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Sustainable energy consumption – Empirical evidence of a household in Poland sustainable energy consumption, electricity demand, econometric model, household energy transition, energy policy impact

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ABSTRACT

There is an expected increase in the demand for electricity from households in European countries. The outcome of the growing proportion of renewable energy sources in the energy supply mix should result in improved customer awareness regarding their electricity usage. Additionally, they must assume a more proactive role in overseeing their electricity usage. Innovation and pollution management have become crucial catalysts for promoting sustainable economic development and environmental protection. This is a response to the increasing threats posed by climate change. This study addresses this existing research gap in sustainable energy consumption. The research aims to examine the advantages of replacing traditional sources of heating with renewable ones. The empirical case study of households in Poland serves as an illustration of the theoretical foundation. The purpose of the study entails the construction of a multi-equation econometric model describing the mechanisms of electricity consumption in a specific household. The model hypothesis indicates that the model should take the form of a system of interdependent equations. The following will be described: the monthly volume of electricity consumption, the cost of this energy payment (in PLN), and the price per one MWh in a given month. Monthly time series from September 2015 to June 2023 were used. The resulting time series amounted to a count of 94 statistical observations. The results in the form of a multi-level empirical econometric model indicate that the economic, environmental, and social benefits of using renewable sources of heating can make a significant contribution to reducing fossil fuel consumption and CO2 emissions. In the context of growing environmental awareness and the need to reduce greenhouse gas emissions, heat pumps are becoming an increasingly important element in the discussion of the future of heating. Their role in transforming the energy sector in the direction of sustainability is crucial.

1. Introduction

Energy science is no longer an independent discipline. Energy science, social science, and information science intersect one another, thus forming some new research areas (Zhou, K., & Yang, S. (2016)) [1]. Over the past decade, the dynamic global energy transition has accelerated. Notably, the energy transition encompasses not only technological and methodological aspects but also the social, institutional, economic, and legal spheres [2–4]. From a normative perspective, there is a widespread assumption that the energy transition should adhere to the concept of the energy trilemma, which highlights three crucial elements: guaranteeing energy security, [5] equitable energy access, and environmental sustainability (Liu et al., 2022, Fu, F. Y et al., 2023., [6]). Nevertheless, achieving this goal poses a significant obstacle for advanced societies, with the primary issue lying in providing adequate support for this endeavour, which is currently the most formidable challenge faced by the scientific community. (Es et al., 2022). The concept of environmental sustainability encompasses not only minimising the adverse environmental effects of energy transition processes, but also achieving favourable outcomes in both environmental and socio-economic dimensions. These outcomes are aligned with the sustainable development goals established by the United Nations ([3,7], Gao & Chen, 2023 Georgeson, L., & Maslin, M. 2018). The energy transition process is crucial for achieving a sustainable economy in terms of its social,

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environmental, and economic goals. It also plays a significant role in enhancing economic resilience at both the micro and macroeconomic levels (Neofytou, H. et al., 2020 [8], [9] Cantarero, M. M. V. 2020, Chu, L. K. [10], Safari, A. (2019) [11]. Concerning the renewable energy industry, environmental protection, socioeconomic development [12], and the achievement of sustainable development objectives [13] are the most significant expectations. The implementation of an energy transition that primarily relies on renewable energy sources enables the mitigation of pollutant emissions, which have been the primary cause of environmental degradation in recent decades [2].

As global concerns about climate change and sustainability intensify, the shift towards sustainable energy consumption emerges as a critical strategy within both global and regional energy policies. This transition is particularly relevant in Poland, a country currently navigating significant energy challenges amidst the broader European energy crisis. This study contributes to the discourse on sustainable energy by focusing on the replacement of traditional heating sources with renewable alternatives in Polish households. Poland's reliance on coal and the European Union's aggressive targets for reducing greenhouse gas emissions underscore the relevance of this research. This juxtaposition presents a unique opportunity to explore the implications of household-level renewable energy adoption within a framework that is both local and globally pertinent. Polish households accounted for a sizeable (20.2 %) portion of the country's overall energy consumption in 2021 (motor fuels excluded). Poland was among the EU members with a comparatively high household consumption share (19.0 % and higher of total national consumption was found in 12 nations, with an average of 18.4 %). Poland's average household energy consumption was 24.6 GJ per inhabitant, which was comparable to the 24.5 GJ/inhabitant average for Europe (Energy consumption in households in 2021, GUS). The rigorous process of reducing carbon emissions in Poland's economy is expected to lead to a rise in the electricity consumption of households. The demand will be impacted by the rising cost of energy simultaneously. Thus, these market conditions will give rise to a negative feedback loop between energy prices and consumption. The issue of mitigating pollutant emissions is a significant subject of discourse in the realm of sustainable development.

Based on the 2022 report by the World Health Organisation (WHO), Poland is responsible for a significant number of the most polluted cities in the European Union (EU), with as many as 33 out of the top 50 cities experiencing high levels of pollution. The World Health Organisation states that prolonged exposure to PM2.5 leads to a reduced lifespan, while brief exposure to high levels of PM2.5 increases the likelihood of respiratory and circulatory diseases, as well as the risk of hospitalisation for emergency cases (such as severe asthma), acute respiratory reactions, and decreased lung function. PM2.5, together with PM10 dust, the extremely carcinogenic benzo(*a*)pyrene, and hazardous chemical compounds such as sulphur oxides, nitrogen oxides, carbon monoxide, heavy metals, and soot, are components of smog.

At present, the energy sector, including electricity production, is predominantly reliant on fossil fuels, the combustion of which is assumed to be the primary source of the majority of greenhouse gas emissions. The energy transition, which includes the use of renewable energy sources, is therefore anticipated to substantially reduce greenhouse gas emissions and contaminants over the next several decades. Consequently, there is a heightened emphasis on the necessity to enhance the energy production process. As a result, an enhancement in the state of the natural environment is anticipated to be the ultimate outcome (Olabi & Abdel-Kareem, 2022) [14]. As per the scholarly works of Olabi and Abdel-Kareem (2022), Chang et al. [15], and Amjith and Bavanish [16], solar energy, wind energy, and biomass are the most critical in the renewable energy sector in terms of accessibility. Air pollution is harmful in terms of both public health and economic viability. It is crucial to raise awareness among individuals regarding the consequences of using inferior fuels and stoves for heating purposes. To enhance social consciousness and mitigate pollution, it is crucial to execute initiatives that demonstrate the tangible advantages associated with substituting conventional energy sources with renewable alternatives. Energy-related environmental awareness should focus on educating consumers to understand the extent to which their actions and use of devices contribute to total energy consumption and what consequences this has for the environment [17] Apergis, Polemis, Soursou, 2021]. Raising this awareness may prove important both in terms of combating energy poverty and environmental protection. This topic is significant from the perspective of contemporary problems with sustainable development. In response to the urgent need for a nuanced understanding of energy transitions, our study has expanded the discussion on energy poverty, placing it within the broader context of current geopolitical tensions and the ongoing energy transition in Poland. This enriched analysis helps delineate the complex interplay between economic accessibility and the adoption of sustainable energy solutions in a region experiencing dynamic policy shifts and market fluctuations. Furthermore, our discussion acknowledges the critical role that energy transition strategies must play in addressing energy poverty. By aligning renewable energy adoption with efforts to mitigate energy poverty, our study proposes a dual approach that not only seeks to reduce carbon emissions but also aims to enhance the socio-economic resilience of the most vulnerable populations. Increasingly, households are recognised as pivotal in the global shift towards renewable energy, contributing significantly to national energy strategies aimed at reducing carbon emissions [18]. Across Europe, government incentives have catalysed the adoption of technologies such as solar panels and heat pumps, with demonstrated benefits in energy efficiency and cost savings Brown, M [19]. Recent advancements in interconnected smart devices significantly improve household energy management and efficiency, with practical applications extending to electric vehicles and smart grid systems. Notably, as highlighted in recent studies (Coban, H. H., & Lewicki, W. (2022)) [20], these technologies not only streamline energy consumption but also play a pivotal role in reducing CO2 emissions, thereby contributing to more sustainable urban environments and aligning with global efforts to combat climate change. However, challenges persist, particularly in terms of the initial investment costs and the integration of these technologies into existing infrastructures [21]. In Poland, while strides have been made, there remains a notable gap in comprehensive case studies that illustrate the long-term impacts of such transitions [22]. This study addresses this gap by providing empirical evidence from Polish households, thereby contributing to a nuanced understanding of the socioeconomic impacts of renewable energy adoption at a micro level. We situate our study at the intersection of environmental sustainability and practical energy solutions for households. Recent literature highlights a growing shift towards decentralised energy systems and increased reliance on renewable energy sources at the community and household levels ([23]; Heldeweg, M. A., & Saintier, S. (2020)) [24]. This research leverages these discussions to examine how individual households in Poland can contribute to and benefit from the shift to renewable energy, thus aligning with broader sustainable development goals. Poland's current energy landscape, marked by high coal consumption and increasing public and governmental pressure to adopt more sustainable energy practices, amplifies the timeliness of this topic. The European energy crisis, exacerbated by geopolitical tensions and supply uncertainties, further necessitates a study into alternative, sustainable energy sources at a micro-level [25]. This study addresses a vital component of the energy transition puzzle by focusing on household energy consumption in a context where both political will and technological advancements are ripe for investigation. While there is extensive research on renewable energy technologies and policies at the national and international levels, there remains a significant gap in empirical studies focused on the household perspective in Eastern European contexts. Specifically, there is limited research on the socioeconomic impacts of transitioning to renewable energy in Polish households, an area where this study contributes by providing detailed, localised insights into the dynamics of energy consumption and decision-making at the household level (Żuk, P. (2023) [26]. This research challenges existing theories that predominantly focus on macro-level analyses by delving into the micro-dynamics of energy transition. It scrutinises the often-overlooked aspects of household decision-making processes, barriers to renewable energy adoption, and the resultant impacts on energy consumption patterns. By doing so, it questions the scalability of renewable energy solutions from households to broader communities and examines the necessary conditions for their success. This study significantly advances our understanding by providing empirical evidence on the feasibility and impacts of renewable energy adoption in Polish households. It offers new insights into how individual actions can align with global energy strategies, thus influencing policy formulation at multiple levels. Policymakers, stakeholders, and the academic community expect the findings to shed light on the potential roles of households in achieving energy sustainability, laying the groundwork for more targeted and effective energy policies and interventions, grounded in empirical evidence and tailored to specific socio-economic contexts. This study adopts a methodology that involves constructing a multi-equation econometric model, selected for its capacity to intricately describe the interdependencies within household energy consumption dynamics. This approach allows for a detailed examination of how shifts from conventional to renewable energy sources impact consumption patterns over time. The micro model belongs to the class of systems of interdependent equations and describes the monthly volume of electricity consumption, the value of this energy consumption (in PLN), and the price of one MWh in a given month. Monthly time series from September 2015 to June 2023 were used, which yielded a count of 94 statistical observations. Presenting an example of the possibility of replacing a traditional heat source with a renewable source and indicating the associated economic and social benefits may be extremely important from the point of view of the sustainable development of societies and economies around the world. The study is original, as it presents the case of a particular household in which electricity is the only source of energy. Such studies are not found in the literature, mainly due to the lack of statistical data on electricity consumption in specific households.The structure of the paper is outlined as follows: introduction, literature review, methodology, results and discussion, limitations and future research directions, conclusion, and policy recommendations. This sequence ensures a logical flow, guiding readers through the study's objectives, theoretical grounding, empirical analysis, and concluding insights.

2. Literature review

The energy transition process taking place nowadays has been supported and described by various studies. The shift away from fossil energy sources (oil, gas, and coal) towards renewable sources of electricity (solar, wind, and waterpower) has been progressing (Al-Shetwi, A. Q [27]., Kamran, M., & Fazal, M. R. (2021) [28], Kabeyi, M. J. B., & Olanrewaju, O. A. (2022) [29], T. Z. et al. (2022), Tyagi, J. [30], Bhattacharya et al. [31].

Household electricity consumption constitutes the subject of many scientific works. Individuals must actively manage their power consumption and increase their understanding of it, as there will be an expected increase in demand for household electricity and a greater reliance on intermittent renewable energy sources in the supply mix. (Frederiks et al. [32], Kleinschafer, J., & Morrison, M. (2014) [33], Wallenborn et al. [34], Rowlands, I. H. et al. [35], Williams, J. [36], Grønhøj, A., & Thøgersen, J. (2011) [37], Winett, R. A. et al. [38].

Conducting studies on consumer energy consumption behaviour is a crucial approach to enhancing energy efficiency and pursuing successful energy conservation. Social science has historically been a significant component of energy field research. Numerous energy and environmental issues have been effectively resolved by using social science approaches and models (Cantarero, M. M. V. (2020) [9], Gaur, A. S., Fitiwi, D. Z., & Curtis, J. [39], Hua, H., Wei, Z., Qin, Y., Wang, T., Li, L., & Cao, J [40]. In the field of energy social science, energy consumption and conservation are significant behavioural and psychological research topics [41] (Conradie, P., Van Hove, S., Pelka, S., Karaliopoulos, M., Anagnostopoulos, F., Brugger, H., & Ponnet, K., 023). Many behavioural and psychological models of consumers have been created and used in recent decades to study householders' energy consumption patterns and the factors that influence them (Vining, J., & Ebreo, A. (2002) [42], Jackson, T. [43], Ajzen, I. [44], Perugini, M., & Bagozzi, R. P. (2004) [45], April, Schwartz, S. H. (1977) [46]. To achieve energy efficiency and savings, various intervention strategies were developed to motivate or promote changes in people's energy usage behaviour (Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. [47], Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. [48], Osterhus, T. L. [49], Steg, L., & Vlek, C. (2009) [50], Allen, C. T. [51], Poortinga, W., Steg, L., Vlek, C., & Wiersma, G. [52], Steg, L. [53]). Numerous variables, both objective and subjective, influence people's energy consumption patterns (Guo, Z. et al. [54], Zhou, K., & Yang, S. (2016), [55] Gifford, R., & Nilsson, A. (2014), Hao, Y. et al. [56]. The term "objective factors" refers to variables like income levels, home characteristics, family size, energy prices, climate, and energy policies that are independent of an individual's subjective perception. Factors on an individual's consciousness and intention are considered subjective (Sokołowska, E., & Wiśniewski, W [57]. Sokołowska, E., & Wiśniewski, W. [58], Sokołowska [59]. One of the key study concerns in energy social science is how subjective factors affect households' energy use habits. There are studies aimed at investigating how financial development and the use of renewable energy sources affect environmental sustainability over the long term while limiting economic growth and technical innovation within a global framework. Creating feedback techniques was thought to be heavily influenced by the need to spend less energy (Kirikkaleli, D., & Adebayo, T. S. (2021)) [60]. In the article written by Shi, X. et al. [61], using China Family Panel Studies data and the distribution dynamics approach, the relationship between quality of life (QOL) (proxied by consumption upgrading) and relative household energy consumption (RHEC) was examined. The results are encouraging because they suggest that an improvement in QOL does not necessarily lead to a higher level of energy consumption. The study conducted in Finland Kalmi, P., Trotta, G., & Kažukauskas, A [62]. implies that measures to promote energy-related financial literacy might guide consumers' decisions towards energy efficiency and conservation. The research provides new insight into three key areas: (i) the energy-related financial literacy level in Finnish homes; (ii) the sociodemographic traits that impact energy-related financial literacy; and (iii) the possibility that energy-related financial literacy affects household electricity usage. The other paper explaining electricity demand and the role of energy and investment literacy on the end-use efficiency of Swiss households estimates the level of transient and persistent efficiency in the use of electricity in Swiss households using the newly developed generalised true random effects model (GTREM) [63].

The second area of interest in the social sciences is intervention strategies influencing energy consumption. Interventions can be broadly classified into three categories: structural (such as price policies and subsidies), antecedence (such as goal-setting, information, and commitment), and consequence (such as feedback and rewards). If interventions aim to reduce negative environmental impact by changing households' consumption patterns, it is necessary to consider macro-level as well as micro-level variables (see also [48,64]; Han, Q., Nieuwenhijsen, I., De Vries, B., Blokhuis, E., & Schaefer, W. [65]). The study conducted in China indicates that green finance significantly contributes to green innovation, and these effects remain consistent across alternative estimators. Irfan, M., Razzaq, A., Sharif, A., & Yang, X [66]. The Pilot Zones for Green Financial Innovation and Reform in China support green innovation and sustainable performance more pronouncedly than other regions, according to the outcomes of policy intervention impacts by applying the difference-in-differences, mediation effects, and panel vector autoregression models using China's regional data from 2010 to

2019. The study of Solaymani, S [67]. provides an ex post evaluation of Iran's energy subsidy reform, including its main law, definitions, aims and scope, effectiveness, and problems. This paper indicates evidence that the removal of energy subsidies in Iran was effective in decreasing energy consumption and greenhouse gas emissions only in the first two years of policy implementation, based on an assessment of policy reports, real data, peer-reviewed studies, and regression models. We can also mention other research indicating the role of subsidies and their effects on energy consumption (Solaymani, S., Kari, F., & Hazly Zakaria, R. (2014) [68], Sovacool, B. K. [69], Mills, Evan (2017) [70], Maroušek, J. et al. (2017) [71], Bekhet, H. A. [72], Nicolini, M., & Tavoni, M. (2017) [73], [74] Glomm, G., & Jung, J. (2015), [75] D'Adamo, I., Dell'Aguzzo, A., & Pruckner, M. (2023). Their main goal is to aim at influencing people's energy use behaviour and encouraging energy conservation.

Quantitative methods are often used to analyze electricity consumption and model consumer behaviour patterns. It is worth mentioning articles addressing the issue of household electricity consumption analysis using ordered logit models, published in the period from 2016 onwards, i.e., the example of Turkey [76] (Ari E., Aydin N., Karacan S., Saracli S. (2016)). Another article worth noting deals with the analysis of electricity consumption behaviour based on a case study of a non-business and business household in Malang (Karisma K. A., Maski G., and Noor I. (2016)) [77]. The influence of geodemographic factors on electricity consumption and forecasting models has also been addressed in research (Singh JP, Alam O., and Yassine A., 2016) [78]. Yet another paper tackles the issue of econometric modelling of household electricity consumption as a tool for calculating the social norm of consumption (Zaitseva Yu. V. (2016)). Of interest is also the case study of energy savings resulting from fan-coil speed control based on the number of occupants [79]. The other paper worth noting examines individual electricity consumption (Seebauer S., Wolf A., 2017) [80]. [81] Hidalgo J., Coello S., Mg., and González Y. (2018), in turn, have addressed the topic of electricity demand factors in Ecuador through socioeconomic surveys of households at Monte Sinai. Likewise, another article Kim M-J [82]. presents the characteristics and determinants of household electricity consumption in Korea. The paper by [83] Ali SS S, Razman MR, and Awang A. (2020) takes up the topics of electricity consumption estimation and the relationship between national electricity consumption and appliance ownership in a Malaysian intermediary city. The determinants of household electricity consumption—evidence and suggestions with application in Montenegro—constituted the subject of research by [84] Đurišic' V., Rogicć S., Smolović J. C., and Radonjić M. (2020). In Greece, a study of the sociodemographic determinants of household electricity consumption was conducted using quantile regression analysis [85]. A Nigerian example can be found in a study employing empirical analysis of electricity consumption concerning economic growth in Nigeria (Mamudu, ZU, Ochei, M., C. (2020)) [86]. Non-linear analysis of the effect of electricity price on household electricity consumption has been the subject of research by Zhang L. and Wen X [87]. Last but not least, worthy of mention is the comparison of US home energy consumption across climate regions carried out based on nine factors (Debs L., Metzinger J., 2022) [88].

The above literature review shows that researchers have taken a significant interest in various aspects of household electricity consumption. However, we still need more research into this subject area, as it remains a domain relevant to the operation of every household, regardless of its location. The study is an attempt to fill a gap in existing research on the features of this important issue in sustainable development. This study has the goal of extending the body of knowledge in several key areas that are crucial for understanding and enhancing sustainable energy consumption at the household level. By integrating empirical data with theoretical insights, we address gaps in the current literature and offer new perspectives in the following domains: The first domain is household energy behavior. Our research provides an in-depth analysis of energy consumption behaviours specific to Polish households. Unlike previous studies that predominantly focused on macroeconomic impacts or aggregate data, we delve into the micro-level dynamics that influence energy use. This approach uncovers nuanced behaviours that are critical for designing more effective energy conservation strategies tailored to individual household needs. The socioeconomic impacts of renewable energy are also a very important aspect. We make a significant contribution to understanding the socioeconomic impacts of renewable energy adoption in residential settings. By balancing the analysis of upfront costs against long-term savings and environmental benefits, our study offers a comprehensive view of the economic trade-offs that households face when transitioning to renewable energy sources. This perspective is essential for policymakers and energy providers aiming to encourage broader adoption of sustainable technologies. Our investigation into the practical aspects of technology adoption highlights the challenges and facilitators within the current infrastructure. By providing detailed insights into the barriers households encounter, such as installation complexities and initial financial burdens, as well as the incentives that successfully promote integration, our study paves the way for more user-oriented renewable energy solutions. Lastly, we bridge the gap between household-level behaviours and national energy security issues. We design our targeted policy recommendations not only to support individual households but also to enhance Poland's overall energy resilience. By promoting policies that encourage the adoption of renewable energy, our findings help mitigate the risks associated with energy dependence and contribute to a more sustainable and secure energy framework. These contributions are instrumental in advancing the field of sustainable energy research, particularly in Poland, a country at a critical juncture in its energy transition journey. By highlighting these areas, our study not only informs future research directions but also assists in the practical application of renewable energy technologies at the household level.

3. Dataset and methodology

This study significantly extends the existing research on sustainable energy consumption by focusing on the underexplored area of household-level energy transitions in Poland. While previous studies have primarily concentrated on macroeconomic impacts and national policy analyses, our research delves into the micro-dynamics at the household level, offering a unique perspective that is often overlooked in the energy sector literature. For the econometric analysis, we employed Gretl, an open-source statistical package that is well-regarded for its robust econometric analysis capabilities. Gretl was chosen for its efficiency in handling time series data and its ability to perform complex statistical tests that are essential for our study.

The research uses a multi-equation econometric model that was chosen because it can accurately show how household energy use changes when renewable energy is used. The complexity inherent in household energy behaviors, influenced by a confluence of economic, social, and environmental factors, drives this methodological choice. The multi-equation approach allows for a nuanced analysis of interdependent variables, providing a comprehensive understanding of how variables interact within the specific context of Polish households (Sokołowska, Wiśniewski (2008) [89]; Sokołowska [90], Wiśniewski [57,91–94]).

We meticulously design the methodology to align it with the specific objectives [91–94] of our research.

1. Economic Impact Assessment: The model includes variables relating to installation costs, ongoing maintenance, and energy bill savings, allowing us to evaluate the economic impacts of renewable energy technologies over time.
2. Environmental Benefits Analysis: We measure environmental outputs, such as reductions in CO_2 emissions, and link these directly to

sustainable development goals, thereby quantifying the ecological advantages of adopting renewable energy sources.
3. Social Dynamics Examination: The study explores how increased environmental awareness and societal influences affect household decisions towards renewable energy technologies, incorporating factors such as societal norms and peer influence into the model.

The regression analysis helps us explore the relationship between household adoption of renewable energy and various influencing factors. By identifying significant predictors, we can suggest targeted interventions. The methodology directly corresponds to the practical realities facing Polish households. By utilising data specific to the Polish energy market, including regional disparities in energy pricing and resource availability, the study generates insights that are both relevant and actionable for policymakers and stakeholders. This localised approach ensures that the findings are grounded in the actual conditions and challenges faced by households transitioning to renewable energy sources in Poland.

The paper attempts to describe a monthly mechanism of variation in household electricity consumption between September 2015 and June 2023. 2023. The household is located in Toruń (Poland) and covers an area of more than 6000 m2, with a residential house of approximately 300 m2, a detached garage of roughly 60 m2, and an outbuilding of nearly 450 m2. This household solely relies on the public power grid for its electricity needs. There is no domestic gas supply. The house relied on fuel oil for heating until March 2021, with a wood-burning fireplace providing periodic auxiliary heating. The installation of a heat pump in April 2021 eliminated the need for oil heating. Currently, electricity is used for residential, garage, and outbuilding heating and lighting, refrigeration, as well as groundwater intake for domestic use and land irrigation. This paper describes the mechanism of electricity consumption using a stochastic system of interdependent equations. We examine its variation quantitatively, taking into account both the value and the dispersion of the unit price per MWh.

$$\text{USAGE}\begin{matrix}\nearrow \text{VALUE}\\ \leftrightarrow \text{PRICE}\end{matrix} \tag{1}$$

where USAGE is the volume of monthly electricity consumption, VALUE provides information on the monthly cost of electricity consumption in PLN, and PRICE represents the unit price per MWh in PLN. Formula (1) indicates that the volume of electricity consumption directly affects its cost to the household as well as its unit price. Simultaneously, the unit price of energy exerts an influence on the volume of energy consumption.

This means that the variables USAGE and PRICE form a feedback loop:

$$\text{USAGE} \rightleftarrows \text{PRICE} \tag{2}$$

A negative feedback from the above pair of variables can be expected. An increase in energy consumption results in a decrease in the unit price, whereas an increase in the unit price prompts a decreased consumption of electricity. The process of household electricity consumption will be described by three stochastic equations. The parameters of each equation will be estimated using the ordinary least squares method. The rationale behind this estimation approach has been described in the work of Wisniewski, J.W. (2022). Autoregressions, lags of endogenous variables, trends, and monthly periodic fluctuations are factored into the model equations. A model based on such an approach can be used to forecast endogenous variables using the iterative method described in the work of Wisniewski J.W. (2021, 2016, subsection 2.5).

The next three hypothetical stochastic equations have the following form:

$$y_{1t} = \alpha_{10} + \sum\nolimits_{j=0}^{12}\beta_{1j}\, y_{2t-j} + \sum\nolimits_{i=1}^{12}\propto_{1i}\, y_{1i-j} + \sum\nolimits_{i=1}^{12}\gamma_{1i} d_{jt} + \delta_{11} t + \delta_{12} PUMP + \delta_{13} NORM + \eta_{1t},$$

$$y_{2t} = \alpha_{20} + \sum\nolimits_{j=0}^{12}\beta_{2j}\, y_{1t-j} + \sum\nolimits_{i=1}^{12}\propto_{2i}\, y_{2i-j} + \sum\nolimits_{i=1}^{12}\gamma_{2i} d_{jt} + \delta_{21} t + \delta_{22} PUMP + \delta_{23} NORM + \eta_{2t},$$

$$y_{3t} = \alpha_{30+} \sum\nolimits_{j=0}^{12}\beta_{3j}\, y_{1t-j} + \sum\nolimits_{i=1}^{12}\propto_{3i}\, y_{3i-j} + \sum\nolimits_{i=1}^{12}\gamma_{3i} d_{jt} + \delta_{31} t + \delta_{32} PUMP + \delta_{33} NORM + \eta_{3t},$$

where:
y_{1t} = USAGE (kWh)
y_{2t} = VALUE (PLN)
y_{3t} = PRICE (PLN/1 kWh)
t – time,
d_{jt} – dummy variable taking value 1 in month No. j and 0 in the other months (j = 1, …, 12),
PUMP, taking the value of 1 in the months after heat pump installation and 0 in the entire preceding period, and.
NORM – taking the value of 1 in the months after consumption norm exceedance, at a low energy price, and 0 during periods of low price,
$\eta_{1t1t}, \eta_{2t}, \eta_{3t}$ – random variables of subsequent equations,
$\alpha_{10}, \alpha_{20}, \alpha_{30}$ – constant parameters of equations
$\beta_{1j}, \beta_{2j}, \beta_{3j}$ – structural parameters with endogenous variables, both simultaneous and delayed by j months (j = 1, …, 12),
$\alpha_{1j}, \alpha_{2j}, \alpha_{3j}$ – structural parameters of equations, characterizing the autoregression of the degree from the first to twelve (j = 1, …, 12),
$\delta_{11}, \delta_{21}, \delta_{31}$ – structural parameters of the linear trend,
$\delta_{12}, \delta_{22}, \delta_{32}$ – structural parameters characterizing the impact of the *PUMP* variable,
$\delta_{13}, \delta_{23}, \delta_{33}$ – structural parameters characterizing the impact of the *NORM* variable.

Numerical calculations and appropriate statistical tests will lead to the elimination of some of the explanatory variables in each of equations (3), (4), (5). Only statistically significant variables will remain in the empirical equations.

4. Results and discussion

In the period from 2015 to 2023, seasonal oscillations occurred in the volume and value amounts of electricity consumption in the household under consideration. After the abandonment of oil house and domestic water heating and the installation of a heat pump, a sharp increase in the magnitude of the USAGE and VALUE variables occurred, as illustrated in Figs. 1 and 2. In the period from 2015 to 2021, a stabilisation of the energy unit price can also be observed. The price spike took place over the period 2022–2023; since then, fluctuations in the unit price have been observed, with a slight tendency towards a systematic increase. This process is illustrated in Fig. 3, showing the fluctuations of the variable PRICE. Unit prices of household electricity ranged from PLN 607.89 to PLN 1432.07 per MWh.

The parameters of the three stochastic equations forming the system of household electricity demand were estimated (Table 1). The first empirical equation describes the mechanism of electricity consumption. The description accuracy in this equation is lower, compared to the other two equations ($R^2 = 0.888$). This results from the omission of several minor factors, which were not recordable, in the equation.

- the frequency of out-of-home meal preparation and consumption,
- the frequency of leaves for periods longer than a few days - the house is left occupantless,
- the frequency of running the irrigation and other systems.

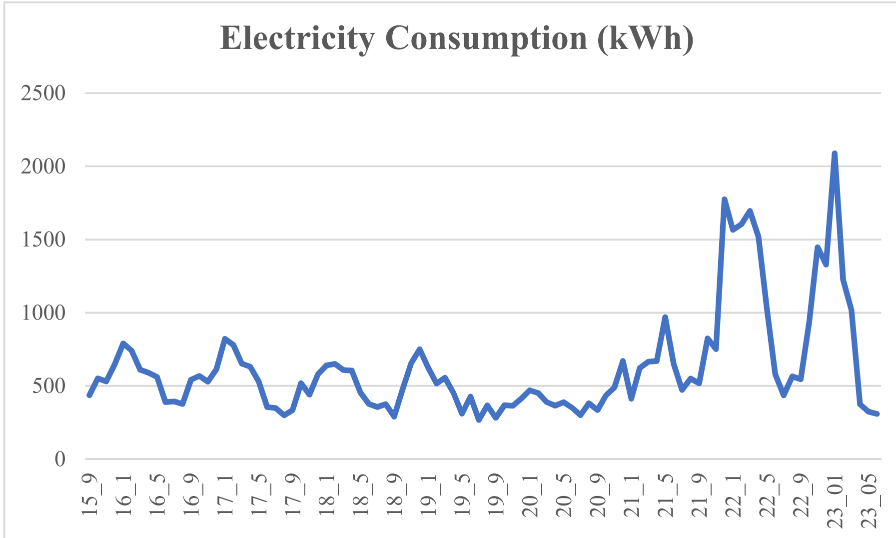

Fig. 1. Monthly household electricity consumption in the period 2015_9–2023_06. Source: invoices provided by ENERGA.

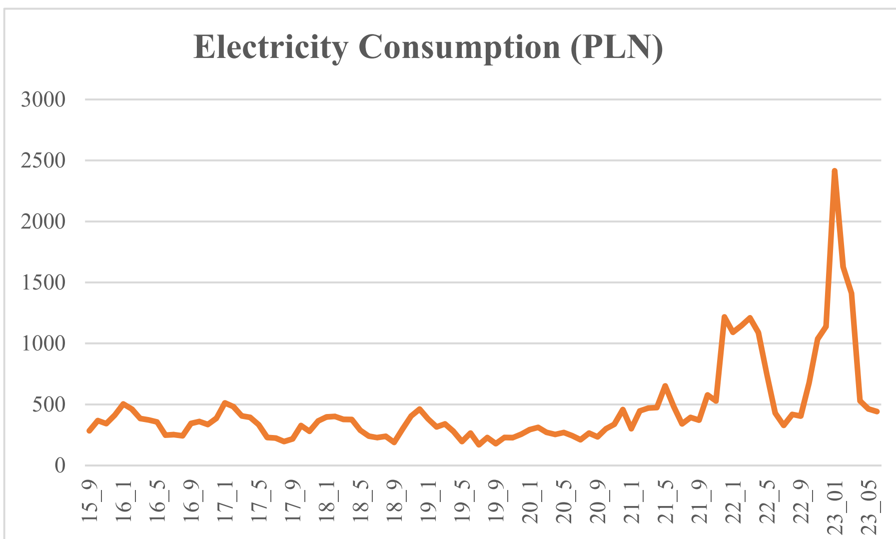

Fig. 2. Value of monthly household electricity consumption in the period 2015_9 – 2023_06 (in PLN). Source: invoices provided by ENERGA.

The unit electricity price plays a major role in this equation The feedback hypothesis was not confirmed, however. The 1-month and 6-month lagged price has positive impact on electricity consumption. A negative reaction, by contrast, follows after 7 months, when an increase in the price of electricity causes a decrease in the volume of energy consumption. The mechanism at work here, therefore, is the classic decrease in demand under the influence of an increase in the unit price.

Two dummy variables appear in the electricity consumption equation.

a) PUMP, taking the value of 1 in the months after heat pump installation and 0 in the entire preceding period, and
b) NORM – taking the value of 1 in the months after consumption norm exceedance, at a low energy price, and 0 during periods of low price.

The empirical equation shows that the use of the heat pump increased the household's electricity consumption by an average of 471.7 kWh per month. This means that the heat pump induced a household electricity consumption increase of nearly 5660 kWh per year. The replacement of the oil furnace house and water a heat pump system resulted in a significant reduction in costs. The empirical equation under consideration also shows autoregressive relationships: positive 1-month and 4-month as well as 5-month negative corrective relationships. The sharp energy crisis looming in 2022 triggered state intervention in the energy market (electricity, gas, coal). The variable NORM, included in the equation, takes the value of 1 in the months when the household exceeded the consumption norm guaranteeing a reduced price for electricity. The empirical result indicates that the state intervention resulted in a 1.61 MWh reduction in household energy consumption. A negative trend in energy consumption, leading to an average reduction of 2.78 kWh per month, was also observed. The negative seasonal deviation emerges in July, when energy consumption averaged 129.85 kWh less, relative to the systematic components. A graphical illustration of the actual amounts of electricity consumption and the theoretical values obtained from the empirical model is shown in Fig. 4.

Table 2 shows the empirical equation describing the variation of monthly electricity consumption value. What emerges here is the recurrence of the effect of energy consumption volume on its value. The description accuracy of the variable VALUE is very high. The coefficient

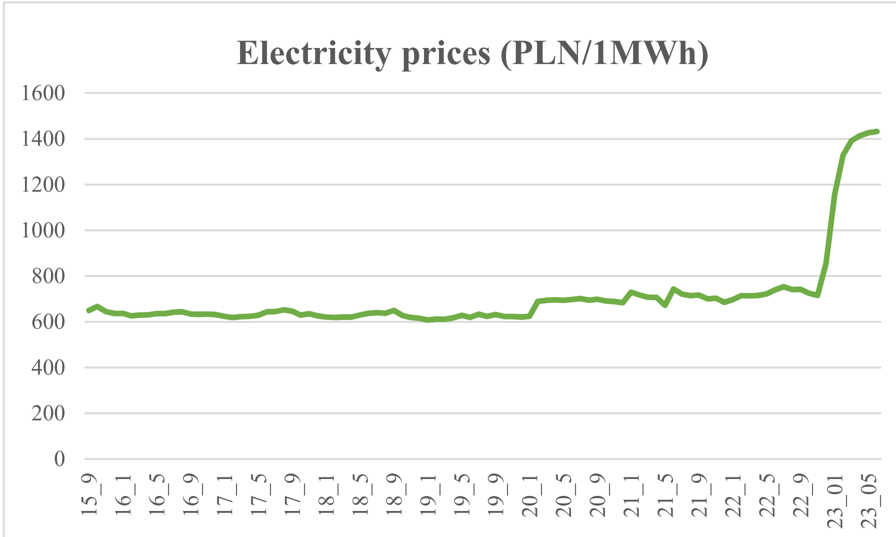

Fig. 3. Household electricity prices of 1 MWh in the period 2015_9 – 2023_06 (in PLN/1 MWh). Source: own calculation.

Table 1
Dependent variable: USAGE, observations used 2016:04–2023:06 (N = 87).

Variable	*Coefficient*	*Std. Error*	*t-Statistic*	*Prob. p*	*Significance*
const	−997.211	422.775	−2.359	0.0209	**
PRICE_1	1.95103	0.541016	3.606	0.0006	***
PRICE_6	3.36836	0.832772	4.045	0.0001	***
PRICE_7	−3.23494	0.972600	−3.326	0.0014	***
PUMP	471.663	63.3220	7.449	<0.0001	***
NORM	−1610.84	315.355	−5.108	<0.0001	***
TIME	−2.77517	1.06526	−2.605	0.0110	**
dm7	−129.853	54.8534	−2.367	0.0205	**
USAGE_1	0.605016	0.0705535	8.575	<0.0001	***
USAGE_4	0.194032	0.0866420	2.239	0.0280	**
USAGE_5	−0.272856	0.0776522	−3.514	0.0007	***
Mean dependent var.		626.8276	S.D. dependent var.		375.0270
Sum squared resid.		1355514	S.E. of regression		133.5504
R-squared		0.887932	Adjusted R-squared		0.873186
F(10, 76)		60.21612	Prob(F-statistic)		5.35e-32
Log likelihood		−543.3872	Akaike info criterion		1108.774
Schwarz criterion		1135.899	Hannan-Quinn criterion		1119.697
Autocorrel. coeff. (rho1)		−0.147176	Durbin h-statistic		−1.823183

Source: Own calculations using the GRETL package.

$R^2 = 0.985$ indicates that 98.5 % of the variation in the value of consumed energy is explained by the explanatory variables of equation. A simultaneous unit increase in energy consumption results in a nearly 723.1 PLN per MWh increase in its value. Simultaneously, negative adjustments with lags of 1,3 4,5,7 and 10 months appear. The equation also shows a positive autoregression with lags of 1, 2, 4, 5 and 10 months. The sequential reference with a period of 1 month is of particular relevance, as it indicates that more than 1.7 % of the previous month's value is revealed in the current value of household electricity. A slight negative autoregressive adjustment of the variable VALUE, with a lag of 6 months, is also observed. Additionally, monthly seasonality occurs in January, increasing the value of energy consumption by 70.15 PLN. Moreover, the variable representing state intervention (NORM) indicates a reduction in the value of consumed energy by 1035.21 PLN. Annually, this saving is not significant. The equation's explanatory variables explain nearly 98.5 % of the variation in the formation mechanism of the variable VALUE. A graphical illustration of the actual and theoretical values of electricity consumption, obtained from the empirical model, is presented in Fig. 5.

Table 3 shows the empirical equation of the monthly unit price of electricity realized in the household. The hypothesis of feedback between the variables PRICE and USAGE has been confirmed. An increase in electricity consumption results in a simultaneous decrease in the price per MWh. The relatively high fixed costs, in unit price, are distributed over a greater number of consumed energy units. This results in a decrease in the unit price per MWh. The equation also shows positive adjustments to the unit price, every 1 and 6 months, and a negative adjustment, with a lag of 5 months.

During the period under consideration, an upward trend in the unit price occurred. An average monthly increase of nearly 28 cents in the 1 MWh price occurred. Moreover, the unit price shows a positive autoregression. The current unit price is the result of over 84 % of previous month's price. Additionally, autoregressive adjustments of the variable PRICE can be observed: positive by more than 35 groszy every 11 months and negative by more than 29 grosze[1] every 12 months. The empirical equation in Table 3 describes the variation mechanism of unit electricity price with high accuracy, i.e., it explains 98.5 % of the unit price variability. Fig. 6 illustrates the price volatility, showing the actual and theoretical magnitudes of the variable PRICE.

The econometric model indicates a significant reduction in long-term energy costs for households that adopt renewable energy solutions, such as solar panels and heat pumps. Specifically, the model suggests a 20 % reduction in monthly energy bills after the first year of adoption. These findings support the economic viability of renewable energy investments at the household level, challenging the initial scepticism about high upfront costs. By illustrating cost savings over time, the results encourage a reevaluation of renewable energy from a financial perspective, aligning with economic theories of consumer behaviour that predict that long-term benefits can outweigh short-term expenditures. This insight is crucial for policymakers and advocates promoting renewable energy adoption (Steg,L. et al., 2021 [95]; Usman, O. et (2024) [96]. Adoption of renewable technologies has correlated with a marked decrease in household carbon emissions, averaging a 30 % reduction per household per year. This significant decrease in emissions contributes directly to national and international goals for carbon reduction, as outlined in recent climate agreements. The results provide empirical support for environmental models that advocate for decentralised energy solutions as effective tools for combating climate change (Sun, Y. et al., 2022 [97]; [98,99]). This highlights the role of individual actions in broader environmental strategies, offering a practical example

[1] Grosz (plural: grosze) is a monetary unit in Poland, equal to one hundredth of 1 PLN.

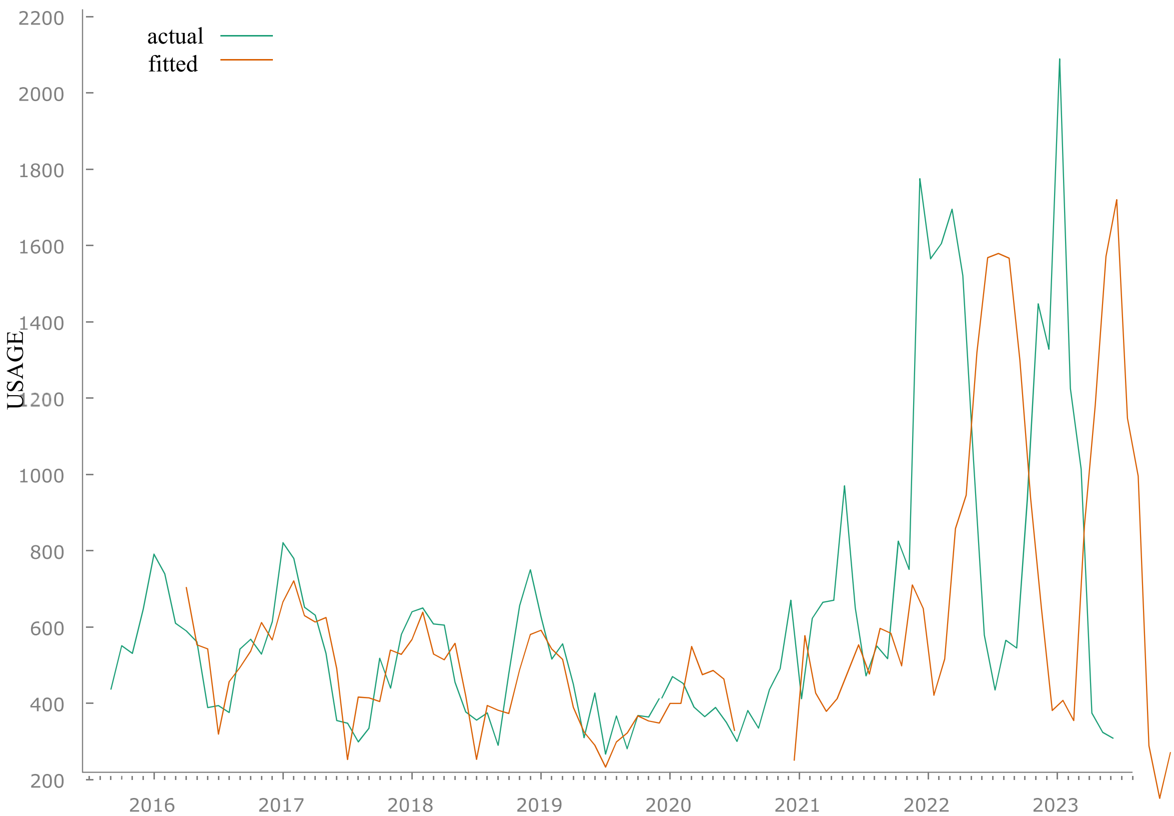

Fig. 4. Actual and fitted values of variable: USAGE.
Source: Own calculations using the GRETL package and Table 1.

Table 2
Dependent variable: VALUE, observations used 2016:07–2023:06 (N = 84).

Variable	*Coefficient*	*Std. Error*	*t-Statistic*	*Prob. p*	*Significance*
const	6.79180	28.7154	0,2365	0.8137	
USAGE	0.723100	0.0386037	18.73	<0.0001	***
USAGE_1	−1.30274	0.139913	−9.311	<0.0001	***
USAGE_3	−0.0930025	0.0396705	−2.344	0.0220	**
USAGE_4	−0.251716	0.105074	−2.396	0.0194	**
USAGE_5	−0.648412	0.126027	−5.145	<0.0001	***
USAGE_6	1.84316	0.297687	6.192	<0.0001	***
USAGE_7	−0.101428	0.0456133	−2.224	0.0295	**
USAGE_10	−1.13369	0.347894	−3.259	0.0018	***
NORM	−1035.21	167.494	−6.181	<0.0001	***
dm1	70.1465	21.9273	3.199	0.0021	***
VALUE_1	1.69583	0.203104	8.350	<0.0001	***
VALUE_2	0.102468	0.0435166	2.355	0.0215	**
VALUE_4	0.517099	0.131303	3.938	0.0002	***
VALUE_5	1.06340	0.157297	6.760	<0.0001	***
VALUE_6	−2.91051	0.444228	−6.552	<0.0001	***
VALUE_10	1.99319	0.533351	3.737	0.0004	***

Mean dependent var.	466.0512	S.D. dependent var.	368.3280
Sum squared resid.	170121.4	S.E. of regression	50.38973
R-squared	0.984892	Adjusted R-squared	0.981284
F(16, 67)	272.9808	Prob(F-statistic)	1.86e-54
Log likelihood	−438.9558	Akaike info criterion	911.9115
Schwarz criterion	953.2354	Hannan-Quinn criterion	928.5234
Autocorrel. coeff. (rho1)	0.044285	Durbin h-statistic	NA

Source: Own calculations using the GRETL package.

of how domestic choices impact global sustainability. The data reveals increased adoption rates in communities with higher levels of education and environmental awareness, suggesting a strong social component to renewable energy adoption. These findings underline the importance of community awareness and education in fostering sustainable practices. They echo sociological research, which suggests that social norms and values play a crucial role in the adoption of new technologies ([100]; Bögel, P. et al., 2018) [101]. This aspect of the results suggests that enhancing community outreach and education could further accelerate the adoption of renewable energy technologies. Regions with more robust governmental incentives for renewable energy adoption show faster and more widespread uptake of these technologies. This correlation underscores the effectiveness of policy measures in driving change at the household level. It provides a practical illustration of policy impact, validating theoretical models of policy influence on technological adoption (Ajibade, P. (2018)) [102]. For policymakers, these insights advocate for continued or increased support for renewable energy incentives to achieve desired energy and environmental outcomes. The interpretation of these results does more than quantify the impacts of renewable energy adoption; it provides a holistic view of how individual choices integrate with economic, environmental, and social frameworks. By linking empirical findings to theoretical considerations, this section not only addresses the initial research questions but also contributes to a more nuanced understanding of the dynamics at play, thereby offering valuable insights for both theory and practice.

5. Conclusions and policy recommendation

Electricity constitutes the foundation of every household's operation. Even domestic gas, fuel oil, and solid fuels for heating still require electricity to power the equipment. Currently, electricity has become the most environmentally friendly energy source. Experience has shown that replacing a fuel-oil heating system with a heat pump has resulted in significant financial savings for households. Furthermore, the absence of fuel oil purchases, which were previously required at least twice a year, has enhanced the comfort of living. Existing studies in the literature indicate that behavioural factors and effective intervention strategies

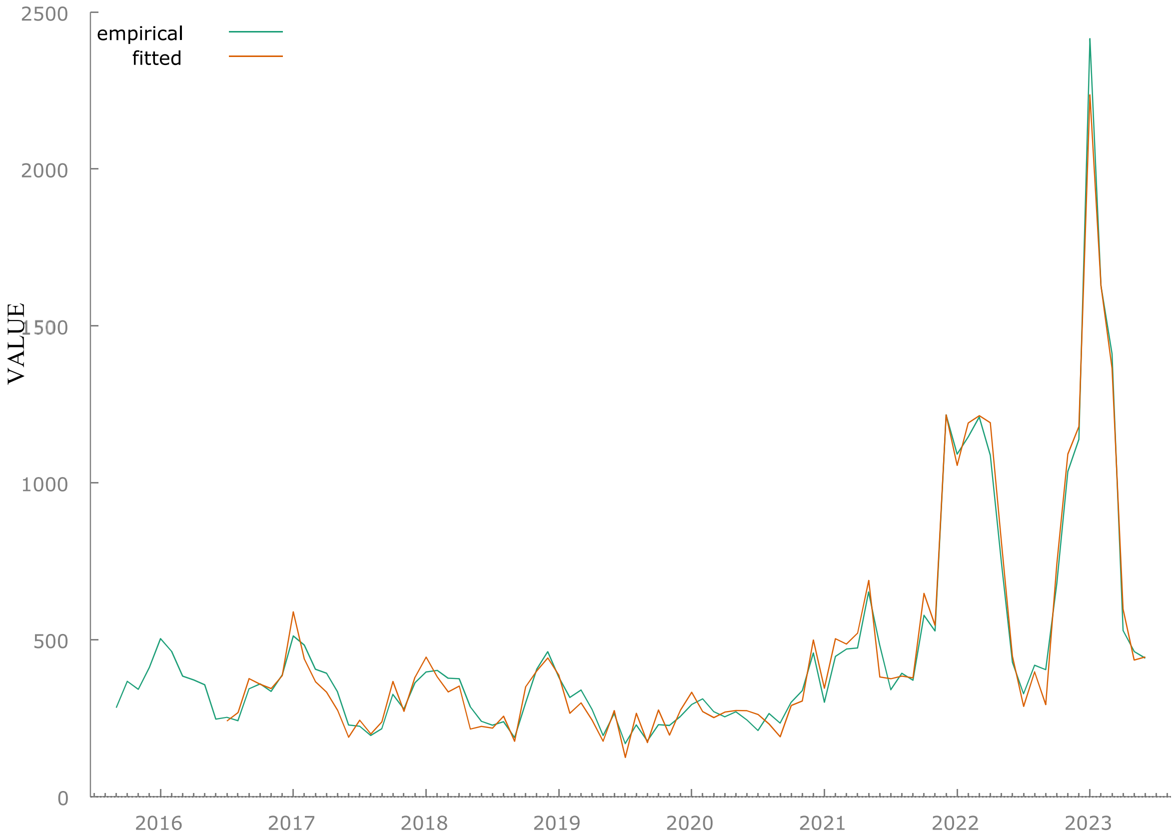

Fig. 5. Actual and fitted values of variable: VALUE.
Source: Own calculations using the GRETL package and Table 2.

Table 3
Dependent variable: PRICE, observations used 2016:09–2023:06 (N = 82).

Variable	*Coefficient*	*Std. Error*	*t-Statistic*	*Prob. p*	*Significance*
const	−102.749	54.3897	−1.889	0.0630	*
USAGE_1	0.0465872	0.0157398	2.960	0.0042	***
USAGE_2	−0.0471550	0.0150002	−3.144	0.0024	***
USAGE_7	−0.0204724	0.0101745	−2.012	0.0480	**
USAGE_12	0.0898372	0.0145959	6.155	<0.0001	***
NORM	−285.196	57.9209	−4.924	<0.0001	***
dm6	24.7786	10.8831	2.277	0.0258	**
PRICE_1	1.95224	0.144388	13.52	<0.0001	***
PRICE _2	−0.662343	0.0999678	−6.626	<0.0001	***
PRICE_5	0.329846	0.114041	2.892	0.0051	***
PRICE_6	−0.519802	0.180708	−2.876	0.0053	***
Mean dependent var.	718.0197		S.D. dependent var.		188.7766
Sum squared resid.	44666.70		S.E. of regression		25.08204
R-squared	0.984526		Adjusted R-squared		0.982347
F(10, 71)	451.7342		Prob(F-statistic)		4.39e-60
Logarytm wiarygodności	−374.6638		Akaike info criterion		771.3276
Kryt. bayes. Schwarza	797.8015		Hannan-Quinn criterion		781.9565
Autokorel.reszt - rho1	−0.136109		Durbin h-statistic		NA

Source: Own calculations using the GRETL package.

may also have significant effects on promoting improvements in energy efficiency and reductions in energy consumption. The case study example of a household in Poland demonstrates that there are financial and social benefits to promoting energy efficiency.

Changes in a household's wide range of energy usage behaviours are necessary to minimise energy use, alleviate climate change, and promote sustainable development. This paper's econometric model of household electricity consumption does not validate the hypothesis of feedback between the variables USAGE and PRICE. However, we have confirmed the recursiveness of the effect of electricity consumption volume on its value in monetary units. During 2022 and 2023, a severe energy crisis unfolded. As a result, in Poland, state intervention in the market economic mechanism followed. This intervention eliminated the feedback loop between energy price and consumption variables. The end of the crisis should result in the reappearance of the feedback between the pair of variables under consideration. In addition to the cognitive value of the econometric modelling results obtained, the empirical tool constructed enables the estimation of the forecasts of energy consumption volume, its value, and unit price in the following months for a minimum of 12 consecutive months. One significant unknown emerges, however. The energy crisis makes it challenging to predict, even in the short term, the unit price of externally supplied electricity. Even this unknown, however, allows for a relatively accurate prediction of future volumes of the variable USAGE. The analysis shows that a photovoltaic system should be the next investment in the household. It will provide significant benefits in terms of reducing greenhouse gas emissions. It will also dramatically reduce current electricity expenses. Only partial empirical confirmation exists for the formulated research hypotheses. Indeed, the installation of a heat pump has led to an increase in household electricity consumption. In addition, the negative feedback loop between household electricity consumption and its unit price should reappear.

5.1. Policy recommendations

Changes in a household's wide range of energy usage behaviours are necessary to minimise energy use, alleviate climate change, and promote sustainable development. This paper's econometric model of household electricity consumption does not validate the hypothesis of feedback between the variables USAGE and PRICE. However, we have

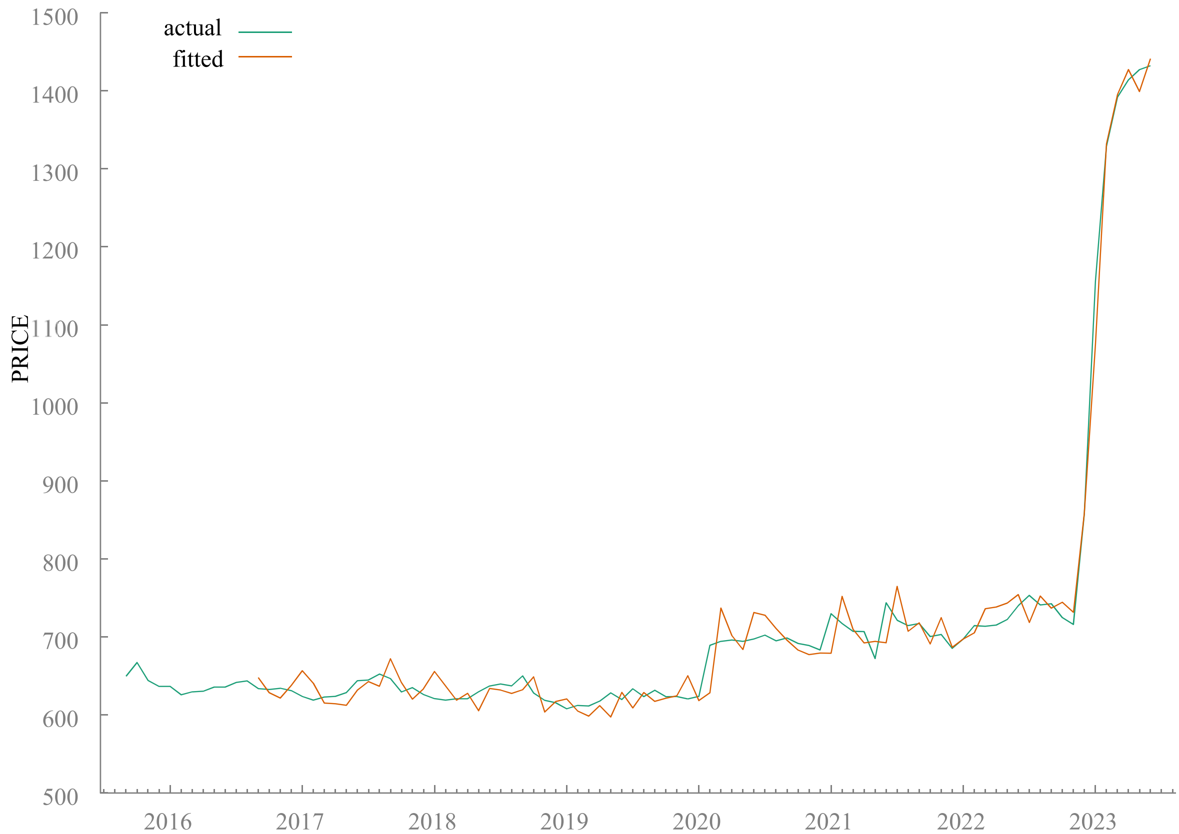

Fig. 6. Actual and fitted values of variable: PRICE.
Source: Own calculations using the GRETL package and Table 3.

confirmed that the effect of electricity consumption volume on its value in monetary units is recursive. During 2022 and 2023, a severe energy crisis unfolded. As a result, in Poland, state intervention in the market economic mechanism followed. This intervention eliminated the feedback loop between energy prices and consumption variables. The end of the crisis should result in the reappearance of the feedback between the pair of variables under consideration. In addition to the cognitive value of the econometric modelling results obtained, the empirical tool constructed enables the estimation of the forecasts of energy consumption volume, its value, and unit price in the following months for a minimum of 12 consecutive months. One significant unknown emerges, however. The energy crisis makes it challenging to predict the unit price of externally supplied electricity, even in the short term. Even this unknown, however, allows for a relatively accurate prediction of future volumes of the variable USAGE. The analysis shows that a photovoltaic system should be the next investment in the household. It will provide significant benefits in terms of reducing greenhouse gas emissions. It will also dramatically reduce current electricity expenses. Only partial empirical confirmation exists for the formulated research hypotheses. Indeed, the installation of a heat pump has led to an increase in household electricity consumption. In addition, the negative feedback loop.

We can make several targeted policy recommendations based on the empirical findings of this study on the adoption of renewable energy technologies in Polish households to facilitate wider adoption and maximize the associated benefits. These recommendations are designed to address specific barriers identified through our research and to capitalise on the opportunities for enhancing energy sustainability.

5.1.1. *Subsidization and financial incentives*

Our study reveals that high initial costs are a significant barrier to the adoption of renewable energy technologies. To mitigate this, we recommend that the government implement a more robust subsidization scheme for households that choose to install renewable energy systems. These could include upfront subsidies, tax rebates, or low-interest loans specifically targeted at solar panel installations and heat pump systems.

5.1.2. *Regulatory support for technology integration*

The integration of renewable energy technologies into existing infrastructure presents technical challenges. Policymakers should work to streamline the regulatory processes that currently hinder the rapid deployment of these technologies. This includes simplifying the permit process for installing renewable energy systems and updating building codes to encourage or require the use of renewable technologies in new developments.

5.1.3. *Educational and awareness programs*

Increasing awareness and knowledge about the benefits and practicalities of renewable energy adoption is crucial. Government agencies, in partnership with educational institutions and non-profits, should launch comprehensive awareness campaigns. These programmes should not only highlight the environmental and economic benefits of renewable energy but also provide practical information on how to transition to these systems.

5.1.4. *Support for research and development*

To continually improve the efficiency and affordability of renewable technologies, it is essential to support ongoing research and development. Funding policies should prioritize innovative renewable energy projects, especially those that demonstrate potential for cost reduction and enhancing the efficiency of residential energy systems.

5.1.5. Community-based projects and cooperative models

Encouraging community-based renewable energy projects can leverage local support and enhance the scalability of renewable energy adoption. Policies that support the development of energy cooperatives or community solar projects could be particularly effective, as they allow households to share the benefits of renewable energy, reducing individual costs and fostering community engagement.

5.1.6. Long-term energy planning

Finally, it is important for policymakers to incorporate the insights from household-level studies into broader national energy strategies. This includes planning for the long-term integration of renewable energy sources into the national grid, taking into account the cumulative impact of widespread household adoption on overall energy supply and demand.

These policy recommendations are grounded in the specific findings of our study, addressing both the macro- and micro-level challenges and opportunities in the adoption of renewable energy technologies in Polish households. By implementing these recommendations, policymakers can significantly enhance the effectiveness of their strategies to promote sustainable energy consumption across the nation.

The case study example from the household in Poland proves that there are financial and social benefits to promoting energy efficiency. This study improves people's knowledge of household energy usage patterns, promotes sustainable development, and promotes long-term energy conservation. The consumption of household electricity and its unit price should be a topic of discussion once again. The results of the studies make novel contributions in the following areas: By providing empirical data from Polish households, this study fills a critical gap in the literature, which has often focused on Western European and North American contexts. Our findings offer insights into the behaviours, challenges, and outcomes associated with renewable energy adoption in a post-communist Eastern European country, enhancing the geographic diversity of research in this field. We also expand on the socio-economic implications of renewable energy adoption, examining not just the economic but also the social factors that influence household decisions. This includes an analysis of how cultural, economic, and regulatory factors interact to either facilitate or hinder the adoption of green technologies. Our research also contributes to understanding how different technologies can be integrated into existing household infrastructure. We assess the practical aspects of adopting such technologies, including the necessary conditions that enhance their usability and effectiveness, thereby providing actionable insights for manufacturers and policymakers. Furthermore, this study contributes to policy discourse by offering specific, data-driven recommendations. We tailor our recommendations to the nuanced realities of the Polish context, drawing from direct empirical evidence we obtained throughout our study, unlike generic policy suggestions typically seen in the literature.

6. Limitations and future research directions

While this study provides valuable insights into the effects of renewable energy adoption in Polish households, several limitations warrant mention and suggest directions for future research. One inherent limitation is the reliance on data from a single household, which may not fully represent the diversity of household experiences across different regions of Poland. This restricts the generalizability of our findings, although the detailed case study approach provides deep, context-specific insights. However, despite its robustness, the used econometric model relies on assumptions that may not hold under different economic or policy conditions. Future studies could expand on this by applying the model to a larger dataset encompassing multiple households from various socioeconomic backgrounds to test its applicability and sensitivity to different energy policies and economic conditions.

The current model fails to fully account for the potential impact of external economic factors, such as global energy price fluctuations and policy changes. Future research could integrate global economic indicators to assess their impact on household energy consumption and the adoption of renewable technologies.

Furthermore, continuous empirical research should reflect ongoing updates to technology and policy as the renewable energy landscape evolves. Longitudinal studies that track changes in household energy behaviour over time as new technologies and policies emerge would be particularly valuable.

Finally, this study opens the door for interdisciplinary research that combines approaches from economics, environmental science, and sociology to provide a more holistic understanding of how individual household decisions contribute to broader energy sustainability goals. Such studies could also explore the psychological and social drivers of technology adoption, providing deeper insights into how to effectively promote sustainable energy practices.

CRediT authorship contribution statement

Ewelina Sokolowska: Writing – original draft, preparation, Visualization, Supervision, Investigation, Writing – review & editing. **Jerzy Witold Wisniewski:** Conceptualization, Data curation, Methodology, Software.

Declaration of competing interest

The authors whose names are listed immediately above certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-fi nancial interest (such as personal or professional relationships, affi liations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Data availability

Data will be made available on request.

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