# Factors affecting Norwegian households' adaptive energy performance upgrades in response to the energy crisis

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## Abstract
Energy performance upgrading behaviours in relation to buildings are crucial in mitigating carbon emissions. The related concept of "building energy performance improvement" is typically associated with building retrofits or investments in energy-efficient appliances. Determinants of flexible energy use adoption and installation of private photovoltaic (PV) panels are understudied in the Norwegian context. The objective of this paper is to identify the key socio-demographic, dwelling, household contextual, and psychological factors that have a significant impact on household energy efficiency behaviours in different categories, including private PV installation, flexible electricity use, and dwelling energy efficiency upgrading. This study applied household-based survey data collected in 2023 from Norway and employed repeated measures ANOVAs and the Lasso regression model. The findings indicate a substantial increase in household energy efficiency behaviours over the past three years, with the anticipated tripling of households for private PV adoption and doubling for flexible energy use for the next three years. After the energy crisis, the substantial increase in electricity prices significantly amplifies households' intentions to adopt PV systems, and the household's commitment to supporting the energy system serves as a motivational factor for respondents to participate in flexible energy use.

## Introduction
The Climate Action Plan for 2021–2030 in Norway delineates a goal to reduce greenhouse gas emissions by a minimum of 50 %, progressing towards 55 % by 2030 compared to 1990 (Norwegian Ministry of Climate and Environment, 2021). The building sector, representing 34 % of the nation's overall final consumption, has been allocated a goal to achieve a reduction in energy consumption by 10 terawatt hours (TWh) by the year 2030, in comparison to the levels observed in 2015 (IEA, 2022). Individual household energy behaviors play a crucial role in promoting energy efficiency and reducing carbon emissions (Harputlugil & de Wilde, 2021). However, the complexity of the predictors of these behaviors poses several research challenges. Overcoming these challenges is necessary to properly value and consider energy behaviors in the energy policy context (Lopes et al., 2012).

Energy behaviours range from energy conservation to clean technology adoption (Wolske et al., 2020). Occupant energy conservation behaviour is often understood as the daily, often habitual practices of energy use reduction actions and energy efficiency improvement behaviours (Pothitou et al., 2016; Trotta, 2018), including building retrofit or investment in energy-efficient appliances. Clean technologies have demonstrated efficacy in enhancing housing energy efficiency. Flexible energy methods and applications, such as intelligent charging for electric vehicles or smart control of heaters and water boilers, are effective in improving energy efficiency by minimizing energy waste (H. Li et al., 2021). Private solar PV could also improve house energy performance by tapping into a renewable energy source and diminishing reliance on traditional grid electricity (Paukstadt, 2019). The energy industry is currently undergoing a rapid diffusion of novel technology, which is promoted by involved investors, electricity suppliers, regulators, and customers (in the case of our analysis: households) in the market in Norway (Geels et al., 2021). In particular, flexible energy solutions and private renewable energy production warrant greater attention in the current Norwegian context of high energy prices and high affinity to technological solutions.

The occupants' complex decision-making has been well-studied with respect to housing retrofitting or renovation measures. The occupants' complex decision-making processes may be investigated based on socio-demographic, contextual, environmental, and psychological factors (Pothitou et al., 2016). Recent research has been increasingly focusing on two aspects, including the influences of structural construction issues (Barbosa & Azar, 2018; Escandón et al., 2018), and the significance of socio-psychological factors on the occupants' decision-making process (Vainio et al., 2019). Boomsma's (2018) study in the UK shows that housing characteristics provide incentives or disincentives for occupants' decision-making on heating-related behaviours by influencing their psychological variables (such as subjective norms), but they are unable to explain other types of energy behaviours beyond the variance explained by socio-demographics and psychological factors (Boomsma et al., 2018). Psychological factors, such as subjective norms and self-efficacy have been validated to be significant (Vainio et al., 2019).

In recent years, there has been a growing academic interest in the determinants of adopting private photovoltaic (PV) installations or incorporating flexible energy use. Factors associated with technology (such as control algorithm) (Basarir-Ozel et al., 2023; Guta, 2020), perceived benefits of flexible energy applications (e.g., healthcare, energy efficiency or home security) (Arthanat et al., 2020), and economic status of adopters (Balint & Kazmi, 2019) have been identified as significant determinants. Psychological variables, including primary motivations and barriers, play a crucial role in the adaptation of flexible energy use (W. Li et al., 2021). In the context of private photovoltaic (PV) adoption, fixed costs, institutional financial support, and the economic status of adopters have been identified as the most influential factors (Qureshi et al., 2017). Additionally, spatial variations in solar irradiation can impact adopters' decisions by influencing the return on investment rate (Dharshing, 2017). In contrast, the effect of energy attitudes and perceptions are ambiguous (Balta-Ozkan et al., 2015). And other psychological factors, such as personal norm, descriptive norm, social norm, etc., are less often being studied. There is limited literature encompassing the full spectrum of influential factors necessary to identify the key determinants in the decision-making process for private PV and flexible energy use adoption.

In this study, we included a wide range of socio-demographic, contextual, environmental, and psychological variables to identify the principal factors for energy performance improvement behaviours that have long-term impacts on housing energy consumption, including private PV panel installation, flexible electricity use with and without technical support, and housing insulation upgrading. Our analysis is based on data from a household survey, which was conducted in 2023 with a representative sample of Norwegian households. This paper describes the self-reported household energy efficiency upgrading status in the past three years before the survey, followed by exploring the main features of households conducting different energy efficiency improvement behaviours. Furthermore, we seek to investigate to what extent these principal factors can promote households to carry out different behaviours, and we aim to understand the impact of the energy crisis on such behaviours.

## Data and Method

### SURVEY AND SAMPLES

The "BEHAVIOUR survey" was first conducted in May 2023 with the purpose of understanding household energy-saving behaviours in Norway after the energy crisis in the categories of PV investments, energy retrofits, and flexible energy use. In total, 3551 adults aged 18 or older participated in the survey. The survey incorporates three arms, as depicted in Figure 1. All participants answered the first section with 28 questions, which included demographic characteristics of the respondents, including gender, age, level of education, and place of residence; contextual variables of the respondents' dwelling, including age, type, mainly used heating methods of the house; contextual variables of the respondents' household, including composition, income level, and house ownership; as well as psychological variables, including their motivations to save energy, perceived comfort; and their innovativeness. Afterward, they are randomly and evenly distributed across the three domains of housing energy performance improvement behaviours, including private PV installation, flexible energy use, and energy retrofit actions. In each domain, the participants are initially asked to answer if they have installed private PV/ used energy flexibly/ retrofitted the dwelling during the last three years, and their intention to do it in the next three years. Second, their relevant attitude, habits, personal norms, social norms, subjective norms, and self-efficacy towards the respective behaviours were asked. Third, around 25 drivers and barriers, which could either promote or decrease their intention for future actions, are measured by a five-point Likert scale, with 1 = strongly disagree and 5=strongly agree.

In total, 2997 valid responses were retained for analyses, including 937 responses for PV installation, 971 for flexible energy use, and 1089 for energy retrofitting measures. 45.1 % of participants fell within the age range of 55 to 74, possessed a higher level of education, and predominantly resided in rural or urban areas with houses constructed between 1948 and 2017. Gender differences among respondents were minimal. Geographically, a significant proportion of respondents were concentrated in the highly centralized city of Oslo and the comparatively densely populated county of Viken, followed by a lesser representation in the centralized cities of Bergen and the Stavanger region, situated along the southwestern coastal line of Norway. Conversely, fewer respondents hailed from less centralized areas, presenting a comprehensive distribution across various locales. This survey's sample composition aptly reflects the demographic distribution of Norwegian households, offering a nuanced understanding of energy-related practices within the country.

### DATA ANALYSES

A comprehensive analysis was conducted utilizing a series of one-way ANOVAs or Chi-Square tests to explore distinctions in socio-demographic, living contextual, and psychological

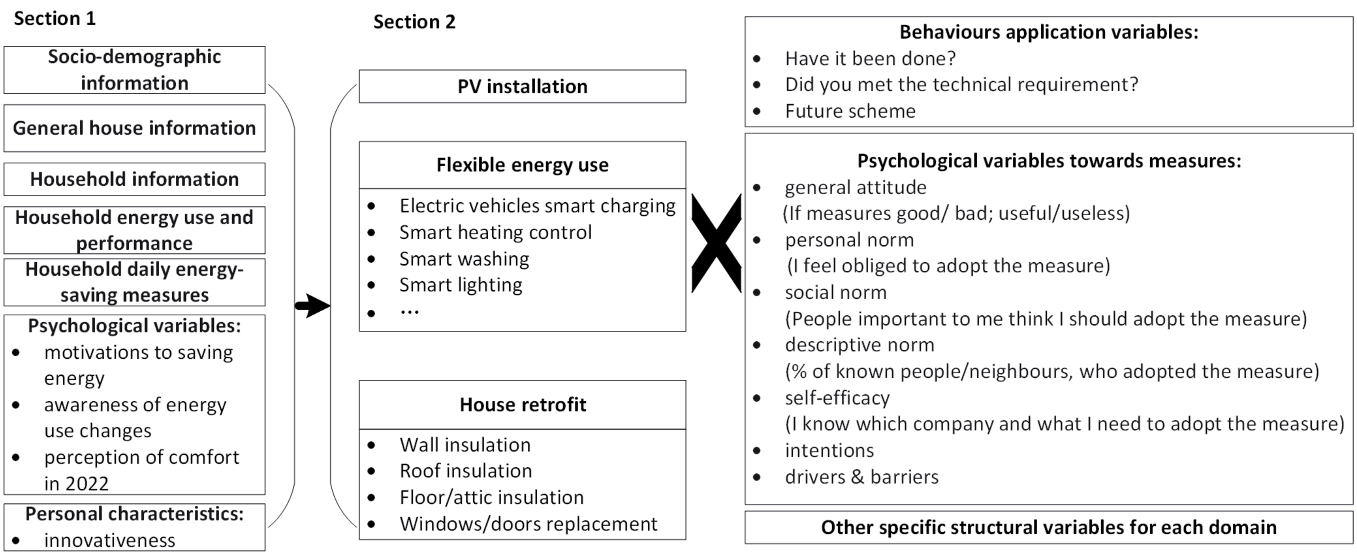


*Figure 1. Survey structure.*

factors among household groups that either adopted or refrained from adopting energy efficiency upgrading behaviours within each specific domain. Furthermore, employing Lasso regression, we scrutinized the extent to which principle variables could effectively promote the intentions of households regarding the adoption of energy efficiency upgrading behaviours. With a large number of independent variables, LASSO is applied to identify a smaller subset that exhibits the strongest effects (Emmert-Streib & Dehmer, 2019). The regularization algorithm is applied to filter out less relevant independent variables by adjusting the penalty term (Ranstam & Cook, 2018). The conventional Lasso model has limitations in its ability to select multiple variables from a set of highly correlated variables, frequently ending in the inclusion of only one variable (Emmert-Streib & Dehmer, 2019). Overcoming this constraint, Lasso linear regression proves to be efficient for interpretation purposes. In particular, Ahrens et al. (2019) suggest the utilization of the extended Bayesian information criterion (EBIC) approach to mitigate overfitting in cases when the independent variable set is large. In this study, we applied the cross-validation (cv) model, the information-based approaches (including EBIC), and adaptive Lasso regression to find an appropriate model to strike a balance between model fit and simplicity.

## Results

### HOUSEHOLD ENERGY EFFICIENCY UPGRADE BEHAVIOUR AND INTENTIONS

The energy efficiency upgrading behaviours and prospective implementation intentions of respondents are presented in Table 2, Table 3, and Figure 2. The intention depicted in Figure 2 are derived from participants' self-identified agreement on the decision-making phases, encompassing Stage 1, not being in decision mode; stage, deciding what to do; Stage 3, deciding how to do; and Stage 4, involving the consideration of how to implement the decision (Klöckner & Nayum, 2016). If they consider they are not in decision mode, they are assigned a status of 1 in Stage 1. If they agree that they are in Stage 4, they have an intention status of 4.

Regarding private solar PV installation, out of 937 respondents, has been relatively uncommon, with only 21 households (2.24 %) having installed private solar PV before the survey. Although private photovoltaic (PV) adoption in households has been historically limited, there is an increase in the number of households expressing an intention to install it in the next three years (6.19 %). But, there are still approximately half of the participants, as illustrated in Figure 2, identified themselves as being in Stage 2 of the decision-making process—contemplating taking action but uncertain about the suitability of private PV as a measure.

Flexible energy use emerges as the most frequently adopted measure in the past, with an implementation rate of approximately 25 % among the 971 respondents. Table 3 illustrates the adoption rates of various flexible energy measures in households. Smart car charging solutions, encompassing smart charging boxes (15.24 %) and other management tools (7.42 %), exhibit the highest adoption. Following closely are temperature automation adjustment tools, with a 4.22 % adoption rate for daily indoor temperature adjustments and 3.4 % for cabin heating adjustments. The least adopted flexible measures are adjusting the time to use the tumble dryer and entertaining, which may largely impact participants' daily routines. In addition, 49.54 % of the participants indicate a willingness to employ flexible energy measures in the forthcoming three years. More than 30 % of participants expressed a willingness to adopt flexible water heating solutions and smart electric car charging boxes. Figure 3 delineates that more than half of the respondents manifest high intention (in Stage 3 or 4). It means they have either decided to adopt or plan to implement a flexible energy measure.

Additionally, among the 1,089 respondents for retrofit, 158 households have implemented individual or multiple retrofitting behaviours. Although there is a lower proportion of respondents planning to retrofit their dwellings compared to those who have already done so, over 30 % (in Stage 3 or 4) of households express a strong intention to engage in retrofitting.

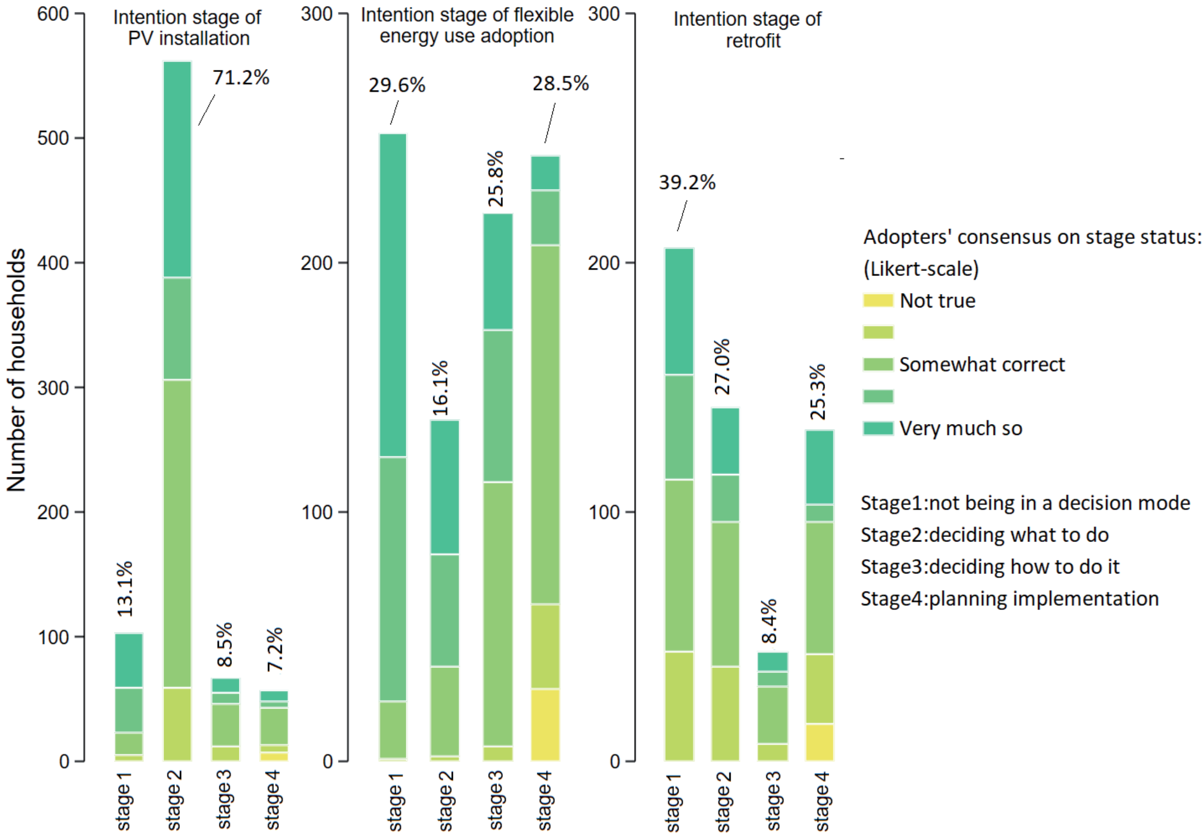


*Figure 2. Household intentions for energy efficiency upgrades in the next three years.*

**Table 2. Household adoption and intention for various energy performance upgrades.**

| Behaviour | | Responders answering the question of installing solar PV (N=937) | | Responders answering the question of flexible energy use (N=971) | | Responders answering the question of house retrofit (N=1089) | |
|---|---|---|---|---|---|---|---|
| | | N | Percentage | N | Percentage | N | Percentage |
| Past | NO | 916 | 97.76 | 725 | 74.67 | 931 | 85.49 |
| | Yes | 21 | 2.24 | 246 | 25.33 | 158 | 14.51 |
| Future | Yes | 58 | 6.19 | 481 | 49.54 | 128 | 11.75 |
| | NO | 879 | 93.81 | 490 | 50.46 | 961 | 88.25 |

These findings suggest that all three energy efficiency upgrading measures are anticipated to be adopted by a substantial portion of households.

### GROUP DISPARITIES IN ENERGY PERFORMANCE UPGRADE MEASURES

Tables 4 and 5 illustrate the differences in socio-demographic, contextual, and psychological variables among households that have either implemented or not implemented various energy efficiency upgrades. The detailed values of categorical variables among the groups are presented in Appendix A. Psychological factors vary significantly between households that have implemented energy efficiency measures and those that have not, across all three domains. Beyond psychological factors, households involved in flexible energy use display significant distinctions in the state of their houses and household contextual variables in comparison to those not engaged in such practices. Additionally, noticeable disparities in the condition of houses are apparent between households that have undergone retrofitting and those that have not.

Tables 4 and 5 reveal substantial differences between the groups of households that have implemented PV installation and those that have not. Socio-demographic and contextual variables demonstrate limited disparities between these two groups. The singularly significant contextual variable pertains to the selection of heating methods, wherein more than 70 % of PV adopters utilize multiple primary heating methods at home. This proportion is twice as high as observed among non-PV adopters. The most notable disparities are observed in the descriptive norm, indicating a multivariate effect of 59.95. The descriptive norm among PV-installed households suggests that, on average, their social networks include 10 % more friends or neighbours who have also installed solar PV. Those who have installed PV also tend to hold a higher value in personal norm, signifying a sense of obligation driven by values or principles to install solar panels on their homes. In addition, PV adopters have a higher value of social norm, which means they are more inclined to consider suggestions from individuals who are important to them and believe they should adopt solar PV. Moreover, they generally exhibit greater confidence in engaging construction companies (self-efficacy) harbor a positive attitude towards private PV technology and are motivated to support energy systems and prioritize environmental protection.

Concerning flexible energy use, households that have adopted it are generally headed by younger and more innovative family members (the respondent or the partner). Household income level emerges as the most distinguishing variable, between households utilizing energy flexibly and those that do not. Households employing flexible energy use are more likely to be larger families with higher incomes residing predominantly in single-family houses, that are on average 27 $m^2$ larger and 6 years newer. Table 5 also indicates that adopters of flexible energy use exhibit higher mean values in motivations, attitudes, social norms, and self-efficacy. This signifies that adopters possess a heightened motivation to support the energy system, a more favorable attitude toward flexible energy technologies, and a greater inclination to value others' opinions supporting the integration of flexible energy into their daily lives (as evidenced by a higher social norm value), and a better understanding of their needs and contacts for the application of flexible energy technologies (self-efficacy).

Regarding house retrofit applications, there are clear connections with house characteristics. The retrofitted households mostly inhabit older single-family houses with heat pumps or electric stoves as the primary heating method, and they experienced higher electricity consumption in 2022. Furthermore, over 50 % of respondents' houses in Nordland and 33 % of respondents' houses in Innland were retrofitted in the past three years. Additionally, the age and type of the house impact personal norms (not shown in the table but appears in further analysis). The degrading, aging physical condition of single-family properties would heighten the adopters' obligation of owners to enhance the energy efficiency of their homes (Jia et al., 2021), which is also shown in Table 5 with a higher value of personal norm. Households that have under-

**Table 3. Household adoptions in flexible energy use measures.**

| Responders adopted flexible energy use measures | Past | Future |
|---|---|---|
| Using the dishwasher during electricity cheap hours by smart management solutions | 26, 2.68 % | 131, 13.49 % |
| Using the washing machine during electricity cheap hours by smart management solutions | 33, 3.40 % | 120, 12.36 % |
| Using the tumble dryer during the electricity cheap hours by smart management solutions | 15, 1.54 % | 87, 8.96 % |
| Postpone heating water in water tank to electricity cheap hours by smart management solutions | 31, 3.19 % | 303, 31.2 % |
| Adjust indoor temperature according to the price of electricity by smart management solutions | 41, 4.22 % | 160, 16.48 % |
| Choose the time to heat the cabin according to the price of electricity by smart management solutions | 33, 3.40 % | 83, 8.55 % |
| Use entertainment electronics when electricity is cheap by smart management solutions | 16, 1.65 % | 95, 9.78 % |
| Distribute the use of electricity throughout the day by smart management solutions | 32, 3.30 % | 199, 20.49 % |
| Charge your electric car during the electricity cheap hours with smart management solutions | 72, 7.42 % | 75, 7.72 % |
| Using a smart charging box | 148, 15.24 % | 303, 31.2 % |

**Table 4. Statistically significant chi-square tests concerning socio-demographic characteristics in relation to each energy performance upgrade measures.**

| | | | Energy performance upgrade measures | | |
|---|---|---|---|---|---|
| | | | PV installation | Flexible energy use | House retrofit |
| Categorial variable | Description | df | $X^2$[a] | $X^2$ | $X^2$ |
| Gender | male/female | 1 | 0.022 | 2.189 | 0.003 |
| Region | Oslo; Viken; Rogaland; Agder; Vestfold&Telemark; Vestland; Trøndelag; Nordland; Troms og Finnmark; Møre&Romsdal; Innlandet | 10 | 6.408 | 11.222 | 19.05** |
| Education | primary education to over 4yrs high education | 5 | 6.086 | 2.846 | 15.60*** |
| House type | Single-family house to multiple-family house | 5 | 2.437 | 24.17*** | 20.77*** |
| Heating methods | Heat pump/electronic stove/ wood stove/district heating | 4 | 14.842** | 16.759*** | 12.219** |
| Ownership | Owner/shareholder/long-term renter/ short-term renter | 3 | 0.977 | 11.013** | 5.555 |
| Household types | Single family to extended family with kids | 6 | 7.742 | 50.59*** | 4.077 |

[a] *Chi-square: Pearson chi-square.*

**Table 5. ANOVA statistics investigating the variance of socio-demographic and psychological Variables on each energy performance upgrade measures.**

| | | Energy performance upgrade measures | | | | | |
|---|---|---|---|---|---|---|---|
| | | PV installation | | Flexible energy use | | House retrofit | |
| **Continuous variable** | **Unit** | **F**[a] | **δ**[b] | **F** | **δ** | **F** | **δ** |
| Age | years | 2.84 | 5.78 | 6.83** | -3.07** | 0.05 | -0.29 |
| House age | years | 2.06 | 11.77 | 5.05** | -5.91** | 12.10*** | 9.91*** |
| House size | $m^2$ | 4.51 | -33.32 | 25.58*** | 27.10*** | 2.65 | 10.28 |
| Household income level | Ordinal-1(low)-9(high) | 2.52 | -0.78 | 30.19*** | 0.89*** | 0.72 | -0.15 |
| Household residential years | years | 3.82 | 6.38 | 6.80** | -2.63** | 2.06 | 1.85 |
| Electricity consumption in 2022 | kWh | 0.05 | 719.0 | 8.02** | 2355.1** | 4.42** | 1817.7** |
| Motivation for money-saving | Ordinal-1(low)-5(high) | 6.35 | 0.56 | 6.24 | 0.18 | 2.19 | 0.12 |
| Motivation for environmental protection | Ordinal -1(low)-5(high) | 9.61** | 0.90** | 2.02 | 0.12 | 1.24 | 0.11 |
| Motivation for supporting to get through the energy crisis | Ordinal-1(low)-5(high) | 1.23 | 0.30 | 6.08** | 0.21** | 3.94** | 0.21** |
| Motivation for supporting the energy system | Ordinal-1(low)-5(high) | 15.41*** | 1.06*** | 11.66*** | 0.276*** | 2.31 | 0.15 |
| Awareness of energy use changes | Ordinal-1(low)-5(high) | 6.68** | -0.47** | 1.40 | 0.07 | 1.80 | 0.09 |
| Perception of comfort in 2022 | Ordinal-1(high)-4(low) | 0.30 | 0.11 | 0.07 | -0.01 | 0.24 | 0.04 |
| Perception of comfort in the past | Ordinal-1(high)-4(low) | 1.68 | 0.24 | 3.26 | -0.11 | 0.41 | 0.04 |
| Innovativeness[c] | Ordinal-1(low)-5(high) | 1.46 | 0.15 | 16.19*** | 0.17*** | 14.50*** | 0.19*** |
| Attitude | Ordinal-1(low)-5(high) | 11.27*** | 0.89*** | 9.75** | 0.21** | 18.29*** | 0.41*** |
| Personal norm | Ordinal-1(low)-5(high) | 50.74*** | 1.70*** | 3.64 | -0.15 | 17.04*** | 0.38*** |
| Social norm | Ordinal-1(low)-5(high) | 24.11*** | 1.15*** | 11.79*** | 0.26*** | 3.92* | 0.118* |
| Descriptive norm | % | 59.95*** | 10.14*** | 1.69 | 3.21 | 17.11*** | 5.41*** |
| Self-efficacy | Ordinal-1(low)-5(high) | 22.06*** | 1.23*** | 18.01*** | 0.28*** | 12.18*** | 0.33*** |

[a] *Multivariate effect.*

[b] *Mean differences in variables between households that implemented energy performance upgrades and those that did not. The significance of these differences was assessed using the Bonferroni correction.*

[c] *A latent variable inferred from seven questions, aims to understand participants' innovativeness.*

taken home upgrades exhibit an increased proclivity for innovation (innovativeness), a more favorable attitude towards retrofitting efforts, greater responsiveness to recommendations from others advocating for retrofitting (social norm), and a heightened perception of their expertise in retrofitting methods (self-efficacy).

#### FACTORS AFFECTING HOUSEHOLD INTENTIONS FOR ENERGY EFFICIENCY UPGRADES

In order to find a suitable balance between accurately fitting the data and maintaining simplicity, we compare the Mean Squared Error (MSE) and R-squared ($R^2$) of the Lasso regression models. The model with the Extended Bayesian Information Criterion (minEBIC) is selected as the best fit for each domain. The selection is made from 21 socio-demographic, contextual, and psychological variables, along with approximately 25 barriers and drivers. Table 6 presents the standardized coefficients of the principal factors from the minBIC model.

The variables chosen in relation to households' intentions for each behaviour indicate that the intention for solar PV installation is strongly influenced by factors such as the energy crisis, personal norms, and positive social influences. The energy crisis aroused electricity price increment has the most significant effects in promoting residents' intention to implement private PV in their dwellings. The intention for implementing flexible energy applications is positively associated with the respondent's motivation to contribute to the energy system, supporting the energy supply, social norms, and attitude. The motivation of money-saving and the driver of flexible energy use can lead to energy cost reduction are also play a significant role in increasing the respondant's intention. Conversely, the intention is negatively affected by not aligning with their daily routine (being perceived as inconvenient) and the respondent's feeling of it not yet being the right time for the measure. Piano and Smith (2022) also proved the importance of "being convinced to apply in daily life" for flexible energy technologies. Additionally, if the households feel unable to afford their comfort in 2022, they are less likely to have high intentions in adopting flexible energy use compared to those with better financial status who can afford the costs associated with their daily comfort. The intention for retrofitting is highly correlated with the respondent's age, house type, and other psychological variables. The age of respondents and the house type, particularly apartment blocks, display negative correlations with residents' intention for retrofitting. This suggests that older residents and those residing in apartments are less likely to undertake retrofitting actions in the next three years. The variable creating the most negative impact is finding the right point in time to retrofit ("it is not yet the right time") with a standardized coefficient of -0.2096. Among soc-demographic factors, households comprising three adults establish a positive relationship with the intention. Additionally, other psychological factors also show positive correlations with energy retrofitting intentions. High values of attitude, personal norm, social norm, and self-efficacy would increase the respondents' intentions to engage in retrofitting. In addition, if respondents perceive their current dwelling as a waste of energy and believe they can substantially reduce energy costs by retrofitting, they obtain higher intentions. Notably, prior unsuccessful attempts in retrofitting would enhance residents' intentions to undertake such actions again.

## Conclusion and Discussion

This paper investigates the adoption of adaptive energy performance upgrading measures by households and identifies the key factors influencing their intention to implement these adaptive behaviours after an energy crisis. Based on a survey conducted with Norwegian households, the findings reveal a substantial surge in energy performance improvements between 2020 and 2023. Approximately half of the 21 households installing PV did so within the past three years, contributing to an annual household retrofitting rate of approximately 4.83 %. This rate surpasses both simulation results (3.51 %) from Egner and Klöckner (2022) and the previous yearly energy retrofitting rate of 3.4 % in 2019. Notably, the adoption of flexible energy applications has experienced significant growth, emerging as a mainstream technology despite its historical non-prominence in the market (Statista, 2023).

In summary, private PV installations are indicative of community-based or small group-level diffusion measures for enhancing energy efficiency. This corroborates the findings of Xue, Margaret, and Temeljotov-salaj (2021), highlighting limited examples and communications as significant barriers

**Table 6. Standardized coefficients of selected variables in relation to household intention on each energy performance upgrade measures.**

| **MinEBIC model** | | | |
|---|---|---|---|
| **Variables** | **Solar PV** | **Flexible energy use** | **House retrofit** |
| Age (log value) | | | -0.0260 |
| Comfort affordability | | | |
| 2. not affordable | | -0.0204 | |
| House type | | | |
| apartment block | | | -0.0153 |
| Household composition | | | |
| 4. three-person family without underage kids | | | 0.0086 |
| Motivations | | | |
| Saving money | | 0.0536 | |
| Getting through the energy crisis | | 0.0255 | |
| Supporting energy system | | 0.0709 | |
| Attitude | | 0.0584 | 0.1014 |
| Personal norm | 0.0331 | | 0.0796 |
| Social norm | 0.0804 | 0.0926 | 0.1160 |
| Self-efficacy | | | 0.0450 |
| Barriers and Drivers | | | |
| Leading to a significant reduction in my energy costs. | | 0.0585 | 0.0115 |
| Contributing to energy security | | 0.0099 | |
| The standard of my home insulation is a waste of energy. | | | 0.0426 |
| I am considering applying the measure due to high energy prices. | 0.1755 | | |
| It is not yet the right time. | | -0.0415 | -0.2096 |
| The measure does not fit my/our daily routines. | | -0.0703 | |
| I had negative experiences from previous attempts. | | | 0.0963 |
| I feel that I am doing a good deed for energy supply. | | 0.0177 | |
| I feel that I am doing a good deed for the environment. | | 0.0178 | |

to the diffusion of private PV in Norway. Retrofitting is widely communicated and significantly influenced by respondents' social networks, and is important in the decision-making process. The decision to adopt retrofitting is multifaceted and heavily impacted by the physical condition of the house and changes of household composition. Regarding flexible energy use, while past instances were notably differentiated by household income, type, and house size, future adoptions strongly correlate with social norms, willingness to support the energy system post-energy crisis, and compatibility with daily routines.

The predominant influence of the energy crisis is particularly evident in the domain of solar PV. The escalation in energy prices markedly amplifies respondents' intentions, exerting a direct impact or fostering an increased personal norm regarding the adoption of PV. After the energy crisis, the inclination to support the energy system acts as a substantial motivator for respondents to engage in flexible energy use. Additionally, post-energy crisis, past unfavorable experiences with retrofitting emerge as a driving factor for retrofit decision-making, which contrasts with findings from previous research (Klöckner & Nayum, 2016) and needs to be investigated in future research.

These nuanced insights into the dynamics of household energy efficiency behaviors provide valuable contributions to understanding the complexities of adoption post-energy crisis, highlighting the need for tailored approaches based on specific technologies and contextual factors.

## References


Ahrens, A., Hansen, C. B., & Schaffer, M. E. (2019). Lassopack : Model Selection and Prediction with Regularized Regression in Stata (Issue 12081).

Arthanat, S., Chang, H., & Wilcox, J. (2020). Determinants of information communication and smart home automation technology adoption for aging-in-place. *Journal of Enabling Technologies*, *14* (2), 73–86. https://doi.org/10.1108/JET-11-2019-0050/FULL/XML

Balint, A., & Kazmi, H. (2019). Determinants of energy flexibility in residential hot water systems. *Energy and Buildings*, *188–189*, 286–296. https://doi.org/10.1016/J.ENBUILD.2019.02.016

Balta-Ozkan, N., Yildirim, J., & Connor, P. M. (2015). Regional distribution of photovoltaic deployment in the UK and its determinants: A spatial econometric approach. *Energy Economics*, *51*, 417–429. https://doi.org/10.1016/j.eneco.2015.08.003

Barbosa, J. D., & Azar, E. (2018). Modeling and implementing human-based energy retrofits in a green building in desert climate. *Energy and Buildings*, *173*, 71–80. https://doi.org/10.1016/j.enbuild.2018.05.024

Basarir-Ozel, B., Nasir, V. A., & Turker, H. B. (2023). Determinants of smart home adoption and differences across technology readiness segments. *Technological Forecasting and Social Change*, *197* (June 2022), 122924. https://doi.org/10.1016/j.techfore.2023.122924

Boomsma, C., Jones, R. V, Pahl, S., & Fuertes, A. (2018). Do psychological factors relate to energy saving behaviours in inefficient and damp homes? A study among English social housing residents. https://doi.org/10.1016/j.erss.2018.09.007

Dharshing, S. (2017). Household dynamics of technology adoption: A spatial econometric analysis of residential solar photovoltaic (PV) systems in Germany. *Energy Research and Social Science*, *23*, 113–124. https://doi.org/10.1016/j.erss.2016.10.012

Egner, L. E., & Klöckner, C. A. (2022). Effect of Policy Implementation on Energy Retrofit Behavior and Energy Consumption in a Simulated Neighborhood. *Article in Journal of Artificial Societies and Social Simulation*. https://doi.org/10.18564/jasss.4936

Emmert-Streib, F., & Dehmer, M. (2019). High-Dimensional LASSO-Based Computational Regression Models: Regularization, Shrinkage, and Selection. *Machine Learning and Knowledge Extraction*, *1* (1), 359–383. https://doi.org/10.3390/make1010021

Escandón, R., Silvester, S., & Konstantinou, T. (2018). Evaluating the environmental adaptability of a nearly zero energy retrofitting strategy designed for Dutch housing stock to a Mediterranean climate. *Energy and Buildings*, *169*, 366–378. https://doi.org/10.1016/j.enbuild.2018.03.079

Geels, F. W., Sareen, S., Hook, A., & Sovacool, B. K. (2021). Navigating implementation dilemmas in technology-forcing policies: A comparative analysis of accelerated smart meter diffusion in the Netherlands, UK, Norway, and Portugal (2000–2019). *Research Policy*, *50*(7), 104272. https://doi.org/10.1016/J.RESPOL.2021.104272

Guta, D. D. (2020). Determinants of household use of energy-efficient and renewable energy technologies in rural Ethiopia. *Technology in Society*, *61*, 101249. https://doi.org/10.1016/J.TECHSOC.2020.101249

Harputlugil, T., & de Wilde, P. (2021). The interaction between humans and buildings for energy efficiency: A critical review. In *Energy Research and Social Science* (Vol. 71). Elsevier Ltd. https://doi.org/10.1016/j.erss.2020.101828

IEA. (2022). Norway 2022 Energy Policy Review.

Jia, L., Qian, Q. K., Meijer, F., & Visscher, H. (2021). How information stimulates homeowners ' cooperation in residential building energy retrofits in China. *Energy Policy*, *157* (August), 112504. https://doi.org/10.1016/j.enpol.2021.112504

Klöckner, C. A., & Nayum, A. (2016). Specific barriers and drivers in different stages of decision-making about energy efficiency upgrades in private homes. *Frontiers in Psychology*, *7* (SEP), 1362. https://doi.org/10.3389/FPSYG.2016.01362/BIBTEX

Li, H., Wang, Z., Hong, T., & Piette, M. A. (2021). Advances in Applied Energy Energy flexibility of residential buildings : A systematic review of characterization and quantification methods and applications. *Advances in Applied Energy*, *3*(May), 100054. https://doi.org/10.1016/j.adapen.2021.100054

Li, W., Yigitcanlar, T., Erol, I., & Liu, A. (2021). Motivations, barriers and risks of smart home adoption: From systematic literature review to conceptual framework. *Energy Research & Social Science*, *80*, 102211. https://doi.org/10.1016/J.ERSS.2021.102211

Lopes, M. A. R., Antunes, C. H., & Martins, N. (2012). Energy behaviours as promoters of energy efficiency: A 21st century review. In *Renewable and Sustainable Energy*

*Reviews* (Vol. 16, Issue 6, pp. 4095–4104). https://doi.org/10.1016/j.rser.2012.03.034

Norwegian Ministry of Climate and Environment. (2021). Norway's Climate Action Plan for 2021-2030 Norwegian Ministry of Climate and Environment (Vol. 13).

Paukstadt, U. (2019). A Survey of Smart Energy Services for Private Households. *14th International Conference on Wirtschaftsinformatik*, 24–27.

Piano, S. Lo, & Smith, S. T. (2022). Energy demand and its temporal flexibility: Approaches , criticalities and ways forward. *Renewable and Sustainable Energy Reviews*, *160* (July 2021), 112249. https://doi.org/10.1016/j.rser.2022.112249

Pothitou, M., Kolios, A. J., Varga, L., & Gu, S. (2016). A framework for targeting household energy savings through habitual behavioural change. *International Journal of Sustainable Energy*, *35* (7), 686–700. https://doi.org/10.1080/14786451.2014.936867

Qureshi, T. M., Ullah, K., & Arentsen, M. J. (2017). Factors responsible for solar PV adoption at household level: A case of Lahore, Pakistan. *Renewable and Sustainable Energy Reviews*, *78*, 754–763. https://doi.org/10.1016/J.RSER.2017.04.020

Ranstam, J., & Cook, J. A. (2018). LASSO regression. *British Journal of Surgery*, *105* (10), 1348. https://doi.org/10.1002/bjs.10895

Statista. (2023). Smart Home: market data & analysis. In *the web of Statista*. https://www.statista.com/outlook/dmo/smart-home/norway#revenue

Trotta, G. (2018). Factors affecting energy-saving behaviours and energy efficiency investments in British households. *Energy Policy*, *114*, 529–539. https://doi.org/10.1016/j.enpol.2017.12.042

Vainio, A., Pulkka, A., Paloniemi, R., Varho, V., & Tapio, P. (2019). *Citizens' sustainable, future-oriented energy behaviours in energy transition*. https://doi.org/10.1016/j.jclepro.2019.118801

Wolske, K. S., Gillingham, K. T., & Schultz, P. W. (2020). Peer influence on household energy behaviours. In *Nature Energy* (Vol. 5, Issue 3, pp. 202–212). Nature Research. https://doi.org/10.1038/s41560-019-0541-9

Xue, Y., Margaret, C., & Temeljotov-salaj, A. (2021). Barriers and potential solutions to the diffusion of solar photovoltaics from the public-private-people partnership perspective – Case study of Norway. *Renewable and Sustainable Energy Reviews*, *137* (February 2020), 110636. https://doi.org/10.1016/j.rser.2020.110636

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## Appendix A

| | No PV installation | PV installation | No flexible energy use | Flexible energy use | No retrofitting | Retrofitting |
|---|---|---|---|---|---|---|
| N | 21 (2.2 %) | 916 (97.8 %) | 725 (74.7 %) | 246 (25.3 %) | 931 (85.5 %) | 158 (14.5 %) |
| Gender | | | | | | |
| Man | 11 (52.4 %) | 495 (54.0 %) | 382 (52.7 %) | 143 (58.1 %) | 509 (54.7 %) | 86 (54.4 %) |
| Woman | 10 (47.6 %) | 421 (46.0 %) | 343 (47.3 %) | 103 (41.9 %) | 422 (45.3 %) | 72 (45.6 %) |
| Located Region | | | | | | |
| Oslo | 3 (14.3 %) | 114 (12.4 %) | 99 (13.7 %) | 24 (9.8 %) | 140 (15.0 %) | 20 (12.7 %) |
| Rogaland | 3 (14.3 %) | 79 (8.6 %) | 52 (7.2 %) | 16 (6.5 %) | 75 (8.1 %) | 12 (7.6 %) |
| Møre og Romsdal | 1 (4.8 %) | 47 (5.1 %) | 30 (4.1 %) | 9 (3.7 %) | 33 (3.5 %) | 7 (4.4 %) |
| Nordland | 0 (0.0 %) | 35 (3.8 %) | 39 (5.4 %) | 11 (4.5 %) | 47 (5.0 %) | 14 (8.9 %) |
| Viken | 4 (19.0 %) | 207 (22.6 %) | 170 (23.4 %) | 77 (31.3 %) | 198 (21.3 %) | 27 (17.1 %) |
| Innlandet | 1 (4.8 %) | 60 (6.6 %) | 41 (5.7 %) | 15 (6.1 %) | 60 (6.4 %) | 20 (12.7 %) |
| Vestfold og Telemark | 3 (14.3 %) | 71 (7.8 %) | 56 (7.7 %) | 20 (8.1 %) | 89 (9.6 %) | 9 (5.7 %) |
| Agder | 3 (14.3 %) | 60 (6.6 %) | 44 (6.1 %) | 18 (7.3 %) | 66 (7.1 %) | 6 (3.8 %) |
| Vestland | 2 (9.5 %) | 112 (12.2 %) | 88 (12.1 %) | 30 (12.2 %) | 109 (11.7 %) | 24 (15.2 %) |
| Trøndelag | 1 (4.8 %) | 84 (9.2 %) | 68 (9.4 %) | 20 (8.1 %) | 73 (7.8 %) | 14 (8.9 %) |
| Troms og Finnmark | 0 (0.0 %) | 47 (5.1 %) | 38 (5.2 %) | 6 (2.4 %) | 41 (4.4 %) | 5 (3.2 %) |
| Education | | | | | | |
| Primary education | 1 (4.8 %) | 50 (5.5 %) | 30 (4.1 %) | 9 (3.7 %) | 40 (4.3 %) | 10 (6.3 %) |
| Upper secondary education | 0 (0.0 %) | 101 (11.0 %) | 74 (10.2 %) | 25 (10.2 %) | 88 (9.5 %) | 12 (7.6 %) |
| Upper secondary vocational education | 1 (4.8 %) | 123 (13.4 %) | 102 (14.1 %) | 32 (13.0 %) | 119 (12.8 %) | 34 (21.5 %) |
| Vocational school | 4 (19.0 %) | 84 (9.2 %) | 65 (9.0 %) | 31 (12.6 %) | 115 (12.4 %) | 17 (10.8 %) |
| Higher education with up to 4 years | 8 (38.1 %) | 317 (34.6 %) | 246 (33.9 %) | 80 (32.5 %) | 311 (33.4 %) | 58 (36.7 %) |
| Higher education with a duration of more than 4 years | 7 (33.3 %) | 241 (26.3 %) | 208 (28.7 %) | 69 (28.0 %) | 258 (27.7 %) | 27 (17.1 %) |
| House type | | | | | | |
| Detached House/Villa | 13 (61.9 %) | 485 (52.9 %) | 342 (47.2 %) | 138 (56.1 %) | 485 (52.1 %) | 97 (61.4 %) |
| Semi-detached house | 2 (9.5 %) | 56 (6.1 %) | 42 (5.8 %) | 28 (11.4 %) | 53 (5.7 %) | 14 (8.9 %) |
| Terraced House/Chain House | 1 (4.8 %) | 106 (11.6 %) | 98 (13.5 %) | 30 (12.2 %) | 92 (9.9 %) | 23 (14.6 %) |
| Apartment block | 5 (23.8 %) | 230 (25.1 %) | 204 (28.1 %) | 43 (17.5 %) | 259 (27.8 %) | 21 (13.3 %) |
| Community residential Block | 0 (0.0 %) | 8 (0.9 %) | 9 (1.2 %) | 4 (1.6 %) | 7 (0.8 %) | 1 (0.6 %) |
| Basement apartment/Studio | 0 (0.0 %) | 31 (3.4 %) | 30 (4.1 %) | 3 (1.2 %) | 35 (3.8 %) | 2 (1.3 %) |
| Heatpump | 2 (9.5 %) | 212 (23.1 %) | 165 (22.8 %) | 68 (27.6 %) | 215 (23.1 %) | 53 (33.5 %) |
| Electronic heater | 1 (4.8 %) | 232 (25.3 %) | 220 (30.3 %) | 48 (19.5 %) | 252 (27.1 %) | 39 (24.7 %) |
| Wood stove | 2 (9.5 %) | 94 (10.3 %) | 70 (9.7 %) | 17 (6.9 %) | 101 (10.8 %) | 18 (11.4 %) |
| District heating | 1 (4.8 %) | 80 (8.7 %) | 65 (9.0 %) | 20 (8.1 %) | 83 (8.9 %) | 5 (3.2 %) |
| Multiple types | 15 (71.4 %) | 298 (32.5 %) | 205 (28.3 %) | 93 (37.8 %) | 280 (30.1 %) | 43 (27.2 %) |
| House ownership | | | | | | |
| Owner | 18 (85.7 %) | 725 (79.1 %) | 553 (76.3 %) | 210 (85.4 %) | 727 (78.1 %) | 129 (81.6 %) |
| Shareholder | 2 (9.5 %) | 102 (11.1 %) | 87 (12.0 %) | 17 (6.9 %) | 109 (11.7 %) | 21 (13.3 %) |
| Short-term rental (<2 yrs) | 0 (0.0 %) | 33 (3.6 %) | 37 (5.1 %) | 12 (4.9 %) | 37 (4.0 %) | 1 (0.6 %) |
| Long-term rental (>2 yrs) | 1 (4.8 %) | 56 (6.1 %) | 48 (6.6 %) | 7 (2.8 %) | 58 (6.2 %) | 7 (4.4 %) |
| Household type | | | | | | |
| Single family | 1 (4.8 %) | 211 (23.0 %) | 229 (31.6 %) | 25 (10.2 %) | 245 (26.3 %) | 32 (20.3 %) |
| Two-Adults Family | 11 (52.4 %) | 426 (46.5 %) | 309 (42.6 %) | 125 (50.8 %) | 429 (46.1 %) | 77 (48.7 %) |
| One adult family with a kid | 0 (0.0 %) | 16 (1.7 %) | 5 (0.7 %) | 3 (1.2 %) | 22 (2.4 %) | 3 (1.9 %) |
| 3-person family without kids | 3 (14.3 %) | 56 (6.1 %) | 33 (4.6 %) | 19 (7.7 %) | 40 (4.3 %) | 8 (5.1 %) |
| 3-person family with underage kids | 3 (14.3 %) | 62 (6.8 %) | 54 (7.4 %) | 24 (9.8 %) | 62 (6.7 %) | 15 (9.5 %) |
| Extended family without kids | 0 (0.0 %) | 15 (1.6 %) | 21 (2.9 %) | 5 (2.0 %) | 14 (1.5 %) | 2 (1.3 %) |
| Extended family with underage kids | 3 (14.3 %) | 130 (14.2 %) | 74 (10.2 %) | 45 (18.3 %) | 119 (12.8 %) | 21 (13.3 %) |