of grid electrical power to meet heating/cooling, lighting and appliance loads, and displacement of grid electrical power for water heating from CHP thermal energy. The electrical and thermal energies produced by the CHP for one month are CHP_EAnd CHP_{TH}, respectively. The CHP electrical conversion efficiencyisη_E, and the CHP thermal conversion efficiency isη_H.

Monthly natural gas consumptionV_{NG}For the CHP in units of ccfs can be related to the electrical or thermal energies through division by the corresponding efficiency.

$$V_{NG} = \frac{CHP_E}{\eta_E g} = \frac{CHP_{TH}}{\eta_H g} \quad (3)$$

Here, g is the unit energy from the natural gas in units of kwh per ccf. The cost per unit volume of NG is C_{NG}, leading to a monthly NG cost of:

$$NG\ Cost\ (\$/month) = V_{NG} * C_{NG} \quad (4)$$

The monthly grid power displaced each month from CHP use is determined in the next section, usingthe simulation of the CHP.

The monthly grid electrical power cost will be reduced as a result of employing the CHP. However, the grid power price may increase or decrease, depending on how the CHP is deployed and its impact on monthly LF. The grid power cost dependence on LF is described in section1.3.

Total annual cost for supplying power to the apartments forms a nonlinear objective function, to be minimized over CHP and storage tank capacities. The objective function is:

$$C_{Total} = Annual\ Loan\ Payment + Annual\ NG\ Cost + Annual\ Grid\ Cost \quad (5)$$

1.5CHP Energy Dispatching:-

In this context, this study presents a methodology to identify an optimal mixture of grid electrical power and CHP electrical power and heat, fueledby natural gas, for the apartments to minimize the total cost given in the previous section. A family of optimal CHP systems is developed for various fuel pricing structures.

The CHP is activated at each hour the electrical demand is greater than the peak CHP electrical output. This strategy is chosen in order to use all of the CHP's output electrical energy. The CHP output is not variable; it is either zero or at its rated peak for each hour. With this deployment strategy, a smaller CHP will operate for a greater percentage of hours each month (higher duty cycle) than a larger CHP. Additionally, the heat generated by the CHP will be used to heat hot water directly to meet immediate hot water needs or will be stored in a thermal storage tank. This stored thermal energy can be used later to meet hot water demands.

As shown in Figure 1, the CHP output for every hour(k) is divided into CHP supplied electricity,$S_E(k) = \eta_E * S(k),$ and CHP thermal energy, $S_H(k) = \eta_H * S$(k)where the efficiencies η_E And η_H Represent the fraction of the input energy$S(k)$converted into electricity and heat, respectively. Summing $S_E(k)$ and $S_H(k)$ over one month of time leads to the quantities CHP_E And CHP_H, respectively, used in (3). The quantity$S(k)$ is either equal toCHP_{cap}/η_E Or zero, depending on whether or not the CHP is turned on. The rule for turning on and off the CHP can be expressed as follows.

$$S_E(k) = \begin{cases} CHP_{cap} \text{If } L_E(k) \geq CHP_{cap} \\ 0 \quad\quad \text{if } L_E(k) < CHP_{cap} \end{cases} \quad (6)$$

The electrical load for the apartment complex must be satisfied each hour by the grid and CHP, such that$L_E(k) = G_E(k) + S_E(k),$where $G_E(k)$ Is the remaining power supplied from the grid. Similarly, the hot water load must be satisfied according to $L_{HW}(k) = S_1(k) + R(k) + G_{HW}(k)$, where $S_1(k)$ is directly from the CHP, $R(k)$ is from the hot water tank, and $G_{HW}(k)$ is from the electrical energy supplied by grid for the purpose of hot water heating.

The amount of heat stored in the hot water tank each hour is represented by$E(k)$, which is updated iteratively each hour according to:

$$E(k) = E(k-1) + S_2(k) - R(k) \quad (7)$$

Rules are developed for whether or not heat is added or removed from the storage tank. These are summarized in Table 1.

The dynamic model is initialized by assuming that the hot water storage tank begins with no stored heat. Using the rule for activating the CHP in (6), the storage tank energy balance given by (7) and the rules described in Table 2, a reduced grid supply is determinable. The original load for the grid is simply$L_E + L_{HW}$, and the modified load that the grid must satisfy is:

$$G = G_E + G_{HW} = L_E + L_{HW} - S_E - S_1 - R \tag{8}$$

The total original cost is $\mathrm{C_{Grid}} = \mathrm{C_{Gen}} + \mathrm{C_{Trans}}$ Where $\mathrm{C_{Gen}}$ And $\mathrm{C_{Trans}}$ Are the monthly generation and transmission costs of grid electricity, respectively, given by

$$C_{gen}(LF, E_{month}) = \text{Gen Price}(LF) * E_{month}$$
$$C_{trans}(LF, E_{month}) = \text{transprice}(LF) * E_{month}$$

The dependency of the prices on the monthly load factor LF is illustrated in Figure 3.

$$\text{Original Total Cost} = C_{grid}\left(LF, \sum_k L_E(k) + L_{HW}(k)\right) \tag{9}$$

Condition	Description	Equations
$S_H(k) < L_{HW}(k)$ AND $E(k) = 0$	Hot water load is more than the CHP thermal output, and the hot water tank is empty. Use available thermal energy from CHP, supply the rest from grid.	$R(k) = 0$ $S_1(k) = S_H(k)$ $S_2(k) = 0$ $G_{HW}(k) = L_{HW}(k) - S_1(k)$
$S_H(k) \geq L_{HW}(k)$	Hot water load is less than the CHP thermal output. Satisfy the load with the CHP thermal output, pass the remaining energy into the storage tank. No grid power is used.	$R(k) = 0$ $S_1(k) = L_{HW}(k)$ $S_2(k) = S_H(k) - S_1(k)$ $G_{HW}(k) = 0$
$S_H(k) < L_{HW}(k)$ AND $E(k) > L_{HW}(k) - S_H(k)$	Hot water load is more than the CHP thermal output, and the storage tank contains enough energy to make up the difference. Use storage tank energy and CHP thermal output to satisfy the load, no grid power is used.	$R(k) = L_{HW}(k) - S_H(k)$ $S_1(k) = S_H(k)$ $S_2(k) = 0$ $G_{HW}(k) = 0$
$S_H(k) < L_{HW}(k)$ AND $0 < E(k) < L_{HW}(k) - S_H(k)$	Hot water load is more than the CHP thermal output, and the storage tank does not have enough energy to make up the difference. Use all available CHP output and stored energy for the load, and use grid power to make up the difference.	$R(k) = E(k)$ $S_1(k) = S_H(k)$ $S_2(k) = 0$ $G_{HW}(k) = L_{HW}(k) - S_1(k) - R(k)$

Table 1:-Energy dispatching rules for managing CHP, grid, and stored thermal energy.

After implementing the CHP system, the total cost will include the capitol costs and NG costs, but the grid purchase will decrease to offset these. The total cost after CHP implementation is given by:

$$\text{New Total Cost} = C_{grid}\left(LF_{new}, \sum_k G(k)\right) + \text{Annual Loan Payment} + \text{Annual NG Cost} \tag{10}$$

Where LF_{new} Represents the new monthly load factor seen by the grid, and $G(k)$ is the hourly grid power as given in (8). The new total cost is a nonlinear function of the CHP and storage tank capacities. The cost is minimized over these parameters using a non-linear, constrained optimization solver (fmincon) in Matlab. The optimization problem can be expressed asfinding the optimal CHP and tank capacities that minimize the total cost, subject to the constraint that electrical and thermal loads are satisfied at each hour.

Results:-

2.1 Cost Optimization:-

Figure 4shows a bar graph ofthe actual monthly load totals, split into electricity and demand hot water, along with the total original cost for each month. Hot water represents about 20% of the yearly load, typical for residential demand. The electric component of the load consists of heating, cooling, plug loads, and appliance loads. The electrical load varies seasonally with heating and cooling demands, and month-to-month variations in the hot water load are small in comparison.

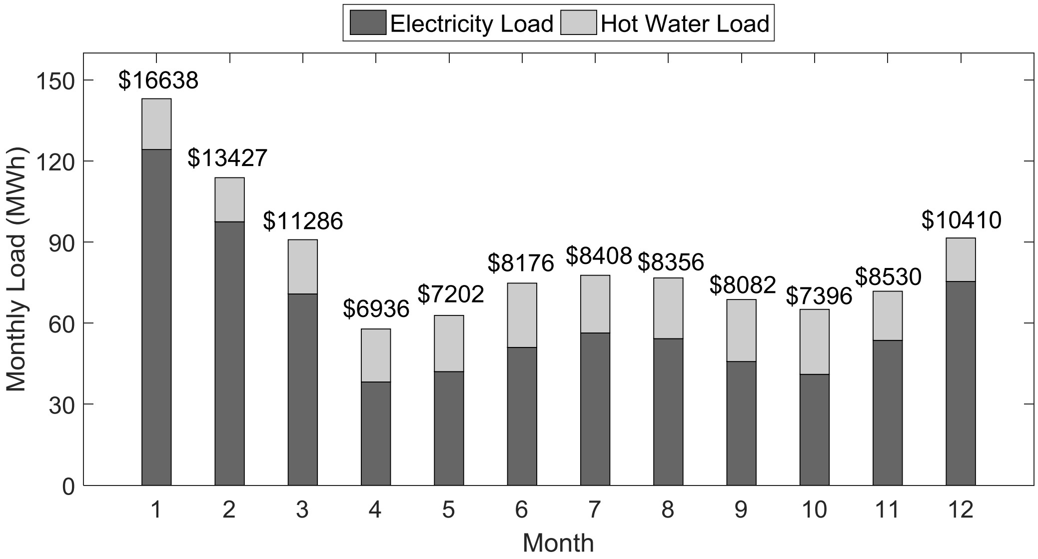


Figure 4:-Original monthlyload totals and costs. The load is divided into an electrical component (heating, cooling, plug loads, and appliances) and a demand hot water component.

The system turns on and off the CHP in order to reduce the peak loads that the grid must satisfy. This is illustrated in Figure5 (top)which shows the hourly total demand for the first eight days of the simulation, along with the on/off action of the CHP to reduce peaks.When the dynamic model is executed, the CHP supplies thermal energy to satisfy the hot water load or, if there is extra hot water, it stores it in the thermal tanks. Figure 5 (bottom) shows the hourly hot water entering the storage tank, the current stored amount of hot water, and the hot water drawn from the tank.

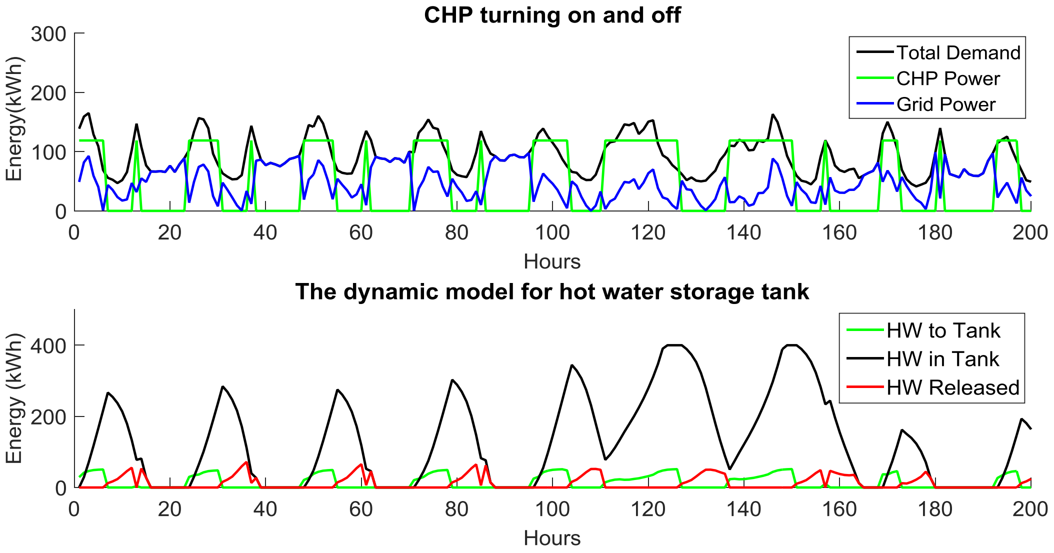


Figure 5:- (Top)Hourly CHP activation, total demand, and grid power for 200 hours (8 days). (Bottom) Dynamic model for HW tank, with hourly energies to and from the tank, along with its current charge level.

The size of the CHP is the strongest factor for determining costs. Figure6 plots total cost (right axis) versus CHP size for three different tank capacities, along with the CHP duty cycle (left axis). Because the CHP is only activated when the load exceeds its size, duty cycle decreases linearly with size. The minimum cost occurs at a CHP size of about 60 kwefor a tank capacity of 400 kwh. The duty-cycle for this size is about 63%; e.g., the CHP is used 63% of the time.

To further explore the effect of CHP capacity on cost, figure7 presents a bar graph that shows the different costs versus CHP capacity, using the optimized tank size of 400 kwh. For each CHP capacity shown along the horizontal axis, the simulation is executed for a year and each type of cost (grid, NG, and investment) is computed.Investment costs increase steadily with CHP size, but the effect on grid cost is more complex, showing a decrease until about 65 kwe followed by an increase. The reasons for this behavior are demonstrated in Figure 8, which shows the effect of CHP capacity on duty cycle and LF. Below 65 kwe, the CHP satisfies more of the load as it increases with capacity, driving down grid purchases. However, due to the decreasing duty cycle, it provides less of the load beyond 65 kwe, and grid purchases then increase. Figure 8 also shows that a larger CHP leads to improved (higher) LF, driving down per kwh grid prices, but the lower duty cycle negates this effect. An increasing LF serves to decreases the grid purchase price, but a decreasing duty cycle leads to greater total grid purchases.

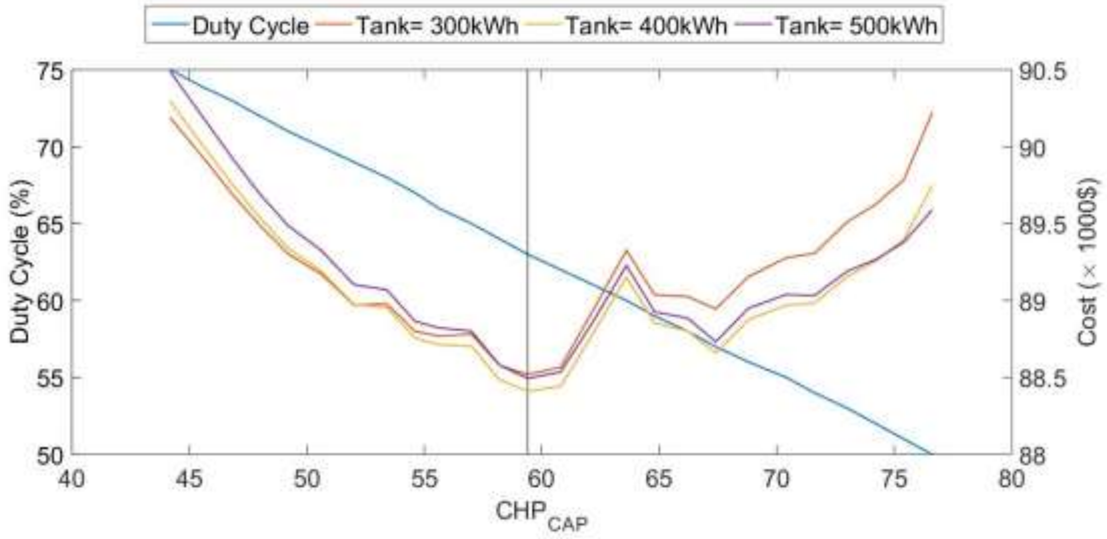


Figure 6:-Duty-Cycle (percentage along left axis) and total cost (right axis, × $\$\mathbf{1000}$) versus $\boldsymbol{CHP_{CAP}}$(kwe) for three thermal storage tank capacities. Vertical line indicates capcity for minimum cost.

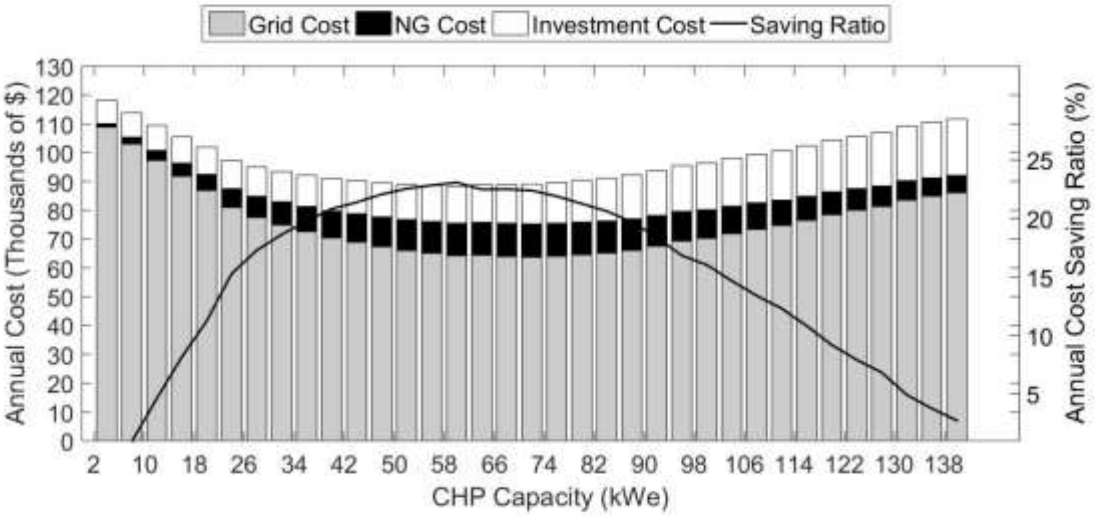


Figure 7:- Cost categories and savings ratio as a function of CHP capacity.

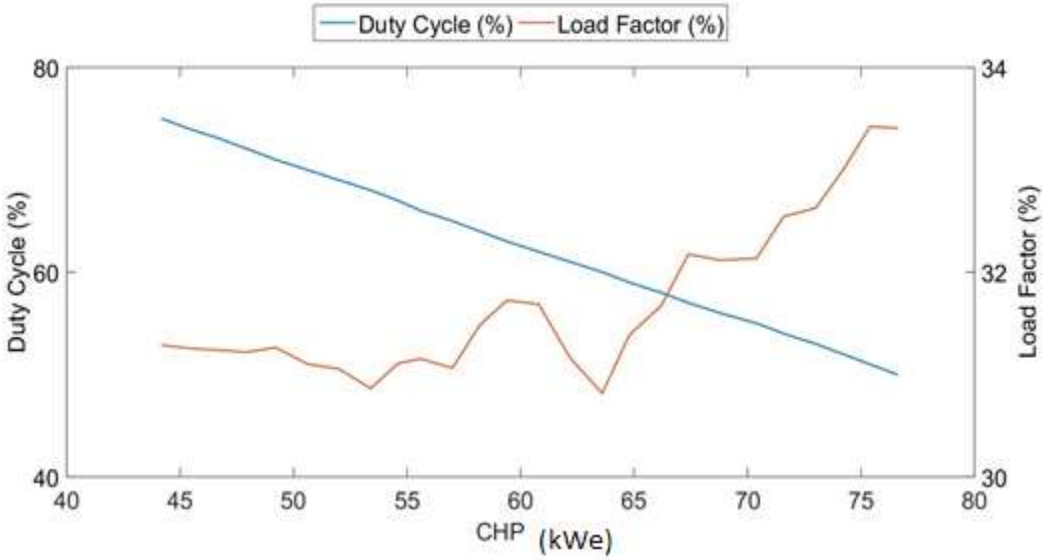


Figure 8:- CHP duty cycle (left axis) and average LF (right axis) as a function of CHP capacity.

The monthly reduction in grid power at theoptimal conditionisillustrated in Figures9and10. The CHP output varies seasonally; for example, there are more peaks in the demand in January, which causes greater CHP operation.Figure 9also summarizes the monthly improvements to the total cost by using the CHP system for the optimal system. The original grid cost is shown next to new grid cost. Figure 10 further illustrates the monthly costs associated with the optimal CHP and storage size broken down by the various costs included in the analysis.

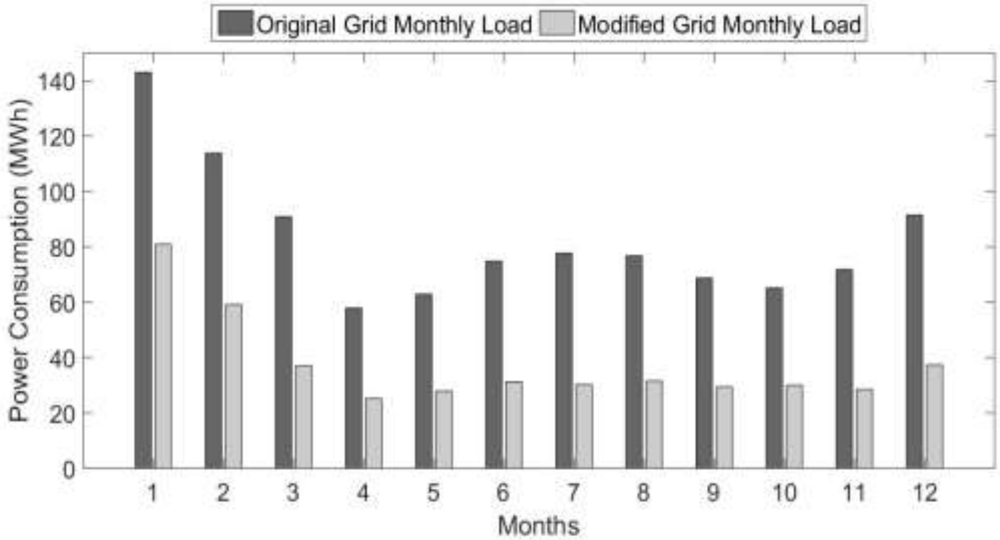


Figure 9:- Monthly energy from the grid before and after the CHP installation.

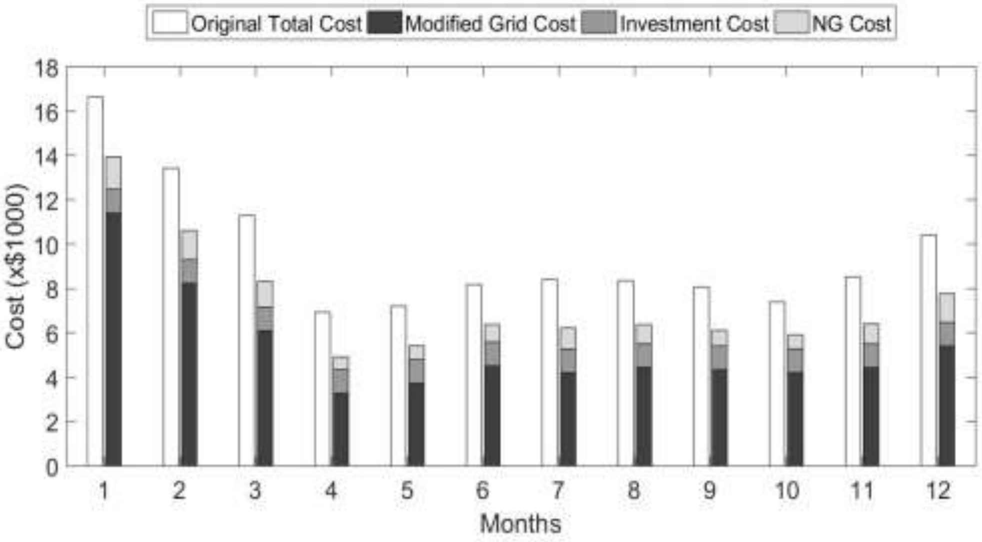


Figure 10:- Summary of montly costs before and after CHP installation.

The present value for each of these yearly savings is computed assuming an interest rate on the loan of 5%. The CHP system capital costs are assumed to be incurred completely at the beginning of the lifetime as a negative quantity, and the summation of these values produces NPV. The IRR for this scenario is defined as the interest rate that would drive the payback time to be the entire lifetime, such that it requires the full 20 years achieving a zero NPV. The IRR is a measure of the value of the initial investment. Table 2 below shows the NPV and IRR calculations.

Table 2:- NPV and IRR calculations for the CHP system.

Conventional Grid Power Cost ($/year)	$115,310
Inflation rate for Grid Power	5%
NG Cost ($/year)	$ 11,331
Inflation rate for NG	3%
Initial Capital Cost	$231,300
Loan Lifetime (years)	20
Loan Interest Rate	5%
Net Present Value	$612,530
Internal Rate of Return (IRR)	20%

2.2 Parameter Sensitivity:-

The annual cost relies on many parameters, such as prices, which are random in nature. Because of this, it is important to understand the sensitivity of the annual cost to variations in these parameters. A Monte Carlo risk analysis is presented here to study this issue. The results of such a risk analysis can help with the decision of whether or not to implement a CHP upgrade. The table below describes the parameters influencing cost and the distributions chosen for each.

Parameter	**Distribution**
NG Price ($/CCF)	Uniform from 0.3 to 0.5
Tank Price ($/kwh)	Uniform from 40 to 60
CHP Price ($/kwh)	Uniform from 1300 to 1700
Demand Distribution Charge ($/kw)	Uniform from 3 to 4
Demand Generation Charge ($/kw)	Uniform from 8 to 10

Table 3:- The parameters influencing cost and the distributions.

The Monte Carlo risk analysis proceeds by randomly selecting values for the parameters in Table 3 according to their distributions, and computing cost. This process is repeated many times, and a histogram of the cost is created. Figure 11 illustrates two such histograms. The histogram centered at $115,000 represents the cost for supplying energy to the building using only grid power. The histogram centered at $88,000 represents the cost associated with the CHP system. Because the histograms have no significant overlap, the CHP system is not likely to increase costs, meaning that implanting the CHP system is low-risk.

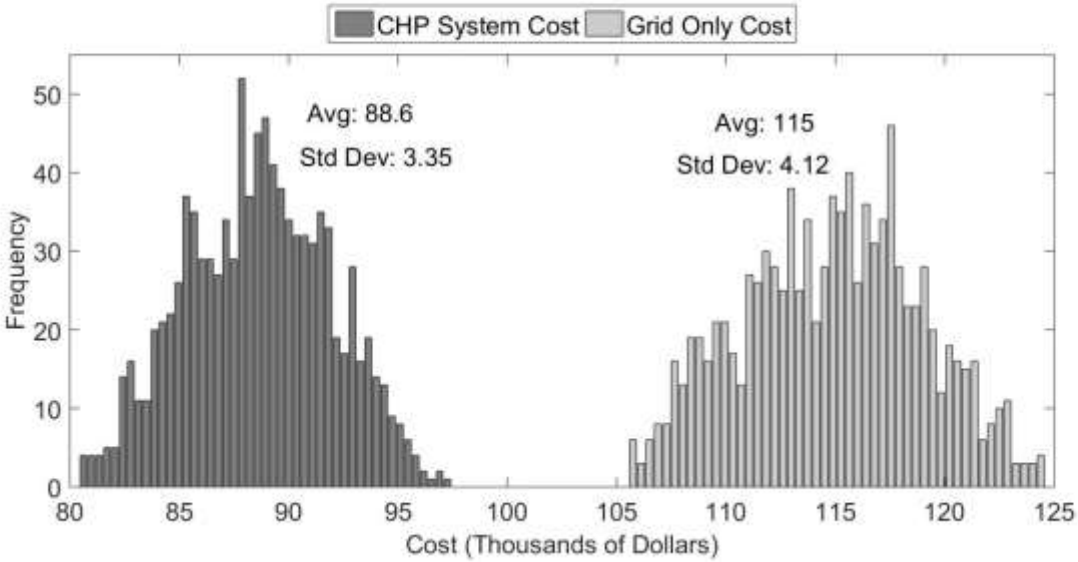


Figure 11:- Distributions of annual cost for the CHP system and for a grid-only supply, using 1000 Monte Carlo repetitions.

To examine which parameter in Table 3 most affects the cost, the Monte-Carlo simulations can be conducted by randomly varying one parameter at a time, while keeping the others constant. Figure 12 illustrates three cost distributions created in this manner, associated with NG price variations, grid price variations, and CHP price variations. The sensitivity of the cost to NG pricing is nearly the same as the sensitivity to grid pricing. Both of these lead to a standard deviation of about 1.6 on the CHP cost. The sensitivity to CHP price is much smaller, which leads to a cost standard deviation of about 0.4.

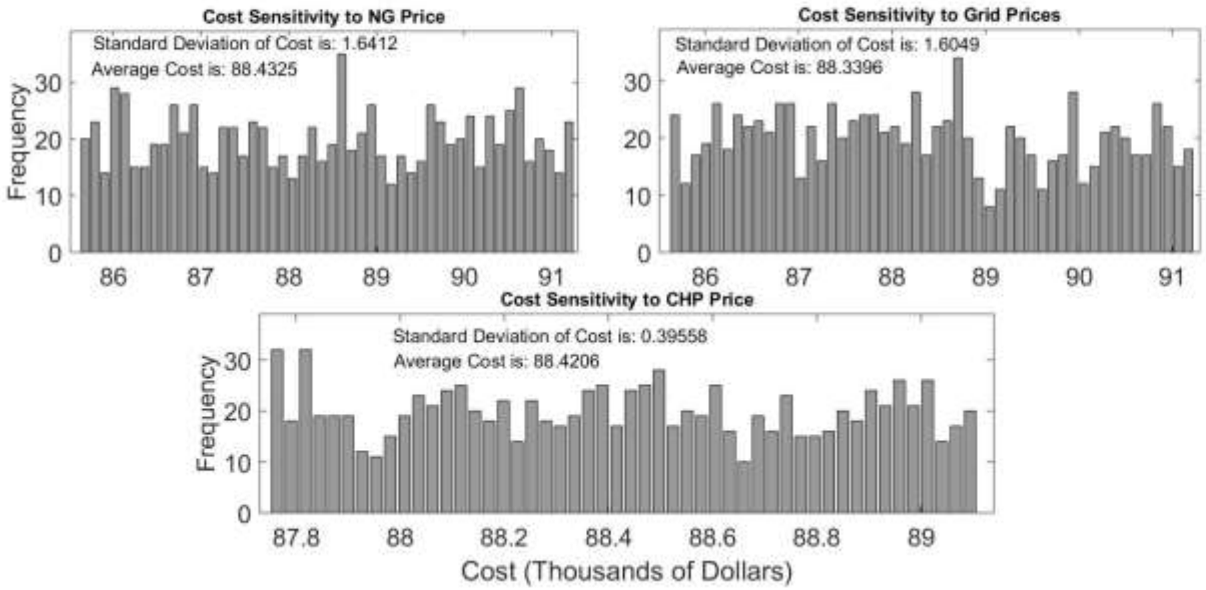


Figure 12:- CHP cost distributions created by varying one parameter at a time, using 1000 Monte-Carlo simulations.

Conclusion:-

In this study, a CHP system is considered in an all-electric multi-family residential building in order to reduce peaks in the total power demand. The CHP thermal energy is used along with a hot-water storage tank to meet some of the building's hot-water demand. A mathematical model is developed for minimizing total cost as a function of the CHP and hot-water storage tank capacities, along with a parameter that governs CHP on-time. Total cost is most sensitive to CHP capacity. As this capacity increases, the CHP can smooth peaks in the electrical load (increasing load factor) and reduce total grid purchases. However, if the CHP is too large, it smooths fewer of the load peaks and runs at too low of a duty cycle to reduce total grid purchases. The balance point at which CHP optimally reduces grid purchases is a function of the load profile, and it occurs at about 60 kwe for the profile tested.

The dynamic modeling for this study indicates that the optimal CHP and hot water tank capacities are 60 kwe and 400 kwh, respectively. In this case, the CHP provides 65% of the total demand, which reduces total annual cost from $114,850 to $88,336(23% reduction). This result is specific to the building load profiles used in this study and the historical data used to derive these profiles. For a different residential building (size, type of construction, location, etc), the load profiles would change, leading to a slightly different optimal point.

This work demonstrates real opportunity for broad inclusion of chps in multi-family residences in supply-side power management schemas. The relatively high hot water heating loads present in multi-family residences are particularly well-suited to CHP application. The demand sensitive grid pricing cost scenario considered here for the Midwest in the US yields quite conservative results. When grid pricing has even greater variation as in US states such as California and New York, the opportunity to employ chps for power and water heating in this building sector is even more promising.

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