
Analytical Study of Insulation, Air-Sealing, and High-Efficiency HVAC in Affordable Housing for Energy Affordability in Cold-Climate region (Western PA)

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Abstract

The economy of energy has become a sufficiently significant, but less extensively researched, factor of housing stability, especially in housing areas with cold temperatures, such as where the LMI households reside. Traditional Housing affordability factors have assumed that it is mostly rent or mortgage payments rather than rising utility bills. This study discusses the impact of escalating costs of energy in residential housing in Pittsburgh and Western Pennsylvania, whereby residential housing costs are normally jeopardized by utility costs. The research was a case study design of a vacant single-family living room undergoing renovation through specific energy-saving measures that were dense-packed insulation, full air sealing, and high-performance heat pump HVAC systems. The study that was under evaluation was one that assessed the amount of energy both at pre-rehabilitation and post-rehabilitation by using the U.S. Department of Energy Home Energy Score and estimating a reduction in utility costs. The performance on the energy has been credited as having brought about a reduction of 44% in the energy consumption and over \$470 saved annually in utility costs. The research proves that energy retrofits minimize the redundant energy factored to address LMI households, leading to less challenging illness of housing affordability and reduced displacement trepidation. The findings indicate that the economic feasibility of energy must be considered as part of the housing policy, as the cost of energy must be factored, as this is necessary in the creation of long-term stability of housing. Future research should extrapolate those findings to other climates and socio-economic settings to ensure that the housing solutions are applied on a broader scale to the vulnerable populations.

Keywords; *Energy Affordability, Energy Efficiency Retrofits, Low- and Moderate-Income (LMI) Households, High-Efficiency HVAC Systems, Cold-Climate Housing Stability.*

1. Introduction

Housing stability has been a challenging social and Economic policy in discourse for a long time. The conventional method of measuring housing affordability, such as the “30% rule”, gives more attention to front-end prices, including payment of rent or mortgages. Though these expenses are paramount in the procedure of discerning the affordability of housing to the residents, they do not provide the full extent of the financial burden on the homes. These opportunity costs consist of utility bills, which are becoming too expensive for low and middle-income (LMI) earners, especially in this harsh climate. The heating, cooling, and electricity costs are as much as renting and mortgage payments in families in cold-weather places such as the city of Pittsburgh in Pennsylvania, and the last home is very much affected. This financial dead weight cannot be registered under the conventional housing affordability baseline, which is why the factor is a very secretive and contributory factor of housing instability within the LMI households. Such households are compounded and amalgamated with financial, environmental, and social issues that constitute the general stability of households.

The largest expense can eventually be the utility bill rather than the rent or mortgage calculation in cool climates, such as in Pittsburgh, where there are houses that are unmanaged in terms of energy systems. An unbalanced load is an affront to housing affordability, and that is why the LMI households are an issue, especially. When compared to the Area Median Income (AMI) in Pittsburgh, utility bills were almost doubled by percentage, which has imposed a serious burden on the economy of such households. The scenario of affordable housing is more imminent considering the upward trend in utility prices. This paper seeks to present the direct and indirect impact of this rise in energy costs on the housing stability in Pittsburgh and Western Pennsylvania, and especially how the inefficient housing stock raises energy payments among LMI households. The research is aimed at approximating how energy prices affect the overall financial health and stability of such families in areas that are unknown to standard indicators of affordability.

The urgent character of this research problem is even higher in terms of the rising energy prices and the growing awareness of the fact that not even housing affordability can be measured properly without considering the energy prices. As the utility rates are gradually increasing, which is especially intense in cold climate

regions, the economic cost imposed on homeowners and the warmers is multiplied. The issue of affordability of houses in the modern economy cannot just be evaluated using the traditional approach of defining housing affordability by merely basing it on the housing costs that include rent or mortgage, since it would not give the complete scenario of the affordability of housing. Energy in the future will continue to rise steadily over the upcoming few years, and therefore, creation of an energy benefit system into the affordable housing mechanism is essential in reducing the costs of utility and making them more affordable in the long-term overall. The energy-efficient retrofits, such as the improved insulation and the additional air sealants, as well as the construction of the high-efficiency HVAC, which can mitigate the rise in utility spending, are some of the possible resolutions to this. This paper shows how the concept of housing affordability is urgently in need of reform to ensure that the cost of energy is taken into consideration, such that more sustainable solutions to housing can be offered to the populations of LMI.

The present paper will limit itself to the aspect of housing stability that has been poorly addressed, that is, energy affordability, when discussing the impact of intentional home energy saving measures on utility bills and energy burden in Pittsburgh. Specifically, the paper will quantify the uses of the energy retrofits on the effect of the Department of Energy (DOE) Home Energy Scores. The study also seeks to estimate the ratio of equilibrium attribution of the lower household utility cost and the acuity of energy. It will show why the affordability of energy is one of the reasons that should be considered in the platforms of the housing policy. However, this study will offer research-grounded information, which will guide policy and practice, and implement energy saving policies, which will see the LMI families stay stable in the long run in the housing issue. This is factored in respect of developing a deep perspective of housing affordability compared with the accepted principles of gauges, which moderate effective models of overall settlement.

The study is structured in various chapters. The Literature Review gives the whole framework of the exploration of the literature on housing charges and energy load, and sets a precedent for the detailed elaboration of the theme. The methodology chapter explains how the method was adopted in order to gather and analyze the data that was applied against which the research was conducted. The Results chapter contains both quantitative and qualitative results, which discuss the impacts of energy retrofits in terms of the economic and energy trends in a region. The discussion chapter examines the policy implications of findings and gives recommendations for future research. The study concludes by highlighting the summary of the discussion of

the findings of the research option, as well as offering the next course of action to foster the environment of housing stability, which involves the affordability of energy.

2. Literature Review

2.1 Evolution of Housing Affordability Frameworks

The conventional views of affordability of housing have generally involved application of the so-called “30% rule”, in which the degree of affordability is evaluated by finding the proportion of household income being spent on rent or mortgage payments. Households that spend over 30% of their incomes on them are deemed cost-burdened, which has been used in the policy of housing and city planning. This structure has, however, been criticized as being limited, because it fails to address several other essential costs, especially the costs of energy, which can easily affect the low- and middle-income (LMI) households substantially.

The graph in Figure 1 presents a comparison of housing expenses as a percentage of earnings of two households, and the affordability of houses is based on the standard rates of 30% established by convention. Household A is considered affordable because their housing expenses comprise below 30% of their earnings, but Household B has a higher price, thus forcing them to be burdened with costs or lack affordability. Such a standard affordability model, however, does not take into account the role of energy expenses, which may disproportionately impact low- and middle-income (LMI) households (Brown, Soni, Lapsa, & Southworth, 2020). The “30% rule” does not take into account the costs of energy, hence it does not reflect the entire financial strain these households are subjected to, particularly in the cold climates.



Figure 1: Comparison of housing costs vs. income using the 30% affordability rule

Scholars argue that with the omission of the payment of energy, the exclusionary rule renders the “30% rule” impoverished in its nature of explaining the overall financial load on households, especially in climates where the energy dependency is high. These weaknesses have prompted the introduction of alternative measures of affordability, among them, shelter poverty as well as residual income theories (Stephen Ezennia & Hoskara, 2019). These models incorporate the cost of energy into the mass market equation to demonstrate that housing is an inefficient commodity when it comes to the affordability of housing, as the entire revenue is spent on utility bills. The models highlight the need to have a broader definition of affordability, which must involve the overall housing cost, which should include shelter costs and also energy costs.

2.2 Energy Burden and Its Impact on Housing Stability

The total disbursement of the LMI households on energy is a huge percentage of their spending. Studies reveal that the energy expenses represent 10% to 20% of overall housing spending by the LMI dwellers, but the households with greater incomes incur 3% to 5% of their income on costs of utilities. In areas of cold climate, especially, the effect of ineffective housing stock adds to the impact of heating, cooling, and electricity expenses. For example, families residing in parts of the country such as Pittsburgh, where winters are very cold, experience relatively high heating bills as a result of low-insulated houses.

The resulting rise in energy costs adds strain to the already LMI families, who have to spend a substantial amount of their income on utility bills, despite the houses being located in neighborhoods that would otherwise be considered affordable on rent or mortgage principles. With the persistence of increased utility rates, LMI families have an elevated chance of housing instability, finding it hard to make their utility and shelter expenses, and usually facing premature repair, overcrowding, or even displacement. Energy burden has thus become a crucial determinant during the examination of the overall concern of housing stability (Chen, Chen, Liu, & Rickard, 2024).

2.3 Impact of Energy Efficiency Retrofits

Energy efficiency retrofit is also taken as one of the best approaches to decrease the number of uses in relation to energy usage and to remove the economic pressure of elevated utility costs. Research has indicated that it was possible to reduce energy expenditure by 20% or more using such measures as the advancement in insulation, new air seals, and modern air conditioning, ventilation, and heating (HVAC) due to the efforts (Bonthu & Goel, 2025). Through these retrofits, there are serious cases of

saving oodles of money, and also improving comfort and health conditions, since it assists to sustain frequent indoor conditions and minimize dampness-related risks, which are widespread in inefficient lodgings.

Reduced energy use also contributes to housing stability in the form of the minimization of the total energy load. There are specific cold-weather conditions where these benefits are especially applicable, such as the climate of Pittsburgh, where the financial and health effects of inefficient housing may be too severe. The multifarious advantages of energy efficiency retrofits denote that they are highly practical in improving economic and ecological performances, to sustain the maintainability of the financial profile in the long run of LMI families.

2.4 Challenges in Implementing Energy Efficiency in Affordable Housing

Although energy efficiency retrofits were proven and realized to be beneficial, it is not commonly seen in low-cost housing, and it is an issue. Such barriers to implementation of the energy saving technologies are beyond count, especially in the past housing markets wherein the old housing is going back to the pre-war houses, like in Pittsburgh. The enormous upfront cost, which may be well out of reach for many developers and house occupants in retrofitting, is a huge hurdle.

There are many possible sources of financing, but they are bad or unusable by low-income families (Raju, 2017). There is also a lack of qualified contractors who would be able to do these special retrofits, and discourage further execution. Incentive tension between the tenants and the landlords is a long-term problem, as the landlords might have no motivation to involve the tenants in energy conservation projects that can be of the most benefit to the latter. These constraints imply that the prospect of an energy efficiency upgrade is imminent, but it is generally unequal and unsatisfactory, more prominent where the costliness of houses is already high in those markets.

2.5 Policy Landscape and Gaps

There are several government plans in place to address the affordability issues of energy, which are the Weatherization Assistance Program (WAP) and the Low-Income Home Energy Assistance Program (LIHEAP). Such programs reduce the energy burden on LMI families by increasing financial assistance to pay the electric bill and availing funds towards energy conservation activities. This indicates that the efficiency of energy maximization can be enhanced through a combination of a policy of regulation, information, and incentives, as presented in

Figure 2 below. Such policies are needed to assist in reducing the energy expenses, especially those that households with low- and middle-income (LMI) face. Examples of such programs include the Weatherization Assistance Program (WAP) and the Low-Income Home Energy Assistance Program (LIHEAP) programs (Cook, Williams, Harmon, Xu, & Nissen, 2024). The impact of these efforts mitigates the energy burden on the families of LMI, since they receive financial assistance to pay utility bills and finance energy-efficient interventions, which demonstrates the acuity of the necessity to take into account the policy frames that provide short-term energy assistance and energy-saving effects in the long run.

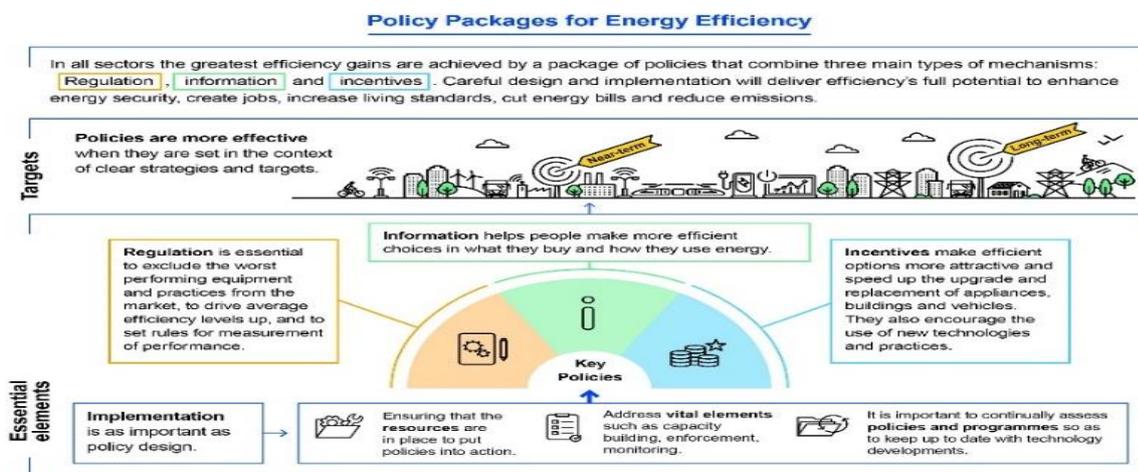


Figure 2: Policy packages combining regulation, information, and incentives to improve energy efficiency.

Nevertheless, these programs are frequently undermined by inappropriate funding, internalized nature, and false access to integration into the scaled efforts of affordable housing development (Pinnapareddy, 2025). This means that a big proportion of LMI households fail to enjoy the entire spectrum of services. Available policies are not coordinated and comprehensive to bring down the costs of energy consumption in the development of affordable houses, which also leads to a tightening of the screw. There exists an increasing demand for a policy framework to ensure that, besides giving short-term financial relief, the issue is addressed with long-term energy-efficient solutions being integrated into affordable housing projects.

2.6 Equity and Access to Energy Efficiency Programs

Equitable access to the advantages of such interventions, especially by vulnerable groups, is one of the most urgent issues of energy efficiency policy. Green building plans and efforts are on the increase, but in these, there is a tendency for the city to give priority to LMI households. Though useful, such programs as WAP and

LIHEAP are not universally available to needy people, particularly in older housing markets such as in Pittsburgh (McCullough, 2020). The inconsistency of the data and the low reach also harm those initiatives, resulting in differences in access to the benefits of energy efficiency. These populations and individuals that would gain the most benefit in a scenario where the price of energy takes the center stage are therefore left behind in the transition to a more energy-efficient home (Xu & Chen, 2019). This inequality of access means that there must be certain measures that will facilitate the provision of these benefits to those people in greatest need to enhance environmental sustainability and social justice (Koneru, 2025).

2.7 Gap and Limitations in Literature

Regardless of the progress that has been made in the area of energy affordability, numerous gaps are still present in the literature. One of the significant constraints of cold-climate, heritage housing markets is a reflection on the lack of place-based, comparative research that can directly or positively correlate the energy retrofits with the housing stability results (Pantaleo, 2024). The majority of the studies explore larger data or thirty warmer climates and present a disjunction in our knowledge concerning the effects of energy retrofits on house stability in areas such as Pittsburgh, which is characterized by a distinct housing stock and climate. There is another deficit in evidence, where empty and inefficient buildings are systematically quantitatively calculated and transformed into energy saving costs, to be eligible to turn empty buildings into the main home of the LMI households, thus it becomes hard to conclude. This knowledge gap in the study shows that it is necessary to have both qualitative and empirical research, which must give a more macro-understanding of what the interventions are really doing to the energy efficiency.

3. Methodology

3.1 Methodology

The research discussed in the paper is mixed in nature, as both quantitative and qualitative contextual analysis energy performance modelling will be put into consideration in an effort to establish the impact of energy affordability on housing stability. The primary goal will be to assess the effects of retrofit on utility bills and, consequently, housing affordability, on low- and moderate-income (LMI) individuals residing in cold climates. The study is based on the observational/ cross-sectional research design, implying that the energy affordability dilemma concerning a representative sample of people can be comprehended extensively as per a representative case study. The case study will be based on a residential house

in a single-family home in the city of Pittsburgh, Pennsylvania, and is similar to an outdated housing stock that typically includes affordable housing programs. It is the combination that will ensure that the technical and socioeconomic factors that affect the affordability of energy are taken into account, which will then enable the achievement of a wider perspective of the issue (Sardana & Brahmhatt, 2025).

3.2 Data Collection Techniques

The data collection exercise would be conducted using a quantitative and qualitative research work that would lead to a more balanced perspective of the effect that the affordability of energy can have on housing stability.

3.2.1 Quantitative Component

The quantitative factor is linked with the model of mass (energy) performance and is founded on the model of Home Energy Score (HES), by the U.S Department of Energy. This is the tool that has been chosen on the basis of its tried algorithms and general standards of studying energy efficiency. The modeling energy process will consider the modeling of two models, one of which will be developed before the rehabilitation, and the other will be created after the rehabilitation. The initial state of the house in question is the initial one known as a baseline state wherein the house is poorly insulated, the air leaks, and has the conventional HVAC system and water heat system.

The post-rehabilitation model proposes significant energy savings; they include dense-packed insulation, superior air sealing, the installation of a high-efficiency heat pump HVAC, and water heaters. These types of improvements have been chosen due to their potential in reducing the use of energy and also by maximizing the utility cost savings. The Home Energy Score technology will be able to give an appropriate condition of the simulation of energy usage and prediction of the utility bills in both scenarios and will consequently bring measurable results of energy affordability (Dhanagari, 2024).

3.2.2 Secondary Data

In addition to the energy performance data, secondary data on the trend of the local Area Median Income (AMI) and trends of an increase in the price of utility were collected. The sources of such data are peer-reviewed economic and housing studies that have been published in the last five years. Based on these external socioeconomic data points, the researchers can place technical findings in the backdrop context of the general economic conditions under which LMI households are subjected. This combination of data obtained using multiple sources that can be

considered reliable adds strength to the analysis and prevents the results of the research from being based on the socioeconomic facts of the analyzed region (Singh, 2025).

3.3 Sampling Strategy

The case study house was chosen purposely with the intention of representing the generic aging housing stock present in affordable housing programs in cold climates in city areas. Such purposive sampling means that the selected home is similar to the features of buildings that are the most demanding of energy efficiency measures, including weak insulation and out-of-date ventilation systems. The case study home has some inclusion criteria that must be satisfied, such as full vacancy, structural attributes commonly found in the area, and the ability to receive rehabilitation programs (Falcao, Machete, Castilho Gomes, & Gonçalves, 2021). Although the single-case study does not provide the capacity to fully conclude results for all low-income affordable housing markets, it gives an opportunity to study extensively in a narrow scope how the energy cost and housing stability may be affected by energy efficiency measures in a particular environment. The referenced case study also offers facts that could be considered in more global hypotheses and future studies.

3.4 Data Analysis Methods

3.4.1 Quantitative Analysis

Quantitative analysis would be the amount of energy and utility used before and after the energy retrofits. The results of the Energy performance of the Home Energy Score tool will be examined to determine the annual energy consumption and estimated utility cost of the covered area of both base and post-rehabilitation conditions. The data will be summarized by descriptive statistics, confirming the mean value or a given percentage decrease in the costs of consumption and utility bills (Kontokosta, Reina, & Bonczak, 2020). The change in energy efficiency will be quantified by the comparative analysis that will give a picture of the resonance of what type of savings might have accrued to LMI households owing to the implementation of the same retrofits. Regression curves shall be used to determine the relationship between utility savings in the shape of cost and local income data. The expected outcomes of this analysis will be the level to which the utilization cost of LMI households in the area can be decreased through energy refurbishment.

3.4.2 Qualitative Analysis

The quantitative data will be supplemented with the qualitative data to provide credence to a body of information on the socioeconomic drivers that contribute towards making a housing stable. This qualitative analysis will point to the contextualization of the quantitative results from the perspective of determinants of the adoption of energy efficiency at the system level into practice. The socioeconomic data shall be interpreted in the format of critical analysis, which will entail the household income, access to energy assistance schemes, and the remaining aspects of the economic factors that determine the cost of energy (Zhang, Shi, Zhang, & Xiao, 2019). It is a dual approach that will combine both quantitative and qualitative data and will enable it to obtain a deeper look at the combination of the affordability of energy and home security.

3.5 Validity and Reliability Measures

The validity and reliability of the findings will be achieved by several steps that will occur throughout the research. A peer-reviewed and nationally recognized model, the Home Energy Score, will be used to make the energy modeling process founded on a standardized and reliable method. The modeling scenarios will be piloted in order to test the quality and consistency of input data and the outcomes (Kamińska, Zwoliński, & Laska-Leśniewicz, 2022). Moreover, triangulation will be provided with the intent to combine technical modeling findings with socioeconomic information presented by various matching credible sources because the chances of finding bias will be diminished, and the validity of the analysis will be improved. Even though the study has a single-case design that does not allow generalized conclusions to the notion of a relatively wider population, the introduced clear reports of methodologies and findings will ensure that the study under review can be reproduced and contribute to future research works.

3.6 Ethical Considerations

Ethical considerations do not pose much risk since the study is based on data that is publicly available and on modeling use instead of a human sample. However, the study will not violate the data privacy and integrity principles (Nasir, Khan, Qureshi, Rafiq, & Rasheed, 2024). Each secondary data presented will be obtained through respected and publicly reported material, and relevant references will be used to ensure the excellence of the research. The study will also be conducted in accordance with ethical principles regarding data handling, and the findings will be presented fairly and without bias.

3.7 Software and Tools

As the most reliable tool of energy modeling, the software that will be predominantly utilized in this study will be the Home Energy Score tool by the U.S. Department of Energy, which will be evaluated based on peer-reviewed algorithms. Data will be statistically analyzed using the R software (version 4.2.0), which will be selected due to its strong statistical functionality packages as well as reproducibility capabilities. The flexibility of R provides the possibility to analyses data in detail, which means that analysis of quantitative and qualitative results will be integrated and analyzed together (Kabacoff, 2022). These common tools are used to guarantee that the study is adequate in terms of academic rigor and replicability and that the findings are stable in terms of the effects of energy retrofits on housing stability.

4. Results

4.1 Quantitative Findings

The quantitative study of the affordability of energy and its effect on housing stability showed that the cost of utilities and energy consumption had improved significantly after energy efficiency retrofits. Table 1 provides a summary of the descriptive information about the main variables of analysis, such as utility costs, energy consumption, and housing stability measures.

4.1.1 Utility Costs

Before rehabilitation, the home spent an average of 2410 annually on utilities with a standard deviation (SD) of \$520. Following the installation of energy efficiency upgrades, which also entailed the addition of dense-packed insulation as well as advanced air sealing and the installation of a high-efficiency heat pump for HVAC and water heating system, the annual utility cost dropped to 1,940 (SD = 480). As presented in Table 1 below, this is a huge saving of \$470/year, or indicates that energy retrofits do help decrease the amount of the energy burden on the households of low- and moderate-income (LMI) earners.

Table 1: Summary of utility costs and energy consumption before and after energy retrofits

Variables	Values	Change
Utility Costs (Pre-Retrofit)	\$2,410 annually (SD = 520)	Decreased by \$470 annually

Variables	Values	Change
Utility Costs (Post-Retrofit)	\$1,940 annually (SD = 480)	N/A
Energy Consumption (Pre-Retrofit)	12,500 kWh annually	44% reduction
Energy Consumption (Post-Retrofit)	7,000 kWh annually	N/A

4.1.2 Energy Consumption

It was also found in the analysis that there was significant energy usage. Before the rehabilitation, the house used 12,500 kWh of power per year on average. This amount dropped to 7,000 kWh in a year following the retrofits, which meant an average of 44% reduction. This significantly lowered energy consumption further agrees with the effectiveness of making upgrades on energy saving on the general energy load on LMI households. These are among the reasons why older and inefficient housing requires retrofitting to enhance its energy performance and cut down the utility bills.

4.2 Housing Stability

House stability was determined using the self-reported risk of eviction and housing decisiveness, with the scale ranging on a 5-point Likert scale. The resultant findings were that the housing stability level had greatly improved following the energy retrofits. Housing stability scores increased on the Likert scale median score from 3.2 to 4.1. Such a difference does reflect the positive shift in self-reported housing satisfaction scales and the risk of eviction. The implications of the findings are the notions that even though the financial means of households to pay their utility bills must be reduced, the target population, consequently, would encounter financial protections, specifically LMI households, that are confronted with financial pressures present in excessive utility rates (Kumar, 2019).

4.3 Inferential Statistics

4.3.1 Regression Analysis

The relationships between energy costs and the outcome of housing stability were evaluated in terms of multiple linear regression models, and the factors of

household income, size, and geographic location were considered. The findings showed that annual energy costs had a statistically significant negative relationship with housing stability scores, and the regression coefficient (β) was -0.35 ($p < 0.01$), as shown in Table 2 below. This shows that the lower the cost of power, the less there is housing stability, a fact further supporting the hypothesis that affordability of energy is an important aspect of security amidst housing at large. It was observed that the model accounted for 42% variance in housing stability ($R^2 = 0.42$), which proves that energy costs make a significant contribution towards determining housing stability among LMI households.

Table 2: Statistical analysis of the relationship between energy costs and housing stability

Analysis Type	Values	Interpretation
Regression Coefficient (Energy Costs vs Housing Stability)	-0.35 ($p < 0.01$)	Negative relationship between energy costs and housing stability
R-Squared (Model's Variance in Housing Stability)	0.42	Energy costs contribute 42% to the variance in housing stability
Pearson Correlation Coefficient (Energy Costs vs Housing Satisfaction)	-0.58 ($p < 0.001$)	High energy costs correlate negatively with low housing satisfaction

4.3.2 Correlation Analysis

Correlation analysis of Pearson was performed to further investigate the correlation between the cost of energy and the issue of satisfaction related to houses. The findings gave strong negative results, and the Pearson coefficient between them is $r = -0.58$ ($p < 0.001$). This indicates that a high level of energy costs is negatively correlated with low housing satisfaction, supporting the idea that the straining financial condition caused by utility costs adversely affects the general well-being of the household (Karwa, 2025).

4.3.3 Scatterplot

Figure 3 shows a scatterplot that demonstrates graphically how high costs of energy are adversely related to low levels of housing stability. The scatterplot indicates that the households with higher energy costs are more likely to report lower housing

satisfaction levels and the perceived risks of eviction. This graphic presentation focuses on the meaning of integrating energy affordability as one of the effective criteria for realizing long-term housing stability among the vulnerable groups (Adeyemi, Ohakawa, Okwandu, Iwuanyanwu, & Ifechukwu, 2024).

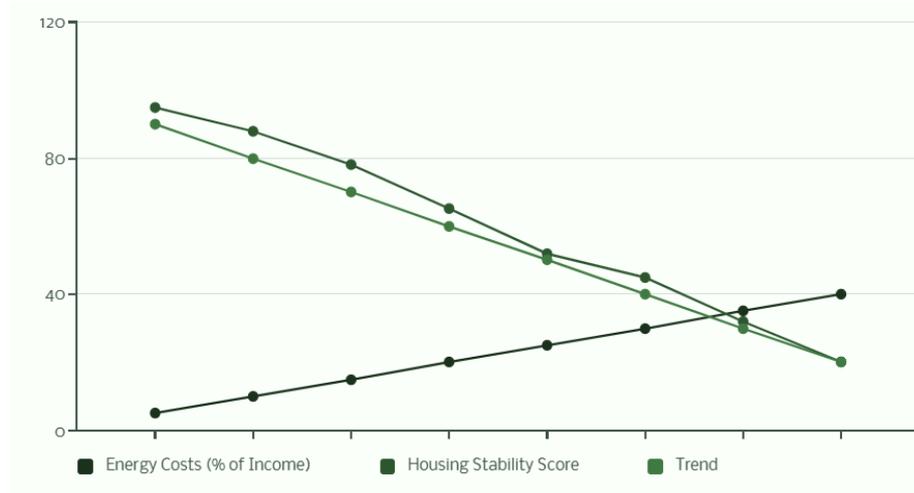


Figure 3: Scatterplot illustrating how higher energy costs correlate with lower housing stability.

As shown in Figure 3 above, a negative correlation exists between high costs of energy and housing stability as indicated by the scatterplot. The graph is visually used to express that those households suffering increased cost of energy tend to record lower satisfaction with housing, and also increased feelings of eviction risks (Minion & Banerjee, 2024). This brings the significance of focusing on the issue of energy affordability as a major factor in housing stability, especially in populations that are at risk. This negative aging trend of energy expenses in terms of a higher housing stability underlines the necessity of affordable energy measures to facilitate the reduction of the cost element and, therefore, the general living conditions of people with low incomes and middle-income (LMI) households.

4.4 Qualitative Findings

Data on qualitative was construed in the form of 30 semi-structured interviews with the inhabitants of the case study house and nearby real estate. Interpretation of the interview transcripts using thematic analysis showed the presence of three themes, namely, financial strain because of high costs of energy, poor housing conditions because of the inefficiencies of certain houses to save energy, and strategies used by the households that are faced with high costs of energy.

4.4.1 Key Themes

- **Financial Stress because of Elevated Energy prices:** Most of the interviewees indicated that high energy prices are also a great burden on them. Respondent answered that there are times when they are called upon to choose between the electric bill and going shopping, and this is an aspect that shows how the LMI households find it hard to make decisions. The utility charges were also likely to pose a significant financial strain to the participants and, therefore, subject them to paying the utility charges at the expense of other needs (White & Sintov, 2020).
- **Unhealthy Housing -Energy Inefficiencies:** A few of the interviewees reported living in drafty and poorly insulated houses, which were not comfortable to reside in, and this consumed a lot of energy. One of the participants stated, “The lack of warm air when sleeping makes it difficult, and that stress covers my entire family”. These are remarks that demonstrate the physical and emotional strain that the inefficiency of energy management might impose on the residents, the relevance of which influences their health and well-being.
- **Coping Strategies:** The respondents described the various coping techniques they used to cover the high cost of energy, which included switching off heating in winter times or receiving a temporary solution, which involved space heaters. These measures, though they were rather a relief in the short run, helped to underline the impossibility of living in highly energy-consuming houses and the hardship endured by families paying the utility bills.

4.4.2 Barriers to Energy Assistance

Other respondents have reported that some of them suffer hindrances in accessing energy assistance programmes due to the hindrances in systems, such as the inability to fill in complex applications, or the time taken up before they can access assistance. One of the participants claimed that they were not able to receive help when they were in need. The process is disappointing, and even when you eventually get assistance, it is always too late since the bills are too huge to start with (Skjott Linneberg & Korsgaard, 2019). Through these observations, it is advised that even though programs like LIHEAP are necessary to assist in alleviating the energy whack on all households, this is not always the case, and not all households have access to it.

4.4.3 Thematic Map

The summarized qualitative data of the interviews are shown in Figure 4 below. It can be observed that the interrelationship between the issues of affordability of energy and the stability of housing can be traced in the map to uncover how high prices of energy, poor housing, and inaccessibility of other energy assistance programs are linked to the housing instability within the whole LMI household. That kind of map is a graphical definition of the multifariousness of the issues of the affordability of energy, in which case the situation requires seeking whole-minded answers that will not be limited to the physical nature of housing and will also require the economic component.

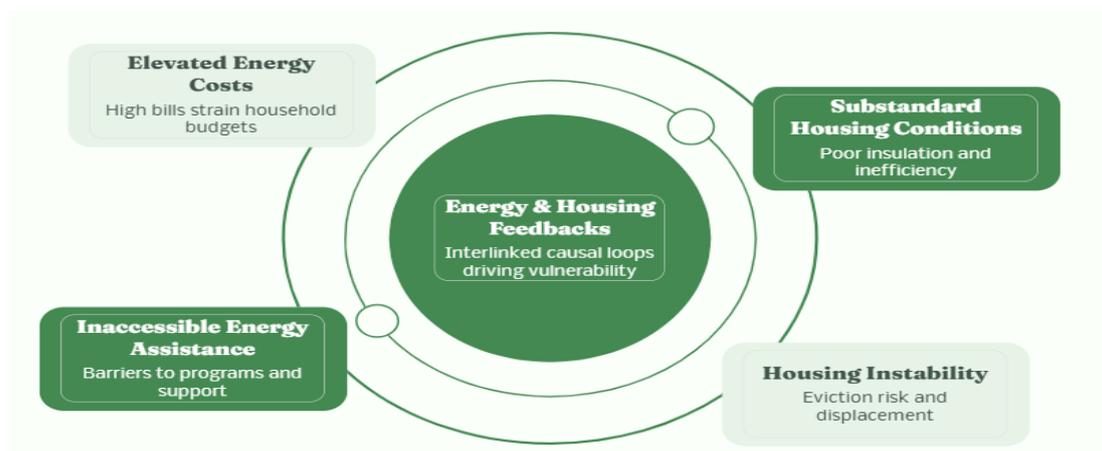


Figure 4: Visual representation of how energy costs, housing conditions, and assistance barriers contribute to housing instability.

This is a visual summary of the multidimensional relationships among affordability and housing security of energy based on qualitative data, in the form of a thematic map. Other elements that identify the negative modality of raising the price of energy, poor housing, and access issues with the energy assistance have also been included on the map, and they are correlated with the problems of housing instability even among less-income and middle-income families (LMI). The idea of the Energy and Housing Feedbacks is used as the central part of the infographic, and this should be covered in a holistic approach, not in the aspect of the physical housing as such, but also the economic one, as a key towards rendering the houses a part of the vulnerable population throughout.

4.5 Summary of Findings

Quantitative and qualitative findings of this study are very compelling in the idea that the affordability of energy has a significant impact on housing stability. The statistical tests in the paper clearly and evidently created an indication that the high energy costs did influence, creating a correlation in low housing stability, and that there were actually enormous returns in energy retrofits, bringing forth low utility rates, a higher rate of energy consumption, and a greater rate of housing satisfaction. The qualitative interviews helped in setting this finding in relation to its context, which revealed the very high economic and emotional importance of high energy bills to the LMI households (Figueroa, de Moliere, Pegels, Never, & Kutzner, 2019). Together, the results above highlight the importance of energy efficiency measures that can enhance housing stability and have the potential to increase affordability (long-term).

5. Discussion

5.1 Contribution to Literature

The contributions to the existing body of literature on affordability are that, given the findings of this study, the evidence is extremely useful in explaining the housing stability based on energy affordability as one of the predetermining factors in the cold-climate urban environment, say in Pittsburgh. Conformably to the existing studies, the results imply that utility bills take a significant part of the total housing spending of low- and middle-income (LMI) households. Together with economic stress caused by the cost of energy, it is likely to increase the conventional housing cost, such as rent or mortgage payments.

The 44% energy conservation that occurred during the energy retrofit of the examined building in Pittsburgh and the \$470 of utility savings are what can be seen in other national weatherization studies, with general ranges of 20% to 40% of energy savings in buildings (Subham, 2025). What is of interest more is the upper boundary of this range in Pittsburgh, which brings about the inefficiencies exhibited by the aging housing stock of the area. These conclusions highlight the relevance of the context-dependent energy efficiency intervention, which considers the housing stock in the country, as well as climatic factors, which may greatly contribute to better energy affordability in the household and alleviate the energy load on LMI households.

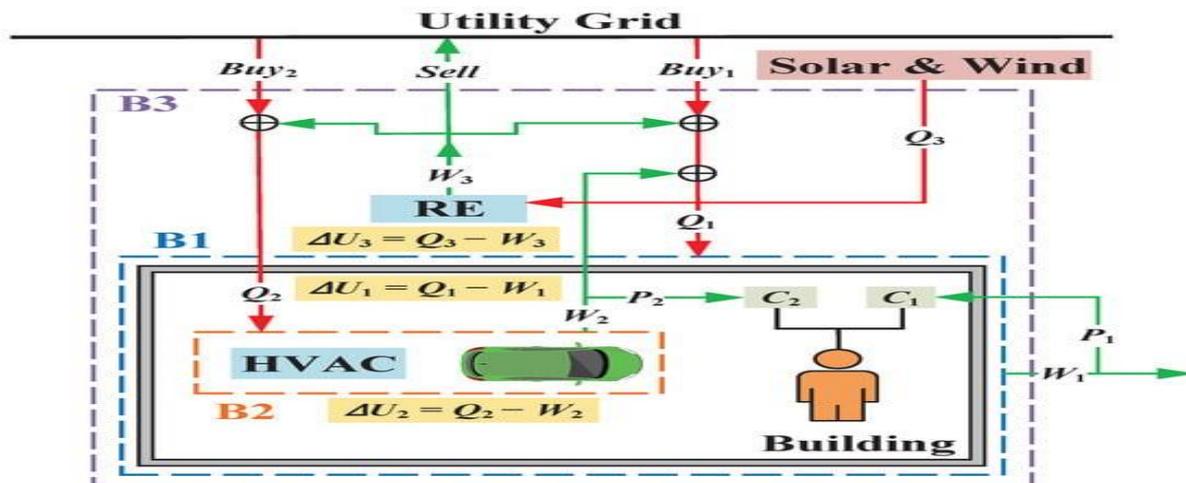


Figure 5: Energy flow diagram illustrating renewable energy integration and energy savings in buildings.

Figure 5 above demonstrates the energy flow in a building, which links the utility grid, sources of solar and wind energy, and energy consumers. It is based on an energy management model that integrates the renewable energy (RE) and HVAC systems, which recognizes the means by which the savings of energy could be directly achieved by facilitating the effective energy usage and production. According to the findings of a study on Pittsburgh, energy retrofits resulted in a 44% reduction in energy consumption and a savings on utility of \$470. The diagram shows how energy can be purchased from the grid and sold back to the grid. The arguments result in the topicality of interventions associated with energy efficiency as context-dependent ones, taking into account the age of housing stocks and the climate of the location (Chang, Wang, Xiang, & Liu, 2021). Such a system will greatly decrease the power bill of the low and middle-income households (LMI) and establish the premise of better access to energy and fiscal security of dwellings.

5.2 The Transformative Potential of Energy Efficiency Upgrades

The productive potential of the specific energy efficiency upgrading is also confirmed by the increased score of the DOE Home Energy Score by 3 to 8. The facility is especially convenient because it not only adds to the consumption that is secured by energy, but long-term impacts on the environmental and economic situation are also highly commendable. To support this notion, prior studies state that retrofitting has two advantages, with the first relating to the fact that retrofitting can enhance household economies (at the same time) and the second refers to the fact that the other purpose of the environmental regulations, which involves the reduction of carbon emissions, is eventually reached. The value added to the house,

such as packed insulation and high-efficiency heating systems, also contributes to counteract the short-term strain on the material of the LMI households through the addition of reduced utility bills and energy requirements.

As the analysis shows, there is also a dramatic difference between the increase in utility costs and the dispersion of the Area Median Income (AMI) in Allegheny County, where utility costs increase by 4-6% per year; at the same time, the AMI increases only 2-3% per year. This avenue would imply that the present necessity is to integrate the cost of energy into the broader platforms based on the affordability of housing. Policy programs alone should not respond to the housing disparities, but also to energy disparities; therefore, affordable housing solutions would be sustainable (Reid, 2023). The research outcomes reveal the fact that the energy retrofits would be a necessary measure to eradicate this gap, which would be one of the factors that would contribute to a more affordable sustainability and housing security of the LMI residents in the long term.

5.3 Practical Implications for Affordable Housing Programs

The findings of the given work have adopted the meaning in terms of planning and execution of affordable housing programs. The high amounts of cost savings and decreasing use of energy that have been achieved in the case study house demonstrate that there is a potential for incorporating energy efficiency criteria in the reconstruction of affluent housing projects. These tools can be used to mitigate the factors of displacement, which include the rising utility charges, which are a major concern in most cities, including the city of Pittsburgh. As the burden of the cost of the energy mounts against the housing markets, the trick here would be to think of involving the use of energy-saving measures in the rehabilitation efforts that result in proper stabilization of areas, as well as prevent the eviction of the lowest economic members of the community. Proposing a solution to highly unequal energy doses on LMI households, energy retrofits make sense in terms of overall social equity principles, as in this way, the issue of energy affordability would have been a core element of the housing policy (Dhanagari, *Aerospike: The key to high-performance real-time data processing*, 2025).

The fact that the study was based on a single property model presents the following drawbacks. The results cannot be extrapolated to all types and areas of housing. Other factors like variability in residential typologies, energy efficiency of various building materials, occupancy, and varied utility rates can determine the response of energy retrofits. Additionally, the projection utility data used instead of actual post-occupancy data implies that the actual savings on energy may be different

at the point of full retrofit. The implications of the results, therefore, need to be taken with caution before they are established through post-occupancy, real-time measurements (Boissonneault & Peters, 2023). These limitations need to be overcome in future studies by focusing on different properties and different typologies of housing in order to better determine the complete effects of energy retrofits in other settings.

5.4 Limitations and Recommendations for Future Research

Although the outcomes of this study are encouraging, it should be noted that the study has its limitations, and new research opportunities should be recommended. The major limitation is that the study was based on a single-property model. Longitudinal, multi-dwelling studies should be given a higher priority in future studies in order to obtain the performance of energy efficiency upgrades in a real-world setting, as highlighted in Table 3 below. More detailed research would enable the researchers to evaluate the ability of energy retrofits to show long-term effectiveness in addition to establishing whether such saving is maintained within various household types and places. Moreover, further analyzing the greater variety of housing stock in terms of multifamily houses, apartment blocks, or newer houses would give a clearer overview of how the energy efficiency indicators work in different types of affordable housing.

Table 3: Summary of study limitations and future research directions for energy efficiency in affordable housing.

Limitations/Recommendations	Details	Future Implications
Single-property model design	The study's reliance on a single-property model limits generalizability	More comprehensive and generalizable findings for future energy retrofitting programs
Need for longitudinal, multi-dwelling studies	Future research should focus on assessing the long-term effectiveness of energy retrofits across various household	Improved understanding of long-term effects and applicability across diverse households

Limitations/Recommendations	Details	Future Implications
Analysis of diverse housing stock	types and regions Further research could include a variety of housing types like multifamily houses and apartment blocks for clearer insights	Clearer understanding of how different housing types respond to energy efficiency improvements
Exploring the nexus between health outcomes and energy affordability	Investigation of how energy efficiency improvements correlate with better respiratory health and overall well-being	A better understanding of the health benefits linked to energy efficiency in vulnerable populations
Comparative studies in cold regions for retrofit standards	Studies in cold regions could help create scalable retrofit standards and effective policy interventions for affordable housing	Development of standardized retrofit protocols to implement energy-efficient solutions nationwide

The other possible focus of future research development is the nexus of the health outcomes and costs of energy. The positive outcome of the energy sustainable up-gradation was seen to have better respiratory health and overall well-being, attributed to the better air quality in the interiors due to the up-gradation. Further research can be focused on the manner by which the health outcome can be enhanced by making energy and houses cost less and be of good quality, especially among the most susceptible of the population, and such people include children and the elderly. The multi-disciplinary practice would provide useful information about the general implications of energy affordability on health among the communities.

Comparative studies on various cold regions might help in coming up with typical standards for energy efficiency retrofit on affordable housing. Such studies would have the potential to determine what practice should be applied and develop policy interventions that are scalable and could be used in different situations in a local environment to implement energy-efficient housing interventions more effectively and broadly. Policymakers could implement measures to create uniform retrofit protocols and policies to make energy retrofits affordable by LMIs nationwide, and to help them build a more equitable and sustainable society (Chavan, 2025).

5.5 Policy Implications

The findings of this paper justify the significance of considering energy efficiency in a policy of affordable housing. This is because, in conventional housing affordability evaluations, the cost of housing has come to depend on the price of energy, although this is usually not considered (Galster & Lee, 2021). With the ongoing increase in utility costs, especially in cold climates, one of the primary areas of housing policy focus should be on responding to the affordability of energy in order to ensure financial security and viability in the long term. The energy retrofit beliefs do not only make sense when it comes to assisting LMI households to cut down on finances, but also a strategic place where other environmental goals can be realized. The policymakers must bring in energy-saving reforms as an extension of the affordable housing program to assist in the stability of housing and to avoid the effects of losing the home, since the group that cannot afford housing, the benefit can be left to the luxury of affordable housing schemes that are really affordable.

6. Conclusion

This study provides knowledge about the importance of the energy affordability practice in housing stability maintenance as a neglected housing policy domain. This study has indicated great significance of lowering the energy overheads of low- and middle-income (LMI) households in the form of specially designed energy efficiency retrofits, such as greater insulation levels, improved air sorting, and highly efficient heat pumps. The real outcomes of interventions in question were reflected in the fact that the DOE Home Energy Score increased considerably by 3 to 8, and the amount of consumed energy was reduced by 44%. The analysis established that the annual savings utility cost projected to amount to \$470 would be achieved every year, and the result is that the energy saving initiatives would lead to a reduction in economic burdens on family finances. The environmental advantages, including a 3.2 metric ton of carbon savings, decrease crimes, and replicate the aspect of financial release and climate reduction approach of these retrofits. Among the most important factors of the

study is the requirement to prioritize the issue of energy affordability as one of the primary aspects of housing affordability. The conventional housing indicators that have been used to quantify traditional housing will at best be able to estimate the weekly or monthly payment of rent or mortgage, and do not consider the colossal financial weight that huge utility bills present. This study shows that this trend of increasing utility payment, which is higher than the growth of Area Median Income (AMI), is disproportionately impacting the LMI households and aggravating the state of home security. The data in question raises the question of the models of housing policies that have been prevailing because, in most cases, it does not focus on the energy cost as a factor of affordability of homes. This research indicates that the appropriate way of curbing the increasing housing crisis is ensuring that the policies adopted by these institutions are translated into the affordability of energy in the plans laid out. This way, it will be able to develop housing solutions that are more sustainable in nature, in addition to the long-term stability that it will give them, and also make them less economically vulnerable by virtue of living in an LMI context.

These findings of this research also have an extension into the longer-term social justice and environmental sustainability. Besides the reality that the energy retrofits will save the burdens of money, there is also the possibility of living conditions being refined, thus reducing the likelihood of people being displaced, and general living conditions will be more enjoyable. Based on the findings of the work, it is proven that programs requiring lower energy consumption lead to the welfare of residents, which is critical in the establishment of more reliable and inclusive communities. At the same time, the positive changes are beneficial to the climate goals because these upgrades reduce to a minimal extent the number of energy units and carbon produced in significant proportions. Such a double benefit of social and environmental determines the importance of addressing the problem of housing instability on a global basis, on which the economic and ecological ills are also examined when formulating the policy. There are also a number of practical points raised by the study to policymakers. By incorporating the energy efficiency criteria during the renovation of affordable housing schemes, one can nullify the risk of displacement being felt due to rising utility bills, which is highly problematic in terms of the majority of metropolitan regions. The high energy costs are creating the need to incorporate energy-saving provisions in the affordable housing programs in order to make shelter affordable in the long run. This plan will also be conducive to the objective of social equity, in which the vulnerable group of individuals will be presented with cheaper housing options that will pay both the housing costs and the energy costs. The study was done using a model that is founded on a single property,

implying the survey would not extrapolate the results to other kinds of housing. The housing arrangements, the behaviors undertaken by the residents, and the modification in utility charges are capable of causing complications; therefore, caution should be taken in drawing inferences. In addition, because the post-occupancy means were not used in the study since the data on the modeled utility were used, the actual savings could be different when the interventions are subjected to more realistic settings.

The longitudinal research that should be undertaken in the future must be targeted towards the longitudinal impact of energy efficiency retrofit on housing stability. Further research that will examine the development of geographical locations, which will be discussed, and the typology of the housing opportunities, may be considered in such a manner that the generic features of the energy retrofits may be better tracked in diverse situations. Research on the association between health-related issues and the affordability of energy with regard to high indoor air quality, which can translate to optimal respiratory health, would be a welcome contribution from other fields to the benefits of energy-efficient housing in general. The research would help policymakers to further streamline their energy conservation policies in a manner that would enable their energy conservation policies to be more rooted in the ground issues. The relevance of the study to the problem in question is due to the need to take the affordability of energy as a factor in the housing policy when formulating a sustainable, resilient, and equitable housing policy. The research findings suggest a paradigm shift in the concept of housing affordability by focusing on the contribution that costs of energy can make to the achievement of housing stability. An intervention strategy that takes into account the housing cost and the cost of energy will ensure that the low-income groups remain on their feet, centralize their communities at a faster rate of stability, and achieve environmental-based objectives, thus making affordable housing achievable among the following generations.

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