Title

STRATEGIES FOR RESIDENTIAL NATURAL GAS DEMAND RESPONSE

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STRATEGIES FOR RESIDENTIAL NATURAL GAS DEMAND RESPONSE

By

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Abstract

Natural gas demand response (GDR) is an emerging technology that has garnered significant attention in recent years due to its potential as a tool for grid management. Despite the growing interest in GDR, a careful examination of the literature suggests that there is still much to learn about the full potential of this technology, particularly with regards to demand-side management which is the response from the customer or user side. In this thesis, we aim to address this critical research gap by proposing various actions and strategies to optimize the utilization of natural gas during Gas Demand Response events, with the goal of encouraging customers to participate in these programs.

This study focuses specifically on the use of multi-source residential heating, with natural gas serving as the primary source. To calculate consumption during periods of high demand, we utilized a simulation model using Open Studio and Energy Plus software, which is funded by the Department of Energy and managed by the National Renewable Energy Laboratory. The simulation model enabled the determination of the heating energy requirements for a typical residential apartment over the course of an entire year, with the ability to break down the demand for each hour based on location and weather conditions. The generated energy requirement was utilized by an optimization tool to decide which source of energy the customer should use based on different incentive and pricing programs. Both the model and the optimization tools allowed us to test different possible solutions and modifications to quantify the energy savings, particularly during Gas Demand Response events.

Through this research, we seek to contribute to the growing body of literature on GDR and advance the understanding of demand response from the demand side. By proposing various strategies to optimize natural gas utilization during Gas Demand Response events, we hope to encourage greater participation in demand response programs and promote the adoption of GDR as a reliable and sustainable solution to grid management challenges. The simulation model represents a valuable tool for testing proposed solutions and modifications, and our findings can inform the development of effective demand response strategies that enhance the overall potential of GDR as a tool for grid management.

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1. Introduction

1.1 Background

Natural gas is recognized as a significant energy source globally and plays a vital role in meeting the energy demands of various sectors. In the United States, it represents approximately 32% of the total energy demand [1]. In addition to renewable sources, natural gas remains one of the most extensively utilized energy resources worldwide, with its utilization expected to increase due to its low environmental impact [2]. The low carbon content of methane in natural gas results in significantly lower CO_2 emissions compared to other fuels, making it a preferred fossil fuel [3].

The residential and commercial sectors utilize natural gas for space heating, water heating, and cooking, while the industrial sector employs it as fuel for power and heat generation or feedstock. Due to its favorable environmental characteristics, the demand for natural gas in these sectors has experienced significant growth in recent years [4], [5]. However, the significant growth in demand for natural gas in residential, commercial, and industrial sectors has resulted in considerable challenges in maintaining a balance between supply and demand [5]. The ability to manage this imbalance effectively is crucial for ensuring the reliability and stability of natural gas systems. This balance could be maintained through several methods from the supply side such as expansion of the grids, or from the demand side such as demand response programs.

Demand response (DR) programs, a strategy aimed at actively managing and adjusting electricity consumption in response to supply challenging conditions or prices, have been widely implemented in the electricity sector for over 40 years to manage peak demand, reduce costs, and improve reliability [5]. DR programs have been successful in the United States and Europe, where they have been used to balance supply and demand and to reduce the need for new power plants and power delivery systems [6], [7]. Recently, there has been an increasing interest in applying DR principles to natural gas systems, which are facing similar challenges in terms of balancing supply and demand, reliability, and cost management.

Electricity and natural gas systems exhibit notable differences in their operational characteristics. The primary dissimilarity between the two systems comes from the inability to store large quantities of electricity with reasonable efficiency, forcing electricity generation to align with consumer demand in real time. Furthermore, electricity possesses a wave-like nature, leading to a unique characteristic, namely, frequency, that lacks equivalence in natural gas systems. The maintenance of a consistent frequency throughout the power system always requires a balance between generation and demand [8]. However, despite these differences, electric and natural gas systems share several other features in terms of their infrastructure, management, and operations.

The similarities between natural gas and electricity systems suggest that existing DR products employed in electricity systems may be adapted for the development of DR programs in gas systems. This approach could be particularly beneficial in smart multi-energy systems, which have emerged as a significant trend in city development [9]. Such DR strategies could be applied to minimize imbalances in the natural gas network, thereby reducing the need to pay significant sums in the short-term wholesale market when the prices spike. Additionally, the creation and implementation of more tailored DR programs for gas systems should be examined due to their potential in improving system efficiency and the flexibility of consumer consumption [8].

In this context, the availability of smart metering infrastructure facilitates the integration of DR programs in gas transmission and distribution systems. The use of "smart gas networks" enables the adjustment of consumption levels to grid availability and limitations [8].

1.2 Literature Review

The current body of literature on Natural Gas Demand Response is limited, indicating a pressing need for further investigation from various perspectives to gain a more comprehensive understanding of the underlying factors and the full extent of its potential. This section provides a summary of selected relevant studies that have focused on demand response in natural gas systems, including a pilot program report developed by the National Grid Company.

The study in [10] focuses on the application of DR strategies for balancing natural gas systems, specifically in a local network located in The Marches, Italy. The authors argue that DR can provide an effective solution for balancing natural gas systems, as it can help to manage imbalances in demand and supply by controlling consumption patterns. The paper presents a case study of the natural gas system in The Marches, where the authors analyze the feasibility of implementing DR strategies in the local network. They propose a methodology that involves the identification of demand response resources, the development of a demand response program, and the evaluation of the program's performance. The authors use simulation models to test the effectiveness of different DR strategies, such as load shifting and curtailment, in reducing imbalances in the natural gas system. They also evaluate the economic benefits of these strategies, which include cost savings for both gas consumers and the gas system operator. Overall, the paper concludes that demand response strategies can be an effective and economically viable solution for balancing natural gas systems. The authors recommend further research to explore the potential of DR strategies in other natural gas networks and to identify the most effective DR strategies for different scenarios.

Another example of contributions in this area is the study in [11] where the authors examine the potential of district heating systems in the Italian Peninsula to act as demand response aggregators. The authors estimate the flexible potential of these systems by analyzing the relationship between heat production and demand for different scenarios, including the integration of renewable energy sources and the use of thermal storage. The results show that district heating systems have significant potential to provide demand response services, with the capacity to adjust heat production by up to 45% in response to price signals or grid needs. The study also highlights the importance of integrating renewable energy sources and thermal storage to enhance the flexibility of these systems. Overall, the paper provides insights into the role of district heating in the energy transition and the potential for these systems to contribute to the decarbonization of the heating sector.

The work in [8] presents a methodology for evaluating demand response strategies in the management of natural gas systems. The authors propose a framework that considers different demand response mechanisms, such as load shifting and curtailment, and analyzes their impact on the natural gas supply chain. The methodology includes a simulation model that integrates different components of the natural gas system, such as pipelines, storage facilities, and distribution networks. The model is used to evaluate the performance of demand response strategies under different scenarios, including changes in demand, supply, and infrastructure constraints. The results of the study demonstrate that demand response can effectively reduce peak demand and improve the reliability of the natural gas system. The authors also identify key factors that influence the effectiveness of demand response strategies, such as the availability of storage facilities and the level of coordination among stakeholders. Overall, the paper provides a valuable contribution to the development of demand response strategies for the management of natural gas systems, highlighting the need for a comprehensive and integrated approach to system optimization.

In addition to these studies, prior research work has explored the integration of electricity and natural gas demand response for manufacturers in the smart grid. An example of work in this direction is the study in [12] where the authors propose an integrated demand response strategy that considers both electricity and natural gas systems to optimize energy consumption and reduce costs. The strategy includes a coordination mechanism that enables manufacturers to adjust their energy consumption based on price signals and system constraints. The authors also propose a simulation model that integrates electricity and natural gas demand response to evaluate the performance of the strategy. The results of the study show that the integrated demand response strategy can effectively reduce energy costs for manufacturers while maintaining the stability of the smart grid. The authors also identify key factors that influence the effectiveness of the strategy, such as the availability of energy storage and the level of communication among stakeholders. Overall, the paper provides valuable insights into the integration of electricity and natural gas demand response in the smart grid and highlights the potential benefits for manufacturers in terms of cost savings and energy efficiency.

In a related study, the authors in [13] investigate the potential of residential natural gas demand response during extreme cold events in electricity-gas coupled energy systems. The authors propose a framework that integrates electricity and natural gas systems to analyze the impact of extreme cold events on energy demand and supply. The framework includes a simulation model that considers different demand response mechanisms, such as load shifting and curtailment, to evaluate the potential for residential natural gas demand response. The authors also analyze the effectiveness of different demand response strategies under different scenarios, including changes in demand and supply. The results of the study show that residential natural gas demand response can effectively reduce peak demand and improve the reliability of the energy system during extreme cold events. The authors also identify key factors that influence the effectiveness of demand response strategies, such as the level of coordination among stakeholders and the availability of energy storage. Overall, the paper provides valuable insights into the potential of residential natural gas demand response in electricity-gas coupled energy systems during extreme weather events. The findings can help policymakers and energy system operators to design effective demand response programs that improve energy efficiency and reduce system costs.

In addition to the aforementioned research studies, a Gas Demand Response Pilot Implementation Plan was implemented by the National Grid Gas from 2018 to 2021 [14]. The pilot aimed to explore the potential of demand response in the gas sector and to develop a framework for implementing demand response programs for gas customers. The report in [14] provides an overview of the pilot program, including the objectives, scope, and methodology. It also presents the results of the pilot, including the evaluation of different demand response mechanisms, such as load shifting and curtailment. The results of the pilot show that demand response can effectively reduce peak demand and improve the reliability of the gas system. The report also identifies key success factors for implementing demand response programs, such as the level of stakeholder engagement and the availability of incentives for customers. Based on the results of the pilot, the report proposes a framework for implementing gas demand response programs, which includes a set of guidelines and best practices for program design and implementation. The framework is designed to help gas system operators to develop effective demand response programs that improve system efficiency and reduce costs. Overall, the report provides valuable insights into the potential of demand response in the gas sector and offers practical guidance for implementing demand response programs for gas customers.

1.3 Gaps and Motivation

Despite the growing interest in natural gas demand response (GDR), the current literature suggests that there is still much to learn about the full potential of this emerging technology. Several studies have focused on demand response strategies for the management of natural gas systems, highlighting the benefits and challenges of GDR implementation. However, further research is needed to fully comprehend the underlying factors and overcome the grid imbalance challenges and limitations. One critical area that has yet to be addressed is the demand response from the customer or user side. Understanding how customers can respond during GDR events can inform the development of effective demand response programs and enhance the overall potential of GDR as a tool for grid management.

Studies investigating demand response in the natural gas sector can also benefit from the experiences and insights gained from similar studies in the electricity sector. By identifying user actions and optimization opportunities in residential and industrial sectors, researchers can develop effective demand response strategies that enhance the overall potential of GDR as a tool for grid management [15], [16].

The National Grid Company's Gas Demand Response Pilot Implementation Plan offers insight into the challenges and opportunities associated with GDR implementation. However, despite the importance of this pilot program, additional research is needed to fully understand the potential of GDR and its utilization to address grid imbalances. Specifically, there is a need to examine GDR from the customer or user side and explore how consumers can be engaged and incentivized to participate in demand response programs. Such research can inform the development of effective demand response strategies and promote the adoption of GDR as a reliable and sustainable solution to grid management challenges.

Motivated by these considerations, the goal of this thesis is to address this critical research gap by proposing various actions and solutions to optimize the utilization of natural gas during Gas Demand Response events, with the goal of encouraging customers to participate in these programs. To this end, we focus on the problem of residential natural gas consumption and use a simulation test bed to illustrate the development and implementation, and evaluate the efficacy, of various DR strategies and solutions. The strategies considered include the use of a multi-zone heating approach to reduce overall natural gas consumption, the use of multiple energy sources which are optimally dispatched to meet the heating requirements, and the introduction of a new tier system for gas pricing that includes an hourly cap. The general methodological framework is presented in Section 2, and the results are given in Section 3. Finally, conclusions are provided in Section 4.

2. Methodological Framework

2.1 Simulation Test Bed

The present study describes a simulation model that has been developed using Open Studio and Energy Plus software, which are funded by the Department of Energy and managed by the National Renewable Energy Laboratory. The model has been designed in accordance with the ASHRAE 169-2013 construction standard for a pre-defined set of a Mid-rise Apartment. The apartment is an 800 ft^2 flat that includes two bedrooms, two baths, and a sitting room with an open kitchen, as shown in Figure 1.

Figure 1: The layout of a mid-rise residential apartment.

The model has been segmented into four thermal zones that can be individually operated using a thermostat to regulate the required heating. The simulation model calculates the required energy to maintain each zone at the assigned thermostat setting temperature. The HVAC system and its equipment have not been modeled, allowing the software to calculate the required energy for heating for each zone regardless of the source. This approach makes the model simpler to converge and enables the decision-making process for the appropriate source of energy based on different factors such as pricing and location.

2.2 Multi-Zone Approach

The current HVAC system relies on a single thermostat located in a primary zone to control the temperature of the entire dwelling. However, this approach lacks flexibility and wastes energy by cooling unoccupied zones. To address this issue, smart thermostats with controllable air vents can be developed easily with the existing capability of technology in the current market. In this research, we explore the use of such technology to improve HVAC efficiency and reduce energy consumption. To this end, the simulation model allows users to assign thermal zones to different areas of the house based on occupancy or physical walls. In this study, the apartment was divided into four major zones: Bedroom 1, Bedroom 2, Sitting Room with Kitchen, and both Bathrooms. The model was first run with a single primary thermostat to calculate the energy required to maintain the assigned temperature throughout the entire apartment. Next, the model was run with different thermostats, each scheduled based on occupancy, to investigate potential energy savings.

2.3 Multi Energy Source Optimization Approach

The economic viability of various sources of energy can be evaluated based on their respective heat value per dollar. While clean sources are typically preferred for their environmental benefits, the availability and suitability of different energy sources can vary depending on location and weather conditions. In certain cases, it may be impractical to rely solely on clean energy sources, making alternative sources more appealing. Given the limitations of clean energy, particularly during night-time hours, optimizing the use of other sources can offer significant cost savings, particularly during Gas Demand Response events. To incentivize such optimization, some power companies, such as National Grid, have implemented reward systems for contributors based on the amount of energy saved per therm. This opportunity can be formalized in the paragraphs below.

The following assumptions have been made for the optimization scenario presented:

- The gas furnace can operate on either natural gas or propane with minor automated changes, such as adjusting the fuel/air ratio using an actuator.
- Each fuel has a minimum run time based on the minimum acceptance operation level, which is assumed to be known.
- The transition state during fuel switching is ignored.
- The baseline consumption is based on the actual energy demand if it were to be provided solely by natural gas.
- Incentives for energy reduction are based on the current system in the National Grid program.
- A maximum incentive applies to allow the optimizer to reduce the load rather than shifting all the load. This assumption aligns with the National Grid program where a maximum incentive is applied for each month.
- The efficiency of the equipment and accessories for each system will not be considered in this formulation.

The formulation for the optimization problem is presented as follows. The problem involves four fuel types (FT): Natural Gas (NG), Propane (P), Clean Power (CP), and Grid Power (GP), and is considered over a time horizon of 24 hours. The required energy for each hour, denoted by RE_H (Wh), is obtained through the simulation model, while the calculated energy for each hour, denoted by CE_H (Wh), is to be determined by the optimization tool. The minimum unit for each fuel, denoted by MU_{FT} (W/min), is a constant, and the cost for each fuel, denoted by C_{FT} ($/W), is a constant that depends on the location. The energy for each fuel, denoted by E_{FT} (W/$), and the integer multiplication factor for the number of units, denoted by X_{FT} (equivalent to 1 minute), are also considered.

The objective of the optimization problem is to minimize the cost of the required energy per hour. This objective is subject to several constraints. The first constraint requires that the calculated energy for each hour should satisfy the hourly demand, meaning that RE_H must be equal to CE_H, which can be relaxed to within ±4% of the demand. The second constraint ensures that the multiplication factor cannot be negative, meaning that X_{FT} must be greater than or equal to zero. The third constraint states that the summation of the multiplication factors for each hour should be 60, meaning that the total energy used must be limited to a fixed amount. Finally, the fourth constraint stipulates that the incentive is only positive and does not exceed the maximum, where the incentive is calculated as the difference between the baseline and the total energy used multiplied by the incentive rate. The baseline is obtained through the simulation.

Based on these considerations, the optimization problem can be formulated as follows:

- Objective function: minimize the cost of required energy per hour.
    - $Min\ \sum_{1}^{H} X_{FT} MU_{FT} C_{FT} - Incentive$
- Incentive:

- $Incentive = Baseline - \sum_{1}^{H} X_{FT} MU_{FT}$

➢ Constraints:

- $RE_H \approx CE_H \quad \forall H$, (within ±4% of the demand)
- $X_{FT} \geq 0$
- X_{FT} $is\ Zero\ or\ positive\ integer$
- $\sum X_{FT} = 60 \; \forall H$
- $Incentive \geq 0$
- $Incentive \leq Maximum\ Incentive.$

This problem falls under the category of Mixed Integer Nonlinear Programming (MINLP) and can be formulated and solved using various software or coding techniques with a suitable solver capable of handling nonlinearity. In this study, Python coding with the Pyomo framework was employed, which offers the ability to evaluate results with multiple supported solvers, including Couenne, Ipopt, and CBC.

The optimization code is a Python script for solving an optimization problem related to energy consumption and cost. It uses the Pyomo library to build and solve the optimization model. The code imports the necessary libraries including pandas for data manipulation, pyomo for optimization modeling, and SolverFactory for selecting the solver. After importing the required libraries, the code reads input data from an Excel file using the panda's library. The input data includes hourly upper and lower limits of energy consumption for a given date. The code then calculates a base line by summing up the required energy. The optimization model is then defined using Pyomo's Concrete Model. It creates variables for each hour and constraints for limiting the variables within certain bounds, subject to assign percentage, and an objective function to minimize the cost of energy consumption. The constraints include the total consumption for each hour, the upper and lower limits of energy consumption, and an available capacity constraint that limits the use of a certain type of energy. The objective function is defined as a linear combination of the cost of natural gas, propane, and grid/clean power. The optimization problem is then solved using a MINLP solver. Finally, the solution is printed for each hour, showing the consumption of natural gas, propane, and grid/clean power for each hour.

2.4 New Gas Tier with Hourly Cap

The existing tier program for gas pricing is contingent upon the monthly consumption of gas. However, advancements in technology, such as the deployment of smart meters, have enabled the measurement of gas consumption on an hourly basis, similar to electric meters. This development presents a prospect to investigate the feasibility of introducing a new tier system, comprising an additional hourly component, alongside the current monthly overall cap.

The proposal of hourly caps for gas consumption can be conceptualized in two distinct ways: either as a singular cap that pertains to the entire designated period, or as a percentage of the projected hourly heating requirements. The percentage selected may vary depending on the desired savings objectives of the supplier organization. A crucial aspect to consider is that during the duration of the hourly cap, prices should be less than the original market price, but once the cap has been exceeded, prices must be raised accordingly. This method serves as a balancing mechanism to ensure that customers receive reasonable prices during the capped period while also allowing producers to maintain profitability when the cap is surpassed.

Finally, this new tier system can be utilized to encourage Gas Demand Response (GDR) and promote load shifting among customers who express their willingness to participate. The optimization formulation described in Section 2.3 in the context of multi energy sources can be adapted to incorporate the new tier system and reflects this scenario.

3. Results and Discussion

3.1 Simulation Model

The simulation model utilized in this study simulates the weather in New York City, where the winter season experiences a temperature drop to 10 F, resulting in a GDR trigger. The model was constructed in compliance with the ASHRAE 169-2013 construction standard for a Mid-rise Apartment, consisting of four thermal zones with individual thermostats to regulate required heating. The simulation model efficiently calculates the necessary energy requirements to maintain each zone at the designated thermostat setting temperature. Also, the model accounts for the number of occupants in the household, activities, and even occasions such as holidays. Moreover, the model is capable of producing a comprehensive energy report that outlines all the energy requirements, including lighting, cooling, and heating needs for an entire year, with hourly breakdowns for each result. The model's four thermal zones allow for individual management, which provides the potential for further optimization based on each zone's projected activity. The generated report includes data including but not limited to:

- Annual energy overview.
- Monthly heating/cooling requirements.
- Monthly peak for heating/cooling.
- Outside temperatures.
- Each zone conditions including temperature and humidity.
- Occupancy activity and schedule.
- Equipment sizing such as HVAC.

Extracted energy are provided below for the annual energy overview (Figure 2) and HVAC load profiles (Figure 3).

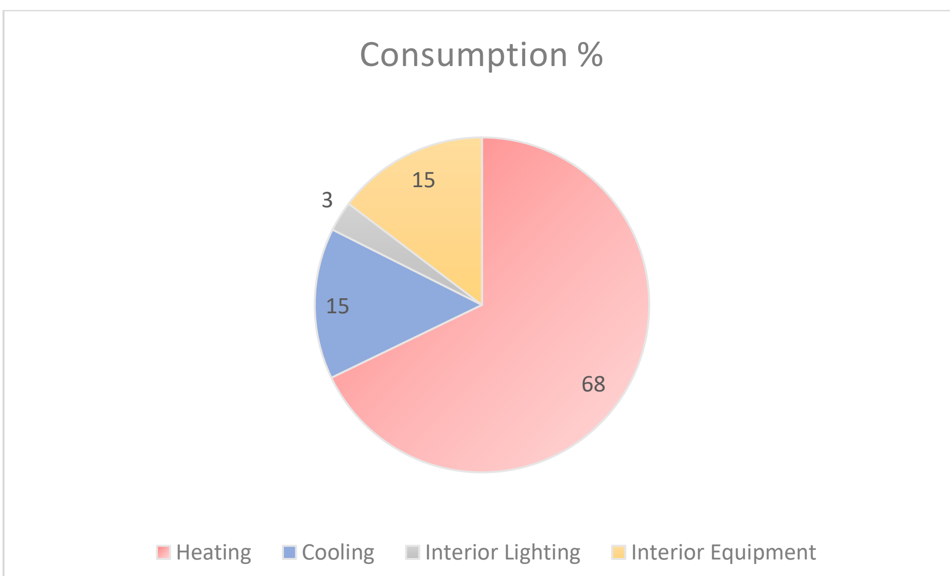

Figure 2: Apartment annual energy overview.

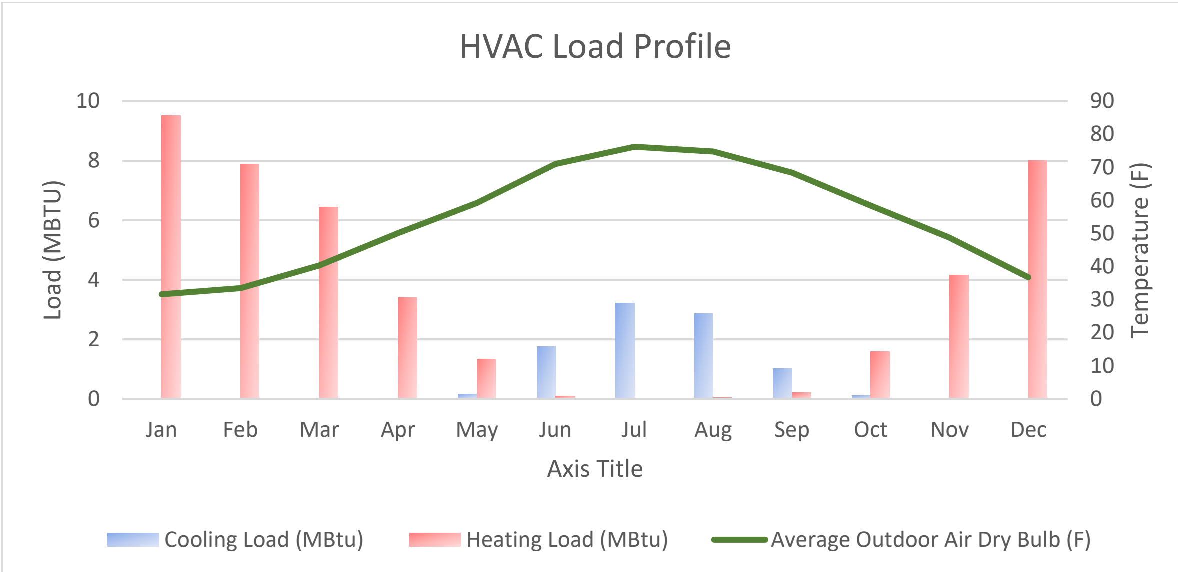

Figure 3: HVAC load profiles.

3.2 Multi-Zone Approach

The availability of a well-constructed simulation allows us to control the environment and investigate different scenarios with a range of changes. As previously proposed in Section 2.2, a multiple zone approach, to reduce the required energy for heating during normal days and especially during GDR, can be evaluated with relaxed or very severe changes to evaluate the effectiveness of the approach. Here, we are going to examine the effect of a 24-hour course where we change the schedule of occupancy for each zone and reduce the thermostat setting temperature. Then, we measure the reduction in the energy demand for that certain day. In this model we divide the apartment into three major zones based on the use of each area; however, only two zones will be subject to the changes. A thermostat schedule for both zones was assigned, and the demand was recorded for each case. The required energy for heating during a year is shown in Figure 4.

3.2.1 Base Case

In this model we established our base line of energy requirement to maintain the space temperature at 71°F all the time.

Table 1: Base case zones thermostat.

Zone	Base schedule
Bedrooms space	The zone is maintained at 71°F all the time
Living space	The zone is maintained at 71°F all the time

3.2.2 Adjusted Temperature Cases

The models utilized in this study involved adjusting the thermostat setting temperature for each zone, according to the occupancy schedule. Specifically, a temperature of 71°F was maintained when the space was occupied, while 68°F was set for times when no occupancy was expected. The resulting thermostat schedule was then used to calculate the required energy for each zone.

Case 1:

Table 2: Thermostat schedule for each zone in Case 1.

Zone	adoptive schedule
Bedrooms space	The zone is maintained at 71°F during night and reduced to 68°F during the day from 10:00am to 8:00pm

Living space	The zone is maintained at 71˚F during daytime and reduced to 68F during the night from 10:00 pm to 8:00 am

Case 2:

Table 3: Thermostat schedule for each zone in Case 2.

Zone	adoptive schedule
Bedrooms space	The zone is maintained at 71˚F during night and reduced to 66˚F during the day from 10:00am to 8:00pm
Living space	The zone is maintained at 71˚F during daytime and reduced to 66F during the night from 10:00 pm to 8:00 am

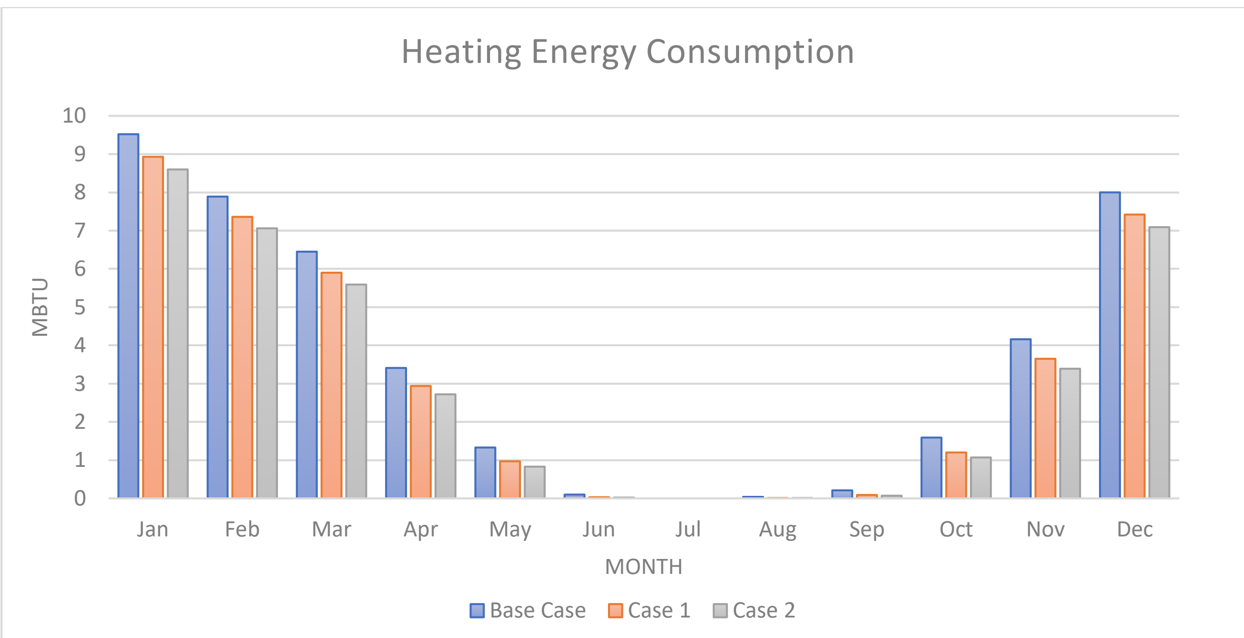

Figure 4: Monthly heating energy for all cases.

The findings of the three cases investigated demonstrate that the savings achieved in terms of required heating energy are significantly influenced by both the thermostat temperature and the zoning schedule employed. Specifically, the second case resulted in an overall savings of 6% compared to the baseline, while the third case yielded a greater savings of 9.6%. Notably, in both cases, the occupancy schedule was taken into account, with no compromise to occupant comfort. These results indicate that the implementation of zoning techniques could potentially yield even greater energy efficiency gains, particularly if coupled with smart metering technology that enables the generation of tailored schedules based on household activity. Although available technology could be utilized to facilitate such enhancements at a reasonable cost, it should be noted that this falls beyond the scope of the current research.

The saving achieved through the multizone approach may vary depending on external weather conditions such as temperature and wind speed. To examine the effectiveness of the multizone approach on a specific date with a high likelihood of a Gas Demand Response (GDR) event, the collected data was analyzed for January 28th, 2016, between 4:00 am and 2:00 pm. During this time-period, the outside temperature ranged between 10 to 14 degrees Fahrenheit, which is the lowest during the winter season. The resulting savings for the three cases discussed earlier are shown in Figure 5.

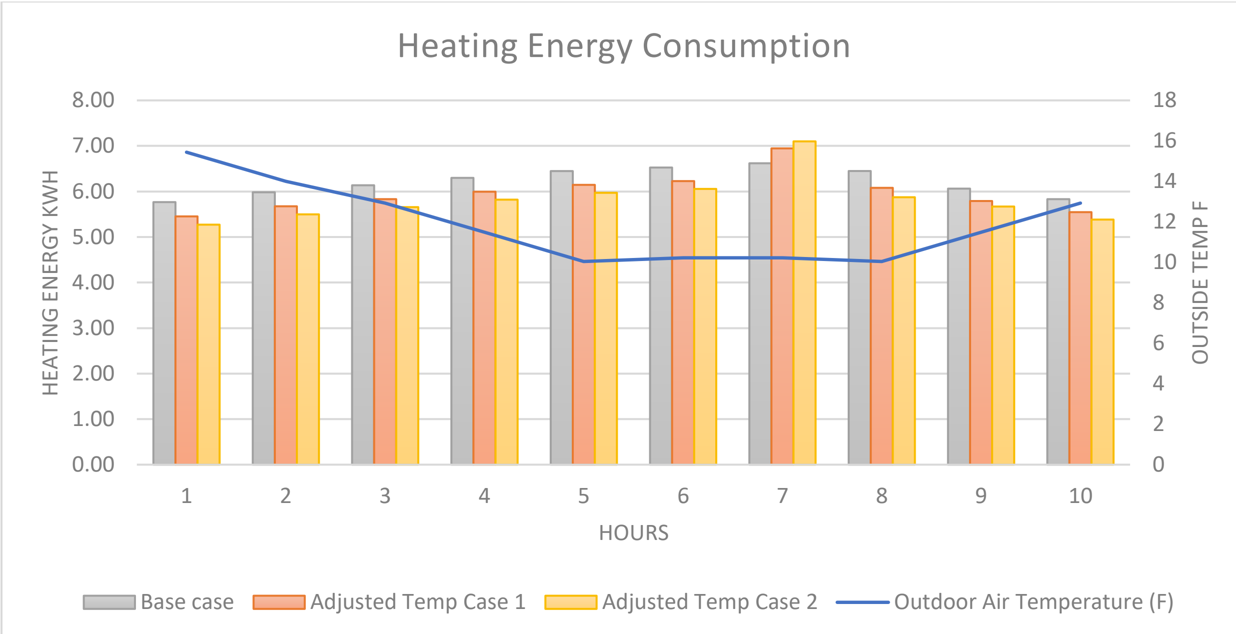

Figure 5: Heating energy during GDR event for all cases.

The observed savings in energy consumption exhibit significant variations depending on the selected period. Specifically, for the chosen period on the 28th of January 2016 between 4:00 am and 2:00 pm, where the outside temperature was considerably low, the savings varied as expected. The first case resulted in a saving of 3.9%, while the second case resulted in a higher saving of 6.2%. Although the savings may seem modest, they are significant during the event of gas demand response, particularly in the residential sector, where even small changes can have a significant impact.

3.3 Multi Energy Source Optimization Approach

In this study, the simulation model serves as a valuable tool in predicting the required energy for specific hours on any given day. The primary objective is to meet the energy demand while exploring alternative sources other than natural gas, such as propane or generated/stored clean energy. The decision to switch to various sources is influenced by two critical factors. The first factor is the prices of each source, which are inherently dependent on the location. The second factor is the availability of incentive programs for energy reduction, which encompass rewards and quantification methods such as usage baselines for individual users and maximum rewards.

The developed Python code employs forecasted energy demand, various source energy prices, and incentives to identify the most optimal energy sources for each hour. Through the evaluation of different GDR durations and incentive limits, we quantify the savings achieved for each scenario. The obtained results facilitate the identification of appropriate incentive values and limits based on the required load reduction of natural gas.

The results obtained demonstrate that the optimization code does not exhibit a specific pattern when diverting energy to alternative sources. Instead, the code prioritizes achieving the minimum cost and utilizing all available clean power, which is considered as free power. However, in situations where a particular pattern, gas reduction, or smoothing of changes based on equipment requirements are desired, the code needs to be subjected to further restrictions and fine-tuning.

The simulation model has provided us with a full year of data, from which we have identified that the lowest outside temperature occurred on January 28th, 2016. During this day, temperatures ranged between 10 to 14 degrees Fahrenheit from 4:00 am to 2:00 pm, as illustrated in Figure 6.

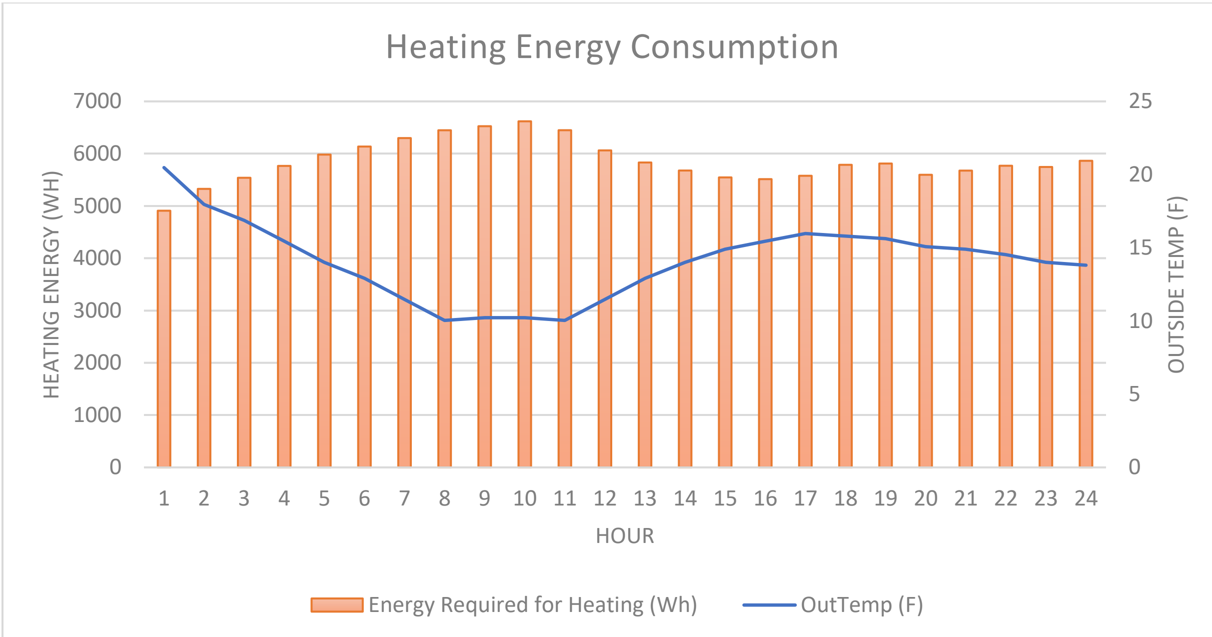

Figure 6: Hourly heating energy for 28th of January 2016.

The above date is provided to the optimization tool (Python code) and a time range from 4:00 am to 2:00 pm is specified to determine the energy source selection, using the data provided in Table 4.

Table 4: Prices and Incentive information.

New York	Price	Unit
Natural Gas	24.56	$/MCF
Propane	3.3	$/Gal
Electricity	0.224	$/kWh
Incentive Rate	20	$/therm saved
Maximum incentive	0.5	$

The optimization code uses Table 4 data with the predefined method of calculation as discussed in Section 2.3 to obtain the hourly required energy and calculate the source of energy for each hour. Results for the selected time event are summarized in both Table 5 and Figure 7.

Table 5: Event overall energy and cost.

	Result
Total energy used (Wh)	60711
Energy Gas Generated (Wh)	53508
Gas Reduction (%)	11.8%
Total Incentive ($)	0.49
Cost if using Gas only ($)	4.81
Cost with Multi-Source and Incentive ($)	4.74
Realize Saving (%)	1.5%

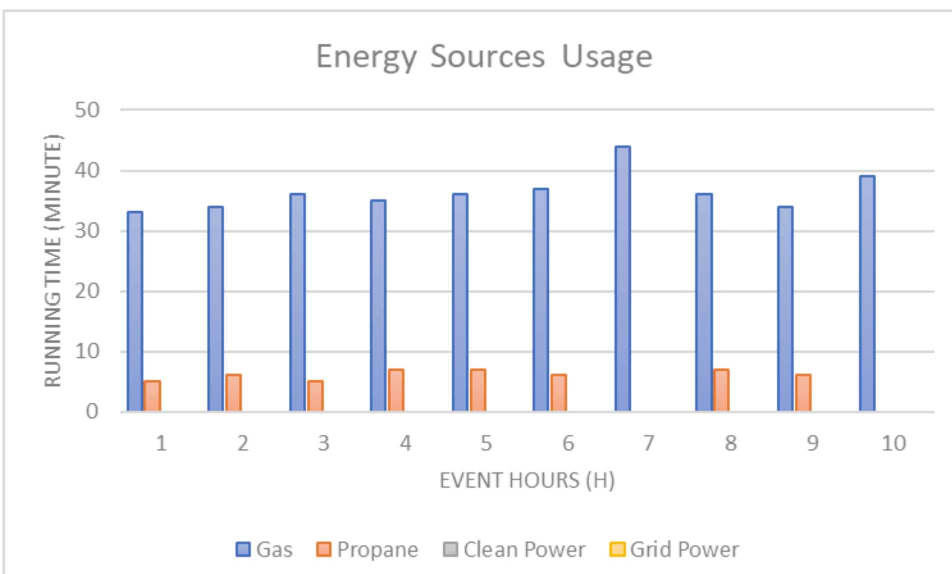

Figure 7: Energy sources distributions.

The bar chart in Figure 7 illustrates the recommended diversion of energy to propane based on the current incentive value and limitations. Notably, no energy is directed to the Grid Power (GP) as its cost is considerably higher compared to other sources. Nevertheless, in case of available clean energy, which is deemed as free energy, the optimization solution will utilize it during the occurrence of GDR.

It is worth noting that the assessment of the optimization code's response is not focused on the availability of clean energy; hence, for the purpose of evaluating the code's performance, a hypothetical amount of 2000 Wh of clean energy is assumed. Consequently, the same scenario as described above is employed, taking into consideration the availability of clean energy. The results for the proposed scenario are summarized in both Table 6 and Figure 8.

Table 6: Proposed scenario overall energy and cost.

Name	Result
Total energy used (Wh)	60359
Energy Gas Generated (Wh)	53067
Clean Energy Used (Wh)	2000
Total Incentive ($)	0.50
Cost if using Gas only ($)	4.79
Cost with Multi-Source and Incentive ($)	4.44
Realize Saving (%)	7.3%

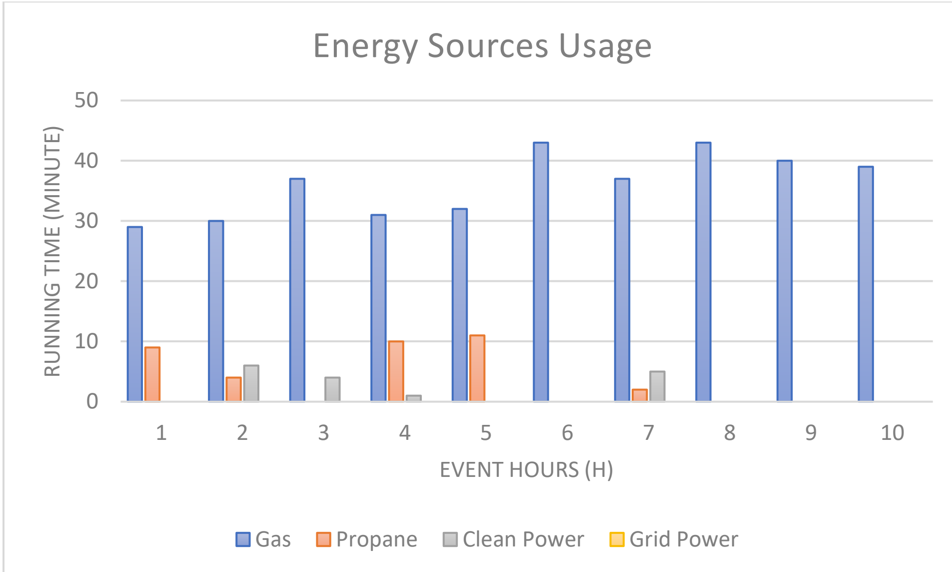

Figure 8: Proposed scenario energy sources distributions.

As anticipated, the optimization solution maximizes the utilization of clean energy within the optimization period. However, no noticeable pattern is observed in the timing of energy usage, as the code prioritizes overall cost minimization. This case demonstrates the aptitude of the optimization code in accurately responding to the provided prices, incentives, and availability of clean energy. Therefore, it is recommended to consider the availability of clean energy only when it is in excess and there is no other usage for it, based on the pricing. If users have the capability to utilize clean electricity instead of the grid, it could result in additional savings on the overall bill.

3.4 New Gas Pricing Tier System with Hourly Cap

The new tier system discussed in Section 2.4 was evaluated using the same optimization tool, but with additional constrains and parameters to account for the hourly cap tier. Similar to the pervious case considered in Section 3.3, the evaluation focuses on a specific event where GDR is more likely triggered. In the present case, the hourly cap is determined as a percentage of the total projected energy requirements for heating, as follows:

$$Hourly\ Cap = 0.5 \times \frac{\sum_1^H ER}{H}$$

The natural gas price is reduced by 10% if the hourly energy usage remains within the hourly cap. Conversely, if the hourly usage exceeds the cap, the natural gas price increases by 10% of its original value. Furthermore, the incentive provided to customers is reduced by 10% to align with the higher-tier pricing of natural gas. A summary of these parameters is presented in Table7.

Table 7: Hourly cap tier prices and incentive information.

New York	Price	Unit
Natural Gas 1	22.10	$/MCF
Natural Gas 2	27.02	$/MCF
Propane	3.3	$/Gal
Electricity	0.224	$/kWh
Incentive Rate	18	$/therm saved
Maximum incentive	0.5	$

To start with, we establish the base case result by running the code with no incentive for the same selected date, which is January 28th, 2016, from 4:00 am to 2:00 pm. The results for the selected time event are summarized in both Table 8 and Figure 9.

Table 8: Hourly cap tier, overall energy and cost.

Name	Result
Total energy used (Wh)	60711
Energy Gas Generated (Wh)	60711
Clean Energy used ($)	0
Total Incentive ($)	0
Total cost ($)	4.83

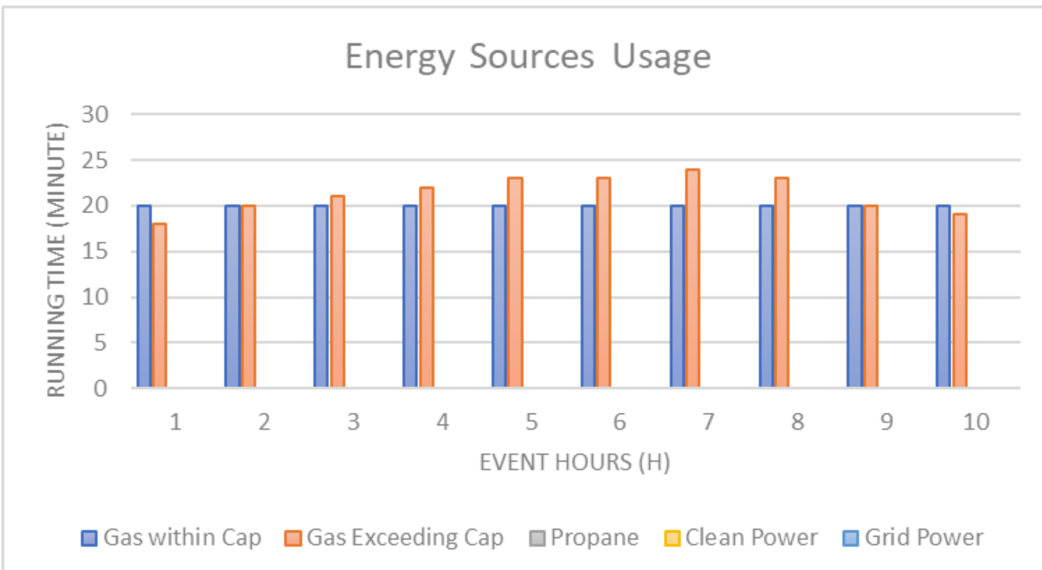

Figure 9: Hourly cap tier, energy source distributions.

As expected, the optimization solution continues to prioritize the utilization of natural gas to meet demand, as the driving force behind the optimization is the pricing strategy. Customers have the potential to achieve savings through load-shifting or demand reduction. However, the incorporation of an award system introduces a greater incentive to utilize alternative sources of energy when the hourly cap has been exceeded.

While this poses a more complex optimization problem, the potential rewards become more appealing.

The following tables present the outcomes of two distinct scenarios, each of which incorporates the application of a new tier system. In the first scenario, incentives are applied solely to customers who agree to participate, whereas in the second scenario, incentives are combined with the availability of clean power. The primary aim of this investigation is to gain greater insight into the resulting outcome. Overall energy results are summarized in Tables 9 and 10, without and with the presence of clean energy, respectively. Also, the energy source distributions are illustrated in Figures 10 and 11, without and with the presence of clean energy, respectively.

Table 9: Hourly Cap Tier, overall energy, and cost in presence of incentive program.

Name	Result
Total energy used (Wh)	60711
Energy Gas Generated (Wh)	52626
Gas Reduction %	13
Clean Energy used (Wh)	0
Total Incentive ($)	0.50
Cost if using Gas only ($)	4.83
Total cost ($)	4.74
Realize Saving (%)	1.9

Table 10: Hourly Cap Tier, overall energy and cost in presence of incentive program and clean energy.

Name	Result
Total energy used (Wh)	60359
Energy Gas Generated (Wh)	52332
Gas Reduction %	13
Clean Energy used (Wh)	2000
Total Incentive ($)	0.49
Cost if using Gas only ($)	4.80
Total cost ($)	4.43
Realize Saving (%)	7.7

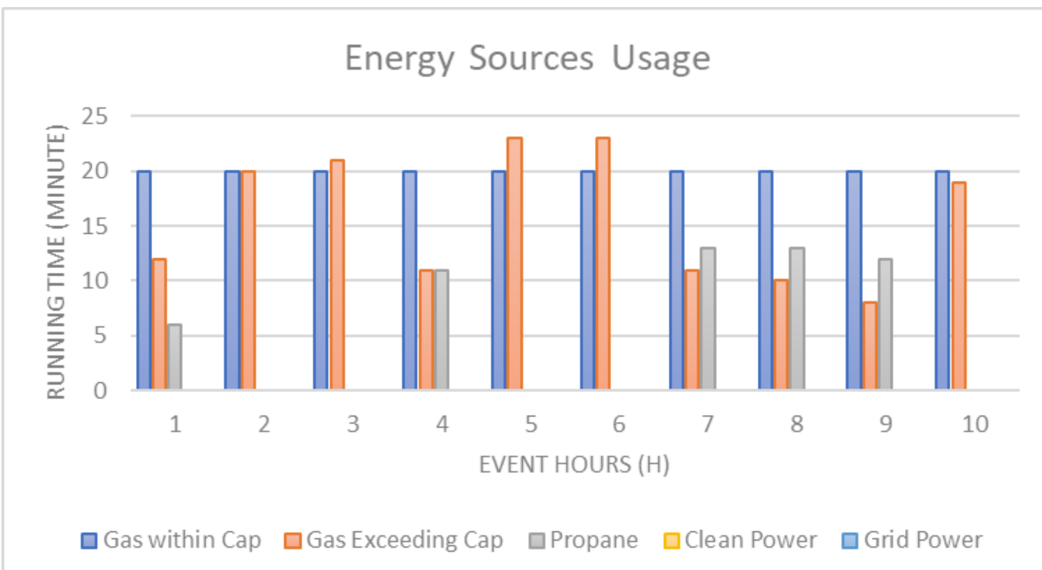

Figure 10: Energy source distribution for hourly cap tier in presence of incentive program.

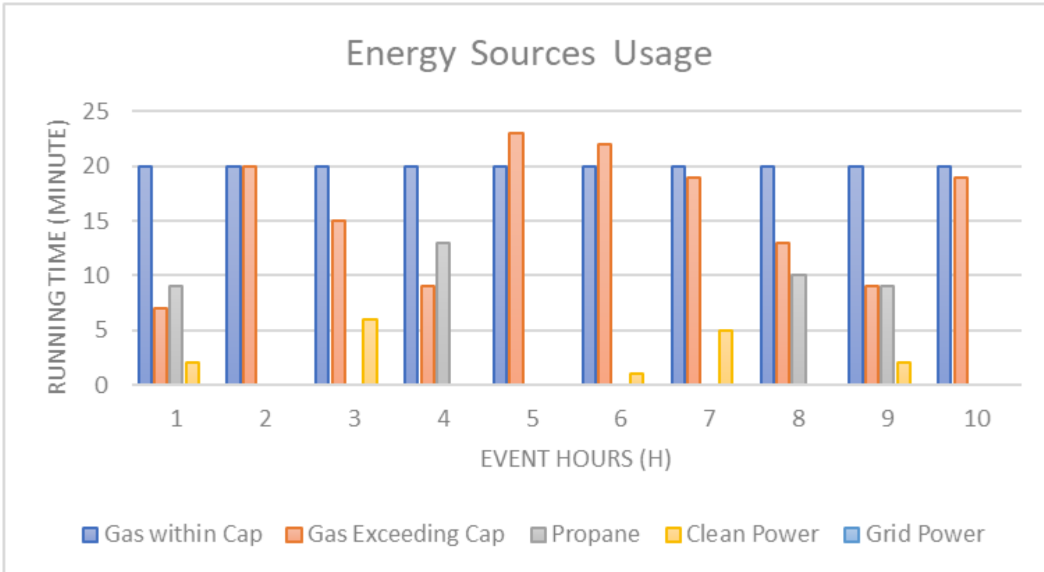

Figure 11: Energy source distribution for hourly cap tier in presence of incentive program and clean energy.

In both scenarios, the optimization solution was successful in diverting energy consumption to alternative sources and reducing reliance on natural gas. However, in the presence of clean energy, greater cost savings can be achieved than in the first scenario. This is not only due to the utilization of the available 2000 Wh of clean energy, but also because the optimization solver has the ability to determine when to utilize this energy. Consequently, the dependence on higher-priced sources is minimized, resulting in reduced total costs for customers.

3.5 Combining Zoning with Multi Energy Source Optimization

In the prior scenarios, the emphasis was placed on implementing a singular measure or optimization strategy that either reduced the heating load or redirected energy consumption to an alternative source, based on the availability of incentive programs. However, the integration of a two-step approach can potentially provide additional opportunities to the case, but only if there is still sufficient room for incentives. In other words, if the implementation of a multizone approach fails to achieve the anticipated savings for the supplier, a multi energy source approach can be implemented as a second step to continue the optimization process. The primary determinant for the continuation of the optimization is the maximum incentive that can be offered.

Furthermore, the second step of the optimization process can be further segmented based on the demand of each zone, rather than optimizing the entire space as a whole. This approach enables a more granular level of optimization and has the potential to generate greater cost savings. This area warrants further investigation in future studies.

To investigate this approach, a hypothetical scenario targeting 10 % savings can be created wherein the anticipated cost savings are not entirely realized through the implementation of a multizone approach. In such a case, a second-step optimization strategy could be considered worthwhile to pursue. Figure 12 illustrates the required energy, in order to maintain the space temperature at the thermostat set-point, for the time period between 4:00 am and 2:00 pm, before and after the implementation of the multizone approach.

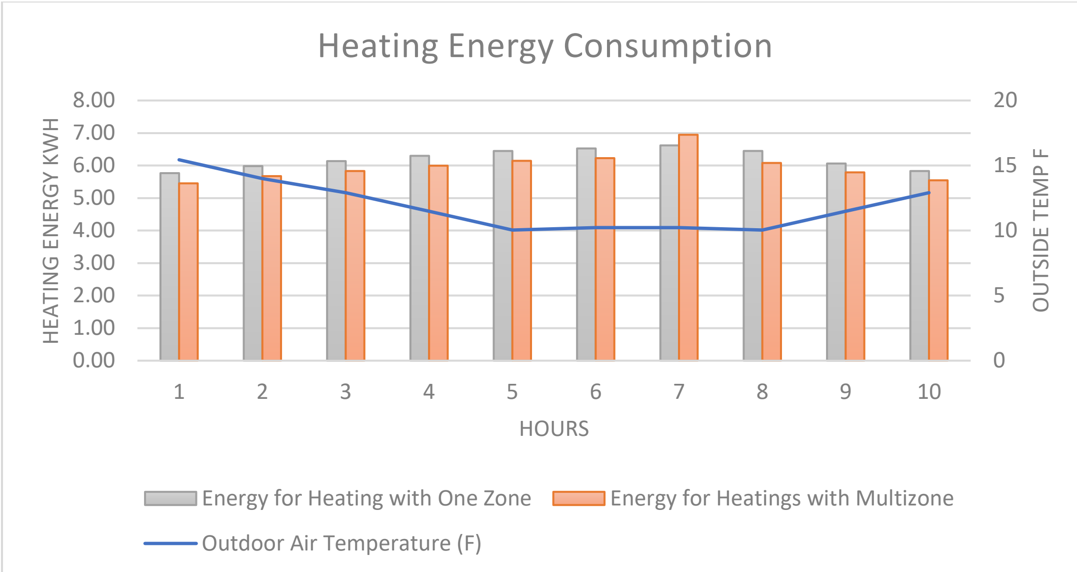

Figure 12: Required energy before and after the implementation of the multizone approach.

In this particular case, the achieved saving during the event is 4.2%, which falls short of the target saving of 10%. Nonetheless, further optimization opportunities exist to bridge the gap and achieve the desired level of saving. The actual saving amounts to 2.5 KWh, corresponding to a value of $0.17 under the assumed incentive program. It follows that there is still potential to optimize the energy source and secure additional savings of $0.33.

Inputting the newly generated hourly data into the optimization code, the resulting data is summarized in Table 11.

Table 11: Overall energy and cost when the multi-zone and multi-source approaches are used.

Name	Result
Baseline (Wh)	60271
Total energy Needed (Wh)	57771
Energy Gas Generated (Wh)	53508
Extra Gas Reduction %	8.1
Incentive ($)	0.33
Cost if using Gas only without Multizone ($)	4.81
Cost if using Gas only with Multizone ($)	4.62
Total Optimized cost ($)	4.36
Total Saving %	9.4

In this case, the calculation of the energy baseline was done without considering the multizone approach. The results showed that the target savings for this scenario were achieved more closely with the utilization of both multizone and multi-energy source approaches.

4. Conclusions

In this work, we explored various ideas and strategies for demand-side management of natural gas consumption in residential systems. The investigation was facilitated using a simulation system test bed of a typical mid-rise apartment in New York City. The use of simulation models is a crucial tool for predicting the energy required to maintain indoor temperatures and forecasting grid disruption risk events. While historical data may be more accurate, it lacks the ability to control the finer details of a household, such as equipment and occupancy activity, and forecast changes in energy demand for different scenarios. Simulation-based models can, therefore, play a vital role in studying the impact of the proposed scenarios. By generating a correlation between outside temperature, house size, type, households, occupancy activity, and energy demand, correlations can be embedded within thermostats to ease the heating system's response in the event of a GDR trigger. This not only empowers customers to manage their demand but also enables suppliers to forecast potential reductions as a whole. Such knowledge helps avoid unnecessary grid expansions to accommodate counted events.

The multi-zone approach, while promising, can be further improved with modern technologies such as smart algorithms and the Internet of Things to understand occupancy activity schedules and manage heating requirements accordingly. The multi-energy source optimization approach, coupled with incentive programs, may result in overall cost savings during GDR events. However, this approach is sensitive to alternative fuel prices and the values of both incentives and their maximums. In locations where propane is relatively inexpensive, it could be used as an alternative source with the presence of incentive programs. This approach shows a promising reduction in the use of gas as fuel, which is the primary target for suppliers. The combination of the multi-zone and multi-energy sources approaches results in even greater savings, particularly with the integration of clean energy sources that can be utilized during GDR events.

The proposal of a two-caps pricing system shows promise since it incentivizes those who contribute to energy savings without compromising the supplier's profits.

Additionally, it encourages load shifting, enabling customers to make even greater savings. Further exploration of this proposal is necessary to determine the most effective pricing system and incentives.

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