Int. J. Renew. Energy Dev. 2024, 13 (1), 31-51

Contents list available at IJRED website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.undip.ac.id

Review Article

Policies and measures for energy efficiency improvement at households: A bibliometric analysis

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Abstract. Recently, governmental subsidies have led to increased renewable energy adoption and household CO_2 emissions reduction. However, energy efficiency improvement and greenhouse gas emission reduction potential in households' sector are not yet fully realized. Decision-making by individuals is also a crucial factor in adopting energy-efficient and renewable energy technologies, which is why this study analyses some important behavioral change-linked issues. This study also focuses on various policies and measures to achieve energy efficiency improvements in households, such as use of renewable energy sources, renovation of residential buildings, use of energy efficient appliances etc. The methodology of the study contains a bibliometric analysis in the field of energy efficiency at households, covering the years of publication 2010-2023 and organizing all documents into 9 classifications. Among them 6 classifications have been further considered: Citation analysis; Authors' networks; High impact journals of publishing; Knowledge mapping of co-authorship collaboration among institutions; Co-authorship among countries; Keywords concurrence analysis. Following a systematic literature review the bibliometric findings reveal the steady increase of literature production in the field of energy efficiency at households, showing also the pivotal role of institutions among developed and industrialized economies. Moreover, there is a densely and steadily growing network of keywords reported, implying the thematic expansion of this topic from the modelling-pilot scales towards the real world and in field applications. Finally, identified research constraints of energy efficiency improvement are that of: high costs, lack of information and knowledge, low priority to environmental and climate change mitigation concerns, and resistance to behavioral change.

Keywords: households; energy consumption; renovation of multi-flat buildings; renewable energy adoption; policies and measures; behavioral changes

Received: 29th August 2023; Revised: 21th Oct 2023; Accepted: 12nd Nov 2023; Available online: 21st Nov 2023

1. Introduction

Reducing global warming is crucial, and households have the ability to play a significant role by implementing climate change mitigation measures. Energy efficiency improvements are the most critical measures, resulting in a win-win situation. Investing in household energy efficiency reduces energy consumption and expenses and greenhouse gas emissions (Gróf, Janky & Bethlendi (2022)).

Households are responsible for more than a quarter of all energy use globally, with OECD household energy use responsible for 14% of all OECD carbon dioxide emissions in 2019 (OECD, 2023). These numbers show the importance of energy efficiency improvements in households (Aboltins, Blumberga, 2018; D'Agostino et *al.*, 2019; Strielkowski *et al.*, 2019; Wilsom et *al.*, 2019; Streimikiene et *al.*, 2020; Fanghella *et al.*, 2021).

Therefore, the improvements to energy efficiency in households are essential to meet Green Deal targets and create a carbon-neutral society by 2050 in European Union (EU). Among the various energy efficiency measures, renovating homes for energy efficiency, using energy-efficient appliances, and adopting energy-saving behaviors yield the best results (Katris & Turner (2021); Sola *et al.* (2021)).

Though there are several essential studies Girod *et al.,* (2017); Trotta *et al.* (2018); Matar (2020); Walid (2020); Zabaloy, Recalde & Guzowski (2019); Lakić, Damigos & Gubina (2021); Solà *et al.* (2021)) dealing with climate change mitigation and energy efficiency improvements in households, there is still a lack of review papers critically analyzing the primary energy efficiency measures in households from various perspectives like technological, social and economic and behavioral. The comparative assessment of policies and measures targeting energy efficiency improvements in households is another important gap in scientific literature.

This study aims to fill a gap in research by performing a comprehensive analysis of measures to enhance energy efficiency in households. This involves a comprehensive literature review to identify key research findings and areas for further investigation. The ultimate aim is to guide future research and help advance our understanding of household energy efficiency as well as the best policies and measures to enhance energy efficiency at households. In the remaining part of Introduction section, the total literature has been organized

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https://doi.org/10.14710/ijred.2024.57769
ISSN: 2252-4940/© 2024.The Author(s). Published by CBIORE

into a rigorous last five years of analysis: 2018-2023, revealing the evolutionary characteristics and the research priorities and challenges that this timespan had to cope with.

Focusing on their consumption behavior, households are responsible for more than 70% of total global greenhouse gas emissions. Therefore, the GHG emission reduction potential due to the household behavior is very high. Energy consumption is the main source of the GHG emission in households. There are two main ways to reduce GHG emissions in households: use of renewable energy, energy efficiency improvement, and energy conservation due to changes in the energy use patterns. The highest energy saving potential in households is linked with building renovation, followed by the use of energy efficient appliances (including lighting). Renewable energy microgeneration technologies in households also provide opportunities for GHG emission reduction (Balezentis *et al.,* 2023).

In particular, improving the energy efficiency of our homes presents an excellent opportunity to reduce greenhouse gas emissions and increase thermal comfort. However, a shortfall exists between the full potential and realized adoption of energy efficiency measures, a phenomenon termed the "Energy Efficiency Gap". In this context a range of nuanced viewpoints, which mapped onto three principal household themes in the relevant literature, are: energy use in terms of the environment, energy in relation to money and apathy towards energy. It is noteworthy that the wider implication is that households that hold proactive energy efficiency viewpoints based on environmental concern may still require specifically targeted incentives to encourage the uptake of energy efficiency measures, i.e. their proactive and environmental beliefs are not alone enough to motivate them to improve the energy efficiency of their home (Pelenur, 2018).

Besides to health risk in low-income households, it was also found that the intervention of raising indoor air temperature by on average 0.84 K as compared with control households, can bring the majority of indoor temperature measurements within the "healthy" comfort zone of 18–24°C, while average daily gas usage can be further dropped by 37% (Poortinga *et al*., 2018). Moreover, external wall insulation was proven the most effective measure to increase indoor air temperature while, from a methodological perspective, the multilevel interrupted time-series approach offers a useful model for evaluating housing improvement programs (Poortinga *et al.,* 2018).

Among developing countries, Colombia was studied regarding its capability to diversify and to decarbonize its energy sector by encouraging the use of non-conventional renewable resources. Among rebound effects, household demand rises in response to cheaper electricity prices due to the increasing shares of wind power. In this respect the assessment of the environmental rebound effect (ERE) in the household sector considered the increased shares of wind power into the Colombian power grid, across six environmental impacts and for the period 2020–2030. The method used combines life cycle assessment, input-output modelling, energy system modelling, econometrics, and re-spending modelling. The results demonstrated that the ERE has the potential to partially, and even completely, offset any environmental savings (backfire effect), depending on the specific impact, year, and modelling choices considered (Vélez-Henao *et al.,* 2020). Among developing countries, it is also common phenomenon the inefficient electrical appliances that continue to flood the markets of most Sub-Saharan African (SSA) countries with just a few of the counties having resolute energy efficiency programs with established energy efficiency standards and labels (Agyarko *et al.,* 2020). The quadruple-helix analytical framework was employed to identify four key sectors of society: government, academia, industry and public/media that drive energy efficiency knowledge and innovations. New energy efficiency policies in Ghana are expected to revise or implement new efficiency standards on a total of 20 product categories by the early of 2020s' (Agyarko *et al*., 2020).

Among developed countries, Canada has experienced large shifts in its residential sector. In such a study researcher applied binary logistic regressions and predicted the odds of households adopting three energy-efficient actions: energy-saving lights, programmable thermostats, and changes to a dwelling following an energy audit. Although it was observed that Canadian households are participating in energy efficiency, not all groups are participating equally. Therefore, it can be adopted a less challenging basket of measures such as energy-saving lights, as opposed to more intensive dwelling upgrades. Additionally, levels of education and income were positively related to the adoption of energy efficiency measures. However, household income can be less of a contributing factor for decisions regarding dwelling changes compared to the financial incentives offered via government grants. It is also proposed an increase energy efficiency education enabling to continue offering financial incentives as the country increases its residential energy efficiency (Das *et al.,* 2018).

From a behavioural perspective in the relevant literature there were explored different factors that influence purchasing decisions and understand, firstly, the importance of energy consumption compared to other attributes, secondly, how consumers weight energy savings, thirdly, what other benefits and costs influence the purchase of energy-efficient goods. In such an analysis the research outcomes showed that there is still an informational gap regarding energy labels, while bounded rationality and end-user behaviour are important limiting factors for the purchase of energy-efficient goods in Spain (de Ayala *et al.,* 2021). From a behavioural perspective it has been also introduced the concept of energy cultures that serves as a useful heuristic to structure the analysis of household energy demand and internal environment. Covering the following three key elements of energy culture: a) material conditions that relate directly to domestic energy use, b) householders' attitudes, perceptions and norms concerning the use of energy and c) observable everyday practices that use energy, and their interactions, authors examined data from 20 households in a social housing estate in Ireland collected before and after retrofitting (Rau *et al.,* 2020). Authors highlighted the urgent need for an integrated approach to energy retrofitting that combines technology-aided changes in material conditions with a parallel re-shaping of householders' views and practices to achieve real and lasting reductions in energy use. On the other hand, the persistence of many energy-intensive domestic activities and the possible emergence of rebound effects, have the potential to cancel out at least some of the savings made through retrofitting (Rau *et al.,* 2020).

From a technological perspective, employing environmentally friendly technologies (EFTs) is proposed as a complicated and difficult process that is affected by multiple factors, researchers are encouraged to explore those influence factors. Therefore, based on a questionnaire survey from 782 Pakistani households, a structural equation modeling strategy yields empirical results, revealing that drivers of adoption intention of EFTs include technological awareness, perceived environmental importance, perceived behavioral control, and perceived benefits. Besides, significant barriers to the adoption intention of EFTs involve the perceived cost of EFTs and the perceived risk-averse behavior of households. It is also noteworthy that among all factors, perceived environmental importance reveals the most substantial contribution, whereas perceived risk-averse behavior shows the least contribution to the adoption intention of EFTs. For this, authors proposed controlling the roaring cost of EFTs, and the provision of rebates and subsidization aiming at upscaling the adoption intention of EFTs by the households (Fatima *et al.,* 2022). In another technologically-oriented study it was suggested that utilizing smartphones and various data of home-scaled appliances, as well as making communication more interactive between the users and service providers, could effectively induce energy-efficient behavior (Kim et al., 2020). At another technologically-driven approach, ICT-based interventions in households are suitable to decrease electricity usage, improve energy efficiency and thus contribute to reducing GHG (greenhouse gas) emissions from the household sector. ICT-based effects on consumer behaviour can reduce household final electricity consumption by 0–5%. Other literature findings have been used to define parameter values, which reflect the efficacy of ICT at changing household energy usage patterns, and ultimately decreasing GHG emissions from the electricity sector. Besides, ICT-based interventions in household energy use could contribute between 0.23% and 3.3% of the EU CO2e reduction target from the energy sector that would keep warming under 1.5 °C, corresponding to 4.5–64.7 mio. tCO2e abated per year (Bastida *et al.*, 2019).

From political and governmental perspective, it is important to denote that energy efficiency in the home is a major concern not only for households, but also for governments and various non-government organizations. Energy efficiency has implications beyond usage and costs, with various co-benefit outcomes such as improved household health and well-being, comfort, air quality, increased productivity, energy security and improved social capital. In a similar study long-run literature overview, covering the period 1990-2019, there were found mixed evidence to support specific types of interventions. Nevertheless, when multiple techniques and activities were used, the intervention's success was more likely. It can be also argued that with policy implications that call for more integrated and methodical explanations of interventions to better support critical decision-making for central governments (McAndrew *et al.,* 2021).

From a commercial perspective it is also worth mentioning that service modularity promotes efficiency at the provider end of the supply chain and customisation at the customer end. In particular, by investigating how logistics service modularity contributes to sustainable development through the means of energy efficiency, logistics services for household waste collection were investigated. It was shown different service modules – standardised or customised – and their contribution to sustainable development operationalised through energy efficiency. Therefore, promising efficiency through standardisation, logistics service modularity has a potential to improve energy efficiency as well. It was also noticeable the use of service blueprinting to analyse logistics service modularity, providing a methodological contribution to that field in general and logistics in particular (Wehner et al., 2021).

From a geographical perspective a selected spectrum of relevant studies included the following countries, especially on the period 2018-2023:

-Africa: A relevant study was focused on investigating the profile of consumers and to determine the socio-demographic and economic indicators and purchase choices considered when purchasing brand-new refrigerating appliances in Ghana (Nsoh *et al.,* 2022); b) A novel qualitative findings from a Randomized Controlled Trial (RCT) evaluated the effects of innovative energy-efficient cooking pots on sustained use of LPG for the first time in a low and middle-income setting, through a semi-structured interviews (SSIs) with 22 of 200 cooks (LPG primary users) from an informal settlement in Nairobi (Nabukwangwa *et al.,* 2023).

- Australia: The Koorie Energy Efficiency Project (KEEP) was a Victoria-based, Australian social marketing initiative designed to provide support to Indigenous households so they could better manage their energy bills by reducing or controlling their energy use (Perényi *et al.*, 2019).
- China: a) A survey data of 396 household appliance consumers in Mianyang City, China, are collected by the interception method, and the theoretical model is tested by structural equation modeling (SEM) (Si-dai *et al.,* 2021); b) A survey data from China households investigated the impact of financial literacy on household energy efficiency. Authors aggregated the household energy use and carbon emissions after calculating the energy and carbon intensity of the related sectors of household expenditure (Ye and Yue, 2023); c) Based on the panel stochastic frontier analysis (SFA) model it was reported that: a) China's household energy efficiency decreased from 0.917 in 2002 to 0.874 in 2021 on average, resulting in growing inefficient energy use from 1779 tons of coal equivalent (tce) in 2002 to 14,773 tce in 2021; b) household energy efficiency in low-income areas is always the highest and decreases slowly, while that in high-income areas is the lowest and decreases faster; c) in the low-income region, household survival needs growth with rising income is the main reason for the decline in energy efficiency. Therefore, household survival needs growth and consumption upgrading drives energy efficiency down before and after 2011, respectively (Zheng *et al.,* 2024).
- European Union: a) A large European survey and a variety of choice models generated from the same survey regarding the adoption of a number of energy efficient appliances and heating systems in 8 EU countries, under a variety of policy interventions (Chappin *et al.,* 2021); b) The energy efficiency policies among European households has been based on large-scale surveys in Italy, Poland, Sweden, and the UK. Through choice experiments they were studied the trade-offs made by households between various policy characteristics including policy target level, dependence on energy imports, policy instruments: education and information programs, standards, taxation, energy consumption limit, as well as costs to the household, and distribution of costs between households and other sectors. Of primary research importance is the determination of the role of trust in government and of environmental identity on the acceptability of these policy characteristics. It was also shown that trust in government helps make coercive policies such as taxes more acceptable, whereas higher environmental identity makes consumption limits more acceptable (Faure et al., 2022); c) A bottom-up stock model with a macro-econometric dynamic general equilibrium model (FIDELIO) was employed to quantify the direct and indirect value added and employment impacts in the EU (Rocchi et al., 2019).

- Greece: Considering the number of persons at risk of poverty or social exclusion in the EU via energy reconstructions in buildings, this is one of the key targets of the Europe 2020 strategy. In this context a longitudinal approach was focused on Hellenic households during economic crisis. This study recorded the energy efficiency measures that were adopted during 2012–2015 in order to overcome cold. This research evidenced being based on a comprehensive study of 491 questionnaires from low-income households mainly from North Greece (Boemi S.-N., Papadopoulos, 2019).
- Latin America: A set of Latin American countries were chosen, namely Brazil, Chile, Colombia and Uruguay, to study energy efficiency policies for household context in 2016. Findings showed that Uruguay and Chile have the best boundary conditions to promote energy efficiency, followed by Brazil and Colombia which has presented difficulties in different boundary conditions. Results also highlight that the implementation of household energy efficiency policies is highly dependent on country context (Zabaloy *et al.,* 2019).
- Spain: A comparability analysis has focused on the effect of alternative retrofitting strategies on thermal energy services' affordability in Spanish vulnerable households (Barrella *et al.,* 2023).
- -Switzerland: Regarding the Swiss energy efficiency policy, this is a substantial consumer of energy in the residential sector in Switzerland, requiring 4.1 PJ electricity in 2015 or 6.4% of the sector's total electricity demand (Heidari *et al.,* 2018).
- Tajikistan: An assessment of energy efficiency in electricity consumption by household consumers was conducted in the city of the Republic of Tajikistan (Tavarov and Sidorov, 2020).
- United Kingdom: a) Considering that fuel poverty affects up to 35% of European homes, which represents a significant burden on society and healthcare systems, significant investment in energy efficiency upgrades for around 40% of UK households to reduce the impact of fuel poverty. This study has conducted in alignment with three data sets, covering housing across England (Household Energy Efficiency Database), Energy Performance Certificate (EPC) and, in the South West of England, the Devon Home Analytics Portal (Sharpe *et al.,* 2019); b) An empirical analysis was employed regarding the effects from using RES in households using an example of the residential households in the northwest region of the United Kingdom (UK) with and without solar photovoltaic (PV) panels and electric vehicles (EV). Four scenarios were conducted to investigate the system dynamics and to provide differentiation between systems in terms of the varying values of the gross demand, tariffs, metered import, and the total revenue. Besides, through the increase of EV penetration, the existing energy efficiency schemes would have to be revised (Strielkowski *et al.,* 2019).
- U.S.: Considering that residential energy use represents roughly 17% of annual GHGs emissions in the United States (U.S.), authors estimated energy use and emissions of 60 million household to clarify how energy efficiency and carbon emissions vary by race, ethnicity, and home ownership (Goldstein et al., 2022).

Conclusively, it can be denoted that the savings in energy use and associated emissions of GHGs may benefit from both policy measures that attain short-run behavioral changes (e.g., nudges, social norms, display of real-time information about usage, and real-time pricing) as well measures aimed at the long run, such as energy-efficiency regulations, incentives on the purchase of high-efficiency equipment, and incentives towards a change of habits in the use of the equipment (Alberini and Filippini, 2018). Moreover, it cannot be undermined the empirical evidence to date on energy efficiency policies and discusses their effectiveness. It is also a common reality of mixed results as they sometimes are effective and in other cases, they could present significant shortcomings. Subsequently, the effectiveness of informational policies is not always ensured as they depend on the country, sector and product category. Information feedback tools also seem to be effective as they work as a constant reminder of energy-efficient behaviour. Therefore, limitations of energy efficiency policies have to be precisely identified, such as the difficulties of implementing codes and standards given that a minimum level need to be achieved, differences in the effectiveness of rebate programs and non-conclusive results in regard to the effectiveness of monetary energy efficiency labels (Solà *et al.,* 2021).

Based on the aforementioned chronological overview it can be denoted that there are various policies and measures addressing energy efficiency in households however some measures like behavioral change targeting policies need to be implemented together with economic or fiscal measures to ensure they effectiveness and realize full energy saving potential in households.

The main input of this paper is the elicitation of energy efficiency measures from technological, social, and economic perspectives based on scientific literature review and bibliometric analysis and the grouping and assessment of the main policies and measures targeting energy efficiency improvements in households based on an appraisal of empirical studies conducted in this field.

The paper is organized as follows: the methods and data are presented in section 2, followed by a generalization of the primary outcomes of the conducted literature review in section 3. Section 4 systematically assesses households' primary energy efficiency measures based on the performed analysis. Section 5 discusses the results, while section 6 provides conclusions, constraints, policy implications and future research orientations and priorities.

2. Method

2.1 Data Sources

In the methodology of this study, a bibliometric analysis was undertaken in the fourth quarter of 2023, covering a last decade time-frame, from 2010 up to 2023, at the Scopus database. In this literature search, the "energy efficiency" and "household" terms were jointly searched at the "article title," and a total of 178 documents were reported. In particular, the type of "article title" was selected, and the pair of keywords of "energy efficiency" and "households" were typed together in the "article title" classification of the documents yielded. The whole range of the document results has been organized and presented in the following 9 classifications:

- Scientific field (top-10), Table 1

Table 1
All top-5 up to top-20 classifications (5 classifications in total included): Scientific field (top-10), Document type (top-10), Source/Journal title (top-15), Source type (top-5), Language (top-8)

Top-number # (in descending order)	Scientific Field, Number of Documents	Document type, Number of Documents (in parentheses, % out of 178)	Source/Journal title (in parentheses, % out of 178)	Source type (in parentheses, % out of 178)	Language (in parentheses, % out of 178)
1	Energy, 100	Article, 137 (77.0)	Energy Policy,30 (16.9)	Journal, 148 (83.1)	English, 169 (94.7)
2	Environmental Science, 65	Conference paper, 28 (15.7)	Energy Efficiency,14 (7.9)	Conference proceeding, 26 (14.6)	German, 3 (1.7)
3	Engineering, 54	Review, 6 (3.4)	Energy and Buildings, 8 (4.5)	Book, 2 (1.1)	Positions #3-#8 (having 1 document each, or 0.6% each): Romanian, 1
4	Social Sciences, 27	Positions #4-#10 (having 1 document each, or 0.6% each): Note	Energy, 6 (3.4)	Positions #4-#5 (having 1 document each, or 0.6% each): Trade journal, 1	Positions #3-#8 Moldovan, 1
5	Economics, Econometrics and Finance, 22	Positions #4-#10 Letter, 1	Energy Research and Social Science, 5 (2.8)	Positions #4-#5 Book series, 1	Positions #3-#8 Moldavian, 1
6	Business, Management and Accounting, 17	Positions #4-#10 Erratum, 1	Energy Procedia, 3 (1.7)		Positions #3-#8 Japanese, 1
7	Mathematics, 12	Positions #4-#10 Editorial, 1	Energies, 3 (1.7)		Positions #3-#8 French, 1
8	Computer Science, 12	Positions #4-#10 Data paper, 1	Positions #8-#15 (having 2 documents each, or 1.1% each): Part 1: Sustainable Cities and Society, 2/Sustainability, 2/Renewable and Sustainable Energy Reviews, 2		Positions #3-#8 Czech, 1
9	Medicine, 6	Positions #4-#10 Book chapter, 1	Positions #8-#15 Part 2: Journal of Environmental Psychology, 2/Journal of Consumer Policy, 2/Journal of Cleaner Production, 2/		
10	Chemical Engineering, 5	Positions #4-#10 Book, 1	Positions #8-#15 Part 3: Energy 2/Building Research and Information, 2		

Table 2
All top-30 classifications (including 3 top-10 and 1 top-20 classifications): Keywords (top-10), Country/Territory (top-20), Funding Sponsor (top-10), Affiliation (top-10)

Top-number # (in descending order)	Keywords	Country/Territory, Number of Documents (in parentheses, % out of 178)	Funding Sponsor Number of Documents (in parentheses, % out of 178)	Affiliation
1	Energy Efficiency, 148	United Kingdom, 32 (18.0)	Undefined, 102 (57.3)	University of Cambridge, 5
2	Energy Utilization, 47	United States, 23 (12.9)	National Natural Science Foundation of China, 11 (6.2)	Positions #2-#10 Economics for Energy, 3
3	Household Energy, 45	China, 22 (12.4)	European Commission8 Horizon 2020 Framework Programme, 7 (3.9)	Positions #2-#10 The University of Sheffield, 3
4	Energy Policy, 41	Germany, 12 (6.7)	Engineering and Physical Sciences Research Council, 7 (3.9)	Positions #2-#10 Trinity College Dublin, 3
5	Housing, 25	Australia, 10 (5.6)	U.S. Department of Energy, 4 (2.2)	Positions #2-#10 Economic and Social Research Institute Ireland, 3
6	Energy Conservation, 25	Positions #6-#7 (having 9 documents, 5.1% each): Spain/Netherlands	European Regional Development Fund, 4 (2.2)	Positions #2-#10 University of Strathclyde, 3
7	Investments, 23	Positions #8-#11(having 6 documents, 5.1% each): Malaysia/Japan/ India/France	Sustainable Energy Authority of Ireland, 3 (1.7)	Positions #2-#10 Tsinghua University, 3
8	Energy Use, 22	Positions #12-#15 (having 5 documents, 2.8% each): Switzerland/Italy/Ireland/Finland	National Science Foundation, 3 (1.7)	Positions #2-#10 University of Melbourne, 3
9	Heating, 17	Positions #16-#20 (having 4 documents, 2.2% each): Part 1: Turkey, 4 (2.2)/ Sweden, 4 (2.2)/Poland, 4 (2.2)	National Key Research and Development Program of China, 3 (1.7)	Positions #2-#10 Universiti Malaya, 3
10	Household Energy Efficiencies, 15	Positions #16-#20 Part 2: Norway, 4 (2.2)/ Lithuania, 4 (2.2)	Economic and Social Research Council, 3 (1.7)	Positions #2-#10 Riga Technical University, 3

- Document type (top-10), Table 1
- Source/Journal title (top-20), Table 1
- Source type (top-5), Table 1
- Language (top-8), Table 1
- Keywords (top-30), Table 2
- Country/Territory (top-30), Table 2

- Funding Sponsor (top-10), Table 2
- Affiliation (top-30) Table 2

Based on these 9 classifications the relevant top-ranking outline of them is presented in the form of Tables 1 and 2. Besides, results' interpretation of the most significant findings, being derived from this sorting, it is also demonstrated. For this while at the Scopus database there was also reported documents classifications under "Author name" and "Open Source", these outcomes are highly dispersed, thus it was decided not to be further considered in the bibliometric analysis. The results of the search have been represented in quantitative terms in the form of Tables 1-2, as follows:

Table 1 contains the following 5 classifications: Scientific field (top-10), Document type (top-10), Source/Journal title (top-20), Source type (top-5), Language (top-8).

Table 2 contains the following 4 classifications: Keywords (top-30), Country/Territory (top-30), Funding Sponsor (top-10), Affiliation (top-30).

Based on data retrieved from Tables 1 and 2 it is noteworthy that the most popular and highly investigated item per each one of these 9 classifications (5 classifications from Table 1, and 4 classifications from Table 2), have been further analysed in the following sections, providing a more detailed analysis of the research outcomes (subsection 2.2),

2.2 Data Analysis

At this subsection the data of the bibliometric analysis has been organized and graphically represented in the form of Figures 1-6. Figure 1 shows the citation analysis of documents. The citation analysis provides a clear understanding of the significant impact and influence of a number of important publications within the expansive field of policies and measures and its complex relationship with energy efficiency improvement at households (Figure 1). Based on Figure 1 it was shown the pivotal contribution to the field of energy efficiency at households is the work of W. Neil Adger that has been in 2005 and demonstrated the highest level of citing recognition of his research, followed by the articles of Ralph Hertwig (2017) and Linda Steg (2008). This significant citation count, firstly, signified its substantial impact on the research discourse and, secondly, revealed critical facets of energy efficiency in households, thus, enriching our understanding of the multifaceted environmental, socio-economic and technological parameters involved in this field of examination. While these studies have left an indelible mark on the research domain, serving as guideposts for future investigations, it cannot be undermined the fact the the majority of these highly-cited articles have been published one or more decades ago, making necessary for policymakers and other energy-designing stakeholders to further explore critical dimensions of energy efficiency adoption in households. These utmost importance dimensions underscore the multifaceted characteristics

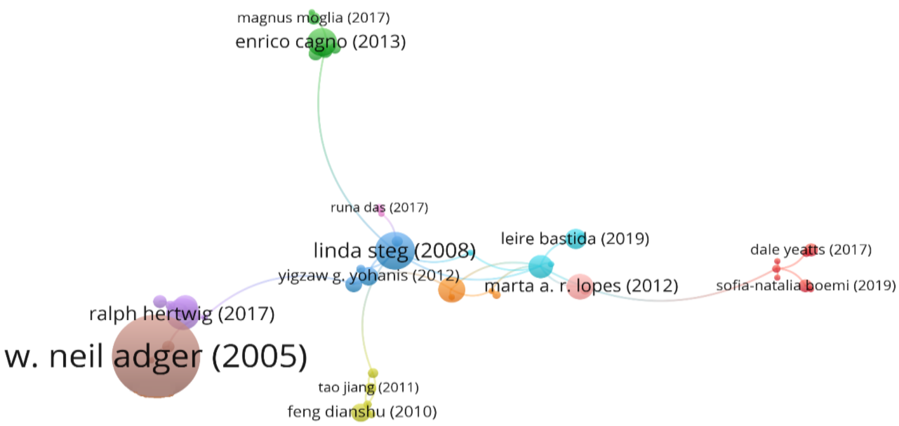

Fig 1. Citation analysis of documents.

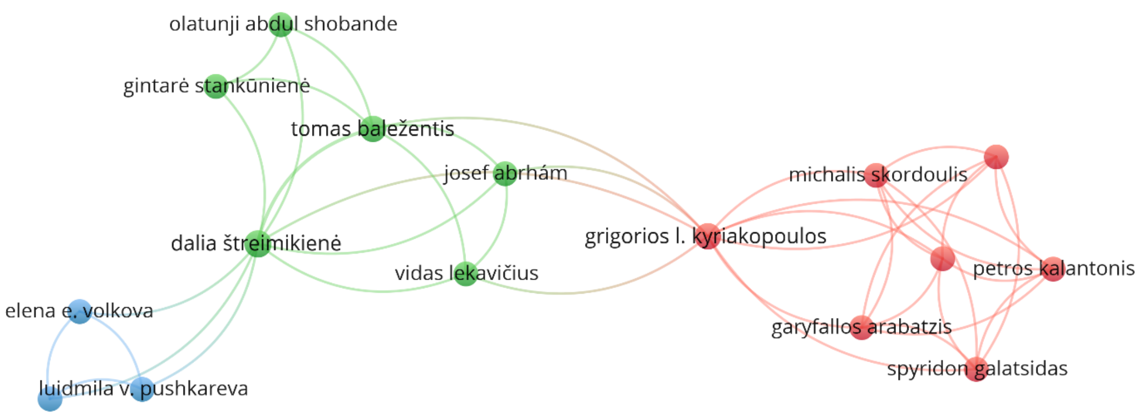

Fig 2. Authors' networks.

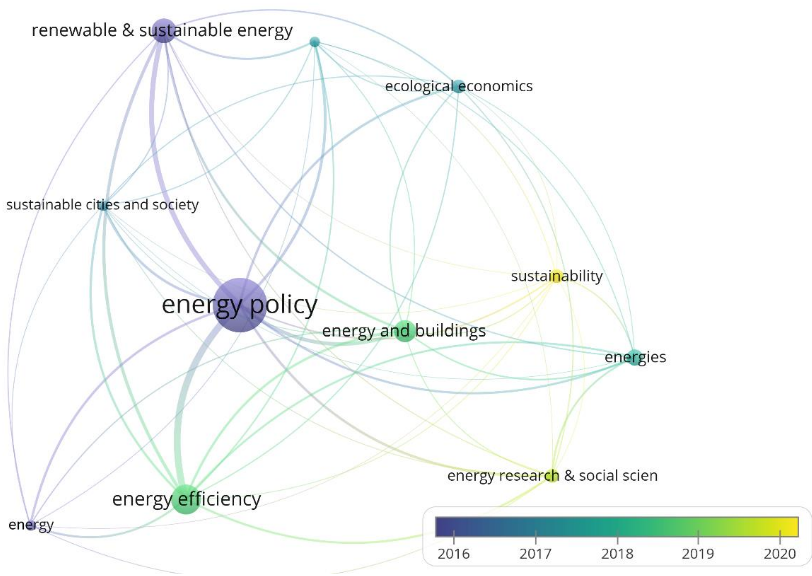

Fig 3. High impact journals (top 10) publishing in the field of energy efficiency at households.

involved in this energy efficiency transition, while encompassing the today economic implications, environmental sustainability, and employment opportunities offered.

As shown the findings of authors' networks (Figure 2), the analysis of co-authorship provides valuable information on patterns of cooperation and the influence of authors in the field of energy efficiency improvement. The time of authors' publishing in the field of energy efficiency at households is spanning to two decades ago and these articles provided comprehensive analyses of the literary contributions made by the authors. These analyses can acquire useful insights pertaining to the present state of research, identify areas where research is lacking, and ascertain the prospective avenues for furthering knowledge in this crucial domain of energy efficiency at households under different geographical and time/chronological contexts of analysis.

Figure 3 represents the high impact journals (top 10) publishing in the field of energy efficiency at households, demonstrating that the journal "Energy Policy" holds the highest number of articles published, with a total of 30 articles, followed by the journals: Energy Efficiency (14 articles), Energy and Buildings (8 articles). Lower production rates have been reported for the journals Renewable and Sustainable Energy Reviews, Energy, Energy Research and Social Science. A substantial link strength has been developed in the year 2016 making it the most frequently referenced source inside the co-citation network, while a low pace of publication density declining was been also reported since then. Based on Figure 3 it is also noteworthy that the most influential searchable topics in impacting research and policy considerations are reported around the fields of renewables, building sector, societal and economic expansion. These fields exhibited their significant influence in the energy efficiency at households. Overall, the co-citation research, as shown in Figure 3, provides insightful information about the key sources over the years, their relationships within policies and initiatives, and how these affect improvements in household energy efficiency. Through the analysis of citation frequency and cumulative link strength, one may determine the influence and importance of these sources on the formation of scholarly discourse.

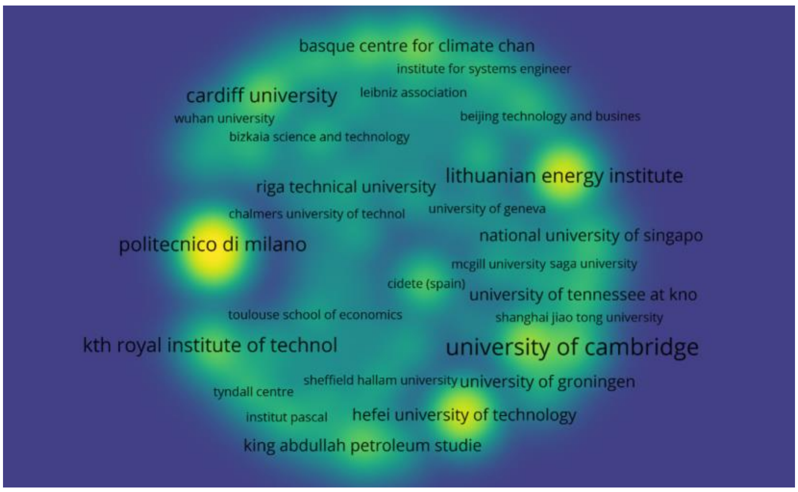

Fig 4. The knowledge mapping of co-authorship collaboration among institutions.

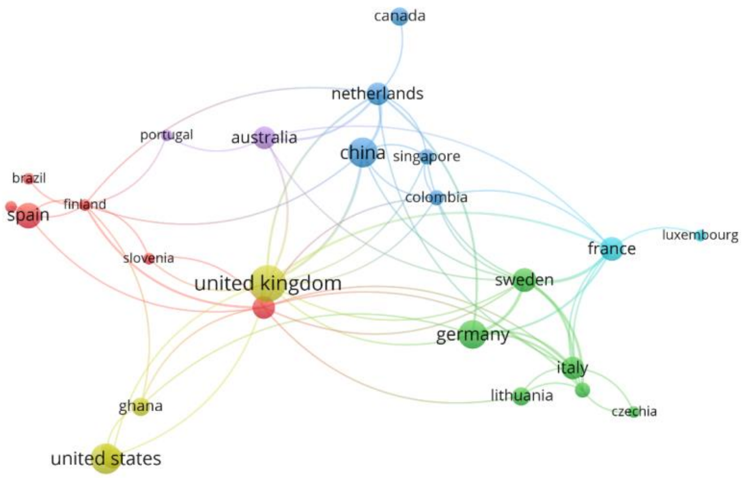

Fig 5. Co-authorship among countries.

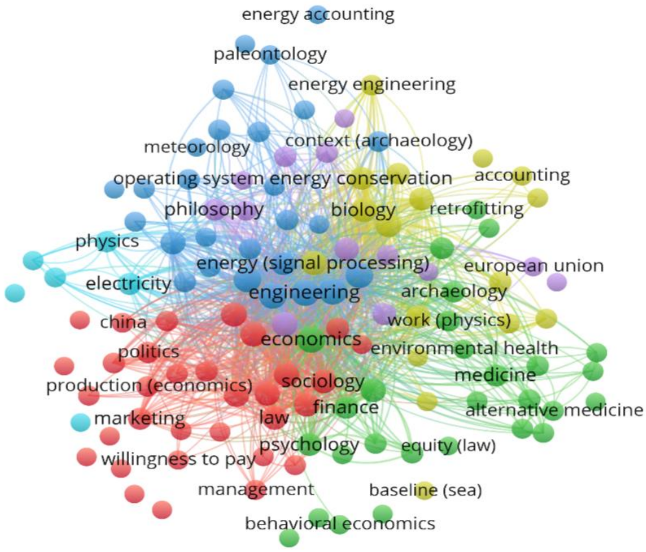

Fig 6. Keywords concurrence analysis.

Based on their publications and citations reported at this bibliometric analysis, the bibliographic coupling study sheds light on the ties between various institutions and countries. The study's conclusions identify the countries with the highest degrees of academic cooperation and information sharing, as shown in Figure 4 (institutions) and Figure 5 (countries).

Figure 4 depicts the knowledge mapping of co-authorship collaboration among institutions. The examination of co-authorship collaboration among institutions offers useful insights into patterns of collaboration and the impact of institutional influence in the joint field of energy efficiency at households, as illustrated in Figure 4. Based on the mapping of Figure 4 there are 7 prevailing institutional contributors reported: Politecnico di Milano, University of Cambridge, Lithuanian Energy Institute, Hefei university of Technology, KTH Royal Institute of Technology, Cardiff University, and Basque Centre for Climate Change. Regarding the spatial and geographical distribution, it can be signified the extensive research output mainly in Europe and Asia, which also underscores the substantial influence of these institutions in terms of research production within the academic community, further indicating a significant level of scholarly significance. Similar to Figure 4, Figure 5 verified the finding of a strengthful co-authorship network developed among (mainly industrialized and developed) European economies.

Regarding the network developed among the keyword's concurrence analysis (Figure 6), the research offers a thorough overview of the relationships between various concepts and research areas by visually representing the co-occurrence of keywords in different clusters and colors. This networking enables the identification of all key themes and potential areas for further investigation and collaboration, all referring to the field of energy efficiency at households. The different colors are assigned to each cluster, in order to indicate different theme regions or topics prevailing. Based on this mapping of Figure 6 it is worthy mentioning the keywords pluralism and the densely developed network of keywords that actually cover all technological, environmental, social, economic, behavioural, and political-institutional aspects involved.

3. Outcomes of analysis

3.1 A technological overview of energy efficiency in households

Researchers widely agree that implementing market-based energy efficiency measures requires access to investments in households and the provision of relevant energy-efficient products from utilities. In this context, utility companies have tested smart home solutions on the market to jointly achieve for household's energy and cost savings and for utility profit generation.

Energy-efficient technologies in households should benefit individuals and generate profit for utilities. These technologies should prioritize economic comfort and security to ensure commercial viability. However, despite the testing of smart home technological solutions, they have yet to demonstrate a significant impact on energy consumption or cost-effectiveness (Aboltins & Blumberga (2018)). Therefore, conducting a thorough qualitative analysis is crucial to determine which energy market factors will incentivize investment in innovative energy efficiency solutions, including consumer behavior, regulatory environment, and investment capability and willingness (Aboltins & Blumberga (2018)).

The advancements in energy efficiency in households are closely linked with the developing of new technologies stimulated by climate mitigation policies. These policies primarily focus on improving the energy system's supply side, followed by customers using energy-saving appliances in their homes. However, while there is significant potential for climate mitigation on the demand side, there needs to be more emphasis on policies that promote innovation in the household sector (Jia, Zhang & Xu (2022)).

Researchers comprehensively studied over 500 policies and measures over three decades (1980-2009) across 21 European nations. Using econometric estimations, they found that high energy efficiency is associated with increased patented energy-efficient inventions, financial subsidies, and energy labels. Additionally, early market adoption of energy-efficient technologies is suitable for encouraging innovation. Another study reported an "investment inefficiency" among household adopters, contrary to rational choice and finance theory. This is because the investment return, rather than individual characteristics, should drive adoption. Therefore, prompting the fast penetration of these technologies and considering the spill-over effects are essential for the implementation of these technologies, especially in light of self-motivation to save money rather than environmental concerns (Diaz-Rainey & Ashton (2015)).

Improved household energy efficiency is achieved using environmentally friendly technologies (EFTs). The effectiveness of EFTs is influenced by various factors, such as awareness of the technology, perceived environmental significance, perceived behavioral control, and perceived benefits (including cost). Researchers must study these factors. Additionally, to encourage the acceptance of energy-efficient technologies by households, it is recommended to increase financial advantages, manage the cost of EFTs, and offer discounts and subsidies. These measures will make EFTs adoption more practical and feasible (Fatima *et al.* 2022)

One of the most noticeable factors regarding household energy efficiency is technological advancements, such as the oil-free dual-piston linear compressor used in refrigeration systems. The results showed that the linear compressor has 11% higher energy efficiency than the former type of compressor and allows significant energy savings in households (Li *et al.* 2023).

By using energy-efficient components that are commercially available, allows to decrease energy consumption in refrigerators by approximately 50% and 70%. The cost of implementing these components would range from $45 to $60 and $100 to $120 per unit (Park, Shah & Phadke (2019)). In economic terms, small refrigerators that are highly efficient have the potential to save costs when compared to standard refrigerators.

It's important to note that these technological advancements are separate from the concurrent rapid economic growth of fast-emerging economies in densely populated regions, such as China, where living standards are rapidly improving (Tao & Yu 2011)).

Chinese households tend to own and use more electrical appliances, including larger refrigerators that consume much energy. This has raised environmental concerns, leading the Chinese government to establish national energy efficiency standards to promote the production and use of high-efficiency refrigerators. These standards are expected to result in significant energy savings, reducing CO_2 emissions by 629-1260 million tons and SO2 and NOx emissions by millions of tons by 2023, depending on the commercial models sold. The cost-benefit ratio for consumers is calculated at 1.45:1, indicating that investing in high-efficiency models is worth it for consumers who expect a return. (Tao & Yu 2011)).

Ensuring that households have high energy efficiency is challenging to address energy poverty, particularly among low-income families (LIHs), which is connected to energy inequality and justice issues. As a result, research has focused on the importance of energy justice in the United States, which refers to appropriate participation rates in energy assistance programs, and access to energy-efficient (EE) appliances. There are differences in energy consumption behavior and energy demand flexibility across income groups in US (Xu & Chen (2019)).

Affordability and accessibility are the primary concerns regarding Low-Income Households (LIHs). LIHs typically have a fixed temperature setting, even with a programmable thermostat, resulting in less energy efficiency. LIHs have a rigid schedule and are limited in their ability to participate in demand response programs, making energy less affordable, accessible, flexible, and environmentally friendly. These issues disproportionately affect underprivileged individuals. (Xu & Chen (2019)).

In today's world, integrating Information and Communications Technology (ICT) in the energy system has opened up new avenues to inform and influence residential electricity consumption. ICT makes it possible to simultaneously reduce electricity consumption, increase of energy efficiency, and decrease greenhouse gas emissions (GHG) in households. Studies have demonstrated that ICT-based methods allow to decrease electricity consumption by 5% in households. In addition, the ICT-based interventions in households could reduce CO_2 emissions by 0.23% to 3.3% from the energy sector (Bastida *et al.* 2019).

3.2 Socio-economic overview of energy efficiency in households

Many national and EU energy-efficiency programs focus on improving energy efficiency in residential buildings. Renovating buildings using up-to-date techniques and accurate planning can increase energy efficiency and reduce energy usage. One of the most critical considerations during the planning energy renovation is the families' financial situation in the buildings being renovated (Gróf, Janky & Bethlendi (2022); Manate *et al.* 2023).

When it comes to renovating homes, complex approaches are necessary, and it's essential to consider the impact of various energy policies in different countries. A study explored the potential level of prebound in Hungary and how it could affect energy-efficient mortgage loans (Gróf, Janky & Bethlendi 2022). The study found that heating expenses can vary depending on the household's income and the technical aspects of the dwelling. Smaller homes saw a reduction in costs and higher monthly savings rates. However, credit constraints, prebound, and rebound effects could limit the implementation of energy renovation programs as well (Gróf, Janky & Bethlendi (2022)).

Within the EU, literature and legislation have primarily focused on addressing common research questions historically explored by researchers. These questions include the following topics: the extent to which consumers take into account possible energy savings when purchasing advanced home heating controls, what is the level of importance individuals place on energy efficiency; What are the discount rates when investing in energy efficiency, and what are the main drivers of these discount rates.

According to a consumer survey conducted in Slovenia in late 2017, energy efficiency is crucial for Slovenians when making purchasing decisions, second only to property price. The survey revealed that females, who tend to be more environmentally conscious, and married individuals are likelier to place a high value on energy efficiency when buying property. They prefer shorter payback periods and higher implicit discount rates. On the other hand, individuals having higher education levels are ready to spend more on energy efficiency improvements (Lakić, Damigos & Gubina (2021))

Many countries prioritize residential energy efficiency as a critical aspect of their decarbonization policies. In the UK, a standard method to achieve efficiency gains is through centralized retrofitting programs, funded through the Energy Company Obligation (ECO) and passed on to customers through their bills (Katris & Turner (2021)). Ongoing discussion exists regarding whether lower-income households household ought to get more access to Energy Company Obligation funding. It is crucial to note that using limited public resources must be evaluated based on the potential long-term economic benefits. Recent research has shown that household and broader economic factors are crucial in determining the resources allocated toward achieving greater efficiency and increasing household disposable income. However, various challenges exist in making trade-offs between pursuing economic growth, social policy goals, household income levels, spending capacity, and overall gains in economic growth, creation of new jobs and increase in household income (Katris & Turner 2021).

A similar study revealed that household energy consumption is responsible for about 17% of annual greenhouse gas emissions in the United States (US). The study (Goldstein, Reames & Newell 2022) found that US housing policies and lending practices harm housing quality in immigrant communities (Goldstein, Reames & Newell 2022). The study analyzed the energy efficiency and GHG emissions differences linked to race, ethnicity, and property ownership. Research has shown that in Caucasian neighborhoods, GHG emissions per capita were higher than in African-American communities, despite the former were living in newer, more modern, and more energy-efficient homes (Goldstein, Reames & Newell 2022). Variations in building age, rates of homeownership, and floor area can explain the paradox of emissions in specific communities. To address this issue, suggested policies include government-funded home retrofits for rented houses, increased access to solar systems in disadvantaged communities, and other measures to reduce energy consumption and GHG emissions in households. Following these policies can achieve a fairer decarbonization of the residential sector in US (Goldstein, Reames & Newell 2022).

One of the noteworthy studies based on the African context dealt with energy efficiency and energy conservation practices in Ghana (Acakpovi, Botwe-Ohenewaa & Sackey 2022). The study revealed that consumers in Ghana need to implement more energy conservation practices due to limited energy generation, and growing population and an increase in households' energy needs. A series of questionnaires about energy conservation practices were given to selected households as part of an energy audit program. The results showed that properly designed questionnaires can effectively test people's knowledge. Implementing energy conservation measures can allow for a significant decrease in energy consumption (by 5.14%), which had positive economic and environmental implications. To promote energy efficiency and conservation, individuals must be aware of these measures and how non-efficient electrical appliances contribute to energy waste. Additionally, implementing policies and strategies for mass education can help ensure that energy-efficient appliances are used locally and globally, ultimately leading to sustainable business practices and poverty alleviation (Acakpovi, Botwe-Ohenewaa & Sackey 2022).

Many studies have looked at the social factors influencing energy-saving behaviors and investments in energy efficiency nationally. One approach is classifying research to identify the most significant socio-demographic, dwelling, and environmental factors having impact on daily energy-saving habits, energy-efficient appliances, and investments in energy-efficient home retrofits. This information can help us better understand how to promote household energy efficiency (Trotta, 2018)

A research study analyzed data from the "Survey of Public Attitudes and Behaviours Towards the Environment" and identified specific patterns in daily household energy-saving behaviors and energy conservation investments in Great Britain. The study also found that income and dwelling type plays an important role in determining energy-saving behaviors and providing insights into where and how energy and emission savings can be achieved. This information can be used to promote energy-responsible lifestyles and encourage energy-efficient retrofit investments (Trotta, 2018).

A study on behavior suggested that several energy policies and programs have been created with assumptions about household behavior and characteristics. This has led to misjudgments about the effectiveness of retrofit measures and energy savings predictions (Ben & Steemers (2017)). To conduct a thorough study, it's essential to acknowledge that the ranking of retrofit measures based on energy savings differs depending on the type of household. Additionally, we need to recognize that retrofit actions impact each household archetype differently, and some retrofits may be better suited for specific households over others. Furthermore, the ranking of retrofit measures in terms of potential energy savings can change based on both the dwelling and household behavior. Consequently, recommendations for energy efficiency policies and measures should prioritize retrofit measures based on household archetypes to provide decision-making support. This approach can ensure that the right retrofits are chosen for each household to maximize energy savings (Ben & Steemers 2017).

In our highly commercialized and social world today, certain behaviors can be linked to the impact of household energy efficiency measures on health and well-being. It is widely acknowledged that policies and measures promoting residential energy efficiency, such as insulation, central heating, and double-glazing allow residents to keep their homes warm and reduce cold-related illnesses. Nevertheless, some of these interventions, such as the materials used or lower ventilation rates, may harm health, resulting in poorer indoor air quality. These impacts must be considered when implementing energy efficiency measures (Maidment *et al.* 2014). A recent study showed that measures to improve residential energy efficiency can positively impact residents' health, even if it is a slight improvement. However, it's essential to consider the health improvements faced by different groups of households, as well as the planning factors having an impact on these outcomes (Maidment *et al.* 2014).

One behavioral characteristic of energy efficiency in households, derived from literature, is the "energy efficiency gap" or energy efficiency paradox. This phenomenon is based on the fact that the household sector is among the highest energy-consuming sectors in Europe, making it a priority in greenhouse gas emissions reduction related to energy use (Solà *et al.* 2021). It is possible to achieve household energy consumption reduction by prioritizing energy efficiency measures in households. However, there are several reasons why households do not make investments in energy efficiency measures. To analyze these reasons, researchers group them into market failures which include informational and behavioral failures etc. There are many policies and measures that can be implemented to address these market failures and encourage the use of energy-efficient technology. These measures are: energy efficiency standards and energy codes, financial incentives, and information programmes (Solà *et al.* 2021). The study (Solà *et al.* 2021) examined multiple instruments for implementing effective policies, but several barriers must be overcome. For instance, subsidies and taxes do not appear to be effective instruments, while rebates can have mixed results and sometimes rebates can be effective tools. Furthermore, the effectiveness of informational programmes is only sometimes guaranteed, depending on the country, sector, product, service, etc. (Solà *et al.* 2021).

One of the most recognizable features of energy efficiency is its ability to decrease the energy needed for indoor heating and reduce global GHG emissions [25]. Nationally, state regulators frequently enforce stricter building code appliance standards for energy efficiency, especially for low-income households. Central governments should or already have implemented energy efficiency programs, which commonly include replacing furnaces, insulating attics, and walls, and reducing infiltration (Kim *et al.* 2020) The term "energy efficiency gap" refers to the misconception that energy efficiency programs effectively reduce energy consumption. A recent study aimed to define the impact of input data on calculating energy savings for low-income residents, which could contribute to the energy efficiency gap. Additionally, both current and projected methods associate the reduction of greenhouse gas emissions with energy savings based on precise measurement results (Kim *et al.* 2020).

To address the "energy efficiency gap" issue, central governments have introduced national energy efficiency and energy audit programs to incite households to have their homes professionally audited for energy efficiency and follow recommended measures and improvements. A Household and Environment Survey conducted in Canada in 2011 and 2013 found that pro-environmental attitudes and behavior like water conservation, waste separation and recycling, purchasing green products with labels, and lowering heating temperatures were good predictors of residents' involvement in these energy audit programs. These findings suggest that in addition to financial incentives, pro-environmental activities offer a more long-term and holistic approach to addressing the residential energy efficiency gap (Gamtessa & Guliani (2019)).

4. Energy efficiency policies and measures in households

One of the most economical methods to control the energy supply and lower greenhouse gas emissions is universally acknowledged to be energy efficiency (Trotta (2018); Poncin (2020)). The potential for energy efficiency improvement in households, particularly for existing structures, is virtually untapped. Improving the energy efficiency of new and old residential buildings can result in considerable and numerous advantages (Al-Homoud & Krarti (2021)). Even more effective results can be achieved by implementing household energy savings and a gradual behavioral response option (Trotta (2018); Yeatts *et al.* 2017; Yeatts et al, 2017; Weber & Wolff, (2018)). In table 3, the policies and means of increasing household energy efficiency are systematized based on an analysis of the scientific literature.

The final energy consumption in households depends on three main factors: 1) the technical characteristics of buildings, including the local environment; 2) the characteristics of households (socio-economic characteristics, individual preferences, income, etc.); and 3) the energy prices (Sorrell (2009); Galvin & Sunikka-Blank (2012); Bakaloglou & Charlier (2018)). Renovation measures and social interventions are the leading solutions for increasing energy use efficiency and reducing household energy demand (Lopes, Antunes & Martins (2012)). According to research (Wiencke (2013); Zalejska-Jonsson (2014); Alberini *et al.* 2018) housing renovation where the use of insulating materials during construction lowers energy consumption, and inhabitants are prepared to pay extra for it. EET like low-energy windows, programmable thermostats, direct-control devices, smart meters, and energy-saving gadgets have produced a number of beneficial results, including better quality of housing, lower environmental and energy costs, enhanced health and well-being for homeowners, and benefits for the nation by reducing energy import dependency (Levesque, Pietzcker & Luderer (2019)). Measures such as appliance, heating, insulation ceiling, concrete masonry walls, cellar insulation, windows, and air leakage reduce the energy demand from the baseline to the optimized building by 90% (D'Agostino, Parker & Melia (2019)) Research by D'Agostino, Parker & Melia (2019) showed that following accounting for embodied energy, the total energy reduction was 55–67% over ten years after construction, and 77–82 percent over 30 years. Byrne *et al.* (2016) found that in all cases, a significant reduction in heat loss across the walls was measured using the insulation of cavities and external walls. Compared to a comparable control group of residences with no record of considered energy-saving measures, cavity wall insulation reduces annual natural gas use by 10.5 percent and yearly

Table 3
Policies and measures for energy efficiency improvement in households

Policies	Means
Information	• Audits, labelling of products; • Programs that expected customers to concentrate on losses rather than benefits.
Regulation	• Campaigns for information; Spread the best practices; • Report of the relationship between space heating demand and greenhouse gas reductions; • Appliance efficiency improvement; • Buildings' renovation; • Energy-efficient technologies (EET) in residential buildings; • Standards for residential buildings ("Green buildings")
Communication	• The energy performance certificates; • Minimum standards for building efficiency; • The requirement of periodic billing for heating energy; • Obligation to include information in formal education
The economic tools	• Higher electricity prices • Taxation of high energy ussage level; • Grants, subsidies, and tax deductions; • Tax advantages, credits, rebates, and guarantees.
The fiscal means	• High GHG taxes; • Efficient billing structure; • Government's financial incentives;
Behavioural change means	• Low-costs methods for motivation ("Nudges"); • People's competencies and knowledge increasing ("Boosts"interventions). • Social incentives • Life policies

energy usage by 8% (Adan & Fuerst (2016)). The customers played a significant part reducing energy consumption in buildings, and comfort was discovered to be the primary motivator for retrofit. Even if the consumer lacks the desire to buy energy-saving products due to credit restrictions or lack of incentives, energy-related requirements for buildings can ensure the optimal energy efficiency level of main components of buildings and (especially) heating installations (Wada *et al.* 2012; Fang, Zhao & Yu (2018)). Krarti & Howarth (2020) claim that programs that enhance minimal energy efficiency criteria for air conditioners and/or incentivize families to purchase high-efficiency cooling systems can drastically decrease energy use, peak electricity demand, and GHG emissions. It is also important that residential building designs that are energy efficient not only save energy during construction but also save energy in the long term (Liu *et al.* 2012). The findings of Liu *et al.* study (2012) showed that adding solar building materials, double-skin facades, and green roof designs into building designs can result in high-energy efficiency improvements in residential buildings. Obligatory measures like minimum standards, also direct metering would be a solution to encourage investment in energy efficiency. It is also possible to set up a financial system where financial support is provided so that the borrower can repay the lender of the energy saved (Charlier (2015)). Consumers can be effectively motivated to acquire energy-efficient products by enhancing the current energy-efficiency information with more precise economic cost data. It is anticipated that a combination of more exact subsidy programs and more effective communication strategies can greatly increase energy-saving behavior in the residential sector (Nie *et al.* 2020).

Another critical factor for reducing energy demand in households is increasing the energy efficiency of appliances. Increasing appliance efficiency is far more affordable than raising productivity in other sectors or use of renewables (Moriarty and Honnery (2019)). At last, as the appliances are electric, they can be powered by renewable energy at home or on the grid (Poncin (2020)). Standards for appliances, construction regulations, and tax breaks or reductions, labeling, Demand Side Management (DSM) programs, and energy-efficiency obligations are evaluated as being incredibly effective and cost-effective (Ürge-Vorsatz *et al.* 2015). Laicane et al. (2015) found out that in five years, improvements in the energy efficiency of some frequently used appliances can result in savings of 1219 kWh (or a 13% decreasing in electricity use compared to the current scenario).

Low energy costs are one of the main elements harming energy conservation initiatives (Ryan *et al.* 2011; Moglia, Cook & McGregor (2017); Jacobsen, Kotchen & Vanderbergh (2010)) However, increasing the efficiency of energy use and reducing the energy demand in households is influenced by many factors related to the behavior of the residents. First, individuals must be aware of the necessity and potential solutions for energy consumption reduction in the home. Second, they must be motivated to save energy. Third, they should be able to accept appropriate behavior (Steg (2008)). Researchers note that household energy savings are lower than the anticipations of technical and economic policies (Bagaini *et al.* 2020). Therefore, in addition to technical (regulation, information, communication) and economic (fiscal) measures for increasing energy efficiency in households, researchers also distinguish behavioral interventions (Yohanis (2012); Pothitou *et al.* 2014; van Sluisveld *et a.*, 2016; Xu *et al.* 2021). One such could be the Nudge intervention, based on the tendency of individuals to make unconscious, passive decisions. (Demarque *et al.* 2015; Kasperbauer (2017); DellaValle & Sareen (2020); Fanghella, Ploner & Tavoni (2021). Another - the opposite - Boost behavioral intervention, which researchers often single out as promoting sustainable behavior, including energy use, based on developing skills and competencies to enable individuals to make desirable decisions (Grüne-Yanoff & Hertwig (2016); Hertwig & Grüne-Yanoff (2017); DellaValle & Sareen (2020); Lazaric & Toumi (2022)). Understanding the importance of energy-efficient behaviors and opportunities and how to implement them is crucial. It comprises organizational and intellectual skills and family awareness (connected to decision-making when purchasing or constructing equipment) (Bagaini *et al.* 2020). Increasing consumer awareness and promoting behavioral change can improve household energy efficiency. Public education, awareness campaigns promoted by national or local electricity agencies, and social networks using social norms (e.g., neighborhood influence) can directly influence the pace of new technologies, such as new EETs (Bagaini *et al.* 2020; Yeatts *et al.* 2017; Matar 2020). The promotion of the usage of PV systems in communities can be aided by community participation and pro-environmental habits of community members. Flexible and practical policies can help identify suitable supporting policies while increasing policy promotion's efficiency and efficacy (Hsueh 2015). The importance of public education was also emphasized by Aldossary, Rezgui & Kwan (2015). The authors state that strict policies and rules are needed to ensure low-carbon design in home buildings. It also identified the need to increase residents' awareness of home energy use and inform people of the value of energy use reduction for the economy and the environment.

Studies of household energy consumption have revealed wide variations in energy consumption among comparable households, indicating that inhabitants are the third significant agent and that their behavior might be just as crucial as the physics of the buildings. The household's reaction to a changing climate is complicated. Still, it can be explained by several variables, such as the socioeconomic makeup of the family, credit availability, knowledge and comprehension of climate change, information about short- and long-range weather forecasts, perception, and political climate (Gonzalez-Hernandez, Meijles & Vanclay 2019) Numerous studies have been conducted on the factors that discourage households from voluntarily addressing climate change (Adger, Arnell & Tompkins (2005); Bryan *et al.* 2009; Faber *et al.* 2012), and in a nutshell, three categories of barriers can be identified: 1) economic (e.g., sinking investments and vested interests), 2) social (e.g., social group alignment, cognitive processes, and values and lifestyles), and 3) political aspects (e.g., opposition to change from vested interests and the unequal field of play). Behaviors that affect how much energy is used in homes can be broadly categorized into two groups: 1) Habitual attempts to save energy by changes in daily behavior, such as how the appliances work, temperature preferences for rooms, how often the windows are opened, etc. and 2) one-time behaviors like the choice of an investment in the tools utilized, such as the energy source and the device for producing energy. Curtailment habit behavior is a low-cost behavior to adopt, even though it can be psychologically very challenging to modify, and people need significant incentives to do so (such as financial incentives, regulations, education, and information dissemination campaigns) (Nauges & Wheeler (2017)) Two alternative strategies for reducing energy use are energy adequacy and efficiency, therefore, combining them in designing policies for a high quality of life will reduce energy use (Samadi *et al* 2017; Trotta, Spangenberg & Lorek (2018); Poncin (2020)). According to van Sluisveld *et al.* (2016), lifestyle changes are the most significant in the end-use sectors and can potentially reduce CO2 emissions by about 15%. Consumption patterns, a lack of understanding of economic returns, a variety of buying options, a decline in faith in public administration, both local and federal, low cost-effectiveness of expenditures, a lack of enticing goods and services, and comfort as a top priority are all associated with behavioral obstacles. These obstacles are frequently brought on by information gaps, which affect both increasing energy efficiency and implementing energy-efficient technologies (Cagno *et al.* 2013; Risholt, Time & Hestnes 2013; Moglia, Cook & McGregor 2017; Bagaini *et al.* 2020). It is challenging to measure consumer behavior in a market and extensive analysis is necessary to address critical issues such as how these flaws impact energy consumption, how behavioral and market flaws are related to them, or whether they can be addressed by practice or learning (Shogren & Taylor (2008)). Human behavior, together with the physical characteristics of the home, is one of the key factors that could have impact on households' energy use, the surrounding environment, the number of occupants and their demographics, household income, way of life, and the presence and use of equipment (Jensen (2008); Yohanis (2012); Pothitou *et al.* 2014). To support the promotion of energy-saving solutions, it is suggested that public awareness of environmental and energy conservation concerns be strengthened (Jia *et al.* 2018). The majority of customers need to be made aware of the impact of their design needs and establish criteria for comfort, the environment, and energy use, according to the research. As a result, there is a pressing need to raise public knowledge about the need to achieve energy efficiency in buildings (Ochedi & Taki 2022). However, it's essential to provide consumers with specialized information and to choose precise feedback instruments for various home types (Vassileva *et al.* 2013) Feedback has aided in reducing home energy usage and the induction of behavioral changes, but it only reaches those interested consumers. The acceptance of energy-saving activities varies based on the economic and socio-demographic features of the consumers (Sardianou (2007)). As a result, an energy-saving campaign should target customers as subgroups with distinct requirements and lifestyle characteristics. Increased energy consumption awareness in low-income households should be given special consideration (Vassileva *et al.* 2013; Sardianou 2007).

5. Discussion

Performed literature review on energy efficiency measures in households showed that this is important to investigate whether households are utilizing energy-efficient options for lighting, water heaters, appliances, air-conditioners, and heaters, as well as better energy-efficiency labels. It is crucial to focus on how energy users are better aware of their consumption and prices over the last two decades, which is linked to rising income and electricity use levels. Policies and recommendations should be directed towards improving efforts to promote energy efficiency improvements and reduce growth of power load, particularly in rapidly emerging and densely populated countries worldwide (Dianshu, Sovacool & Vu (2010))

Household energy efficiency is significant for individuals, governments, and non-governmental organizations. Energy efficiency has wide-ranging implications, including improved health and well-being, greater comfort, better air quality, increased resource productivity, enhanced security of energy supply, and improve quality of social capital. As a result, current research should focus on exploring the effectiveness of measures to increase energy efficiency in developed countries, with a particular emphasis on households. This will help to define the level of evidence supporting their efficacy. (McAndrew *et al.* 2021)

It is common practice to associate theories and frameworks with household interventions, including target populations or groups, techniques, and activities. However, it is also acknowledged that measuring outcomes through quantifiable and realistic proposals is important. Due to the diverse definitions and interpretations of energy efficiency in households, evidence supporting specific interventions can be mixed. However, interventions that utilize multiple techniques and activities are more likely to be successful. Additionally, policy implications may require comprehensive and systematic explanations of interventions to facilitate informed decision-making by the government (McAndrew et al. 2021).

It's important to note that different methods for measuring household energy efficiency exist. One such method is the Non-Intrusive Load Monitoring (NILM) approach, which assesses the the residential appliances in terms of energy efficiency. This approach has been used recently and is considered innovative (Garcia *et al.* 2020). The NILMEE technique can detect the energy consumption of various household devices and evaluate their efficiency, even when there are labeling mismatches. It can also suggest better energy usage practices for specific consumer installations (Garcia *et al.* 2020). Using NILMTK, the algorithm's performance demonstrated that NILM exceeded typical energy usage calculations. This technology acted as a valuable tool, allowing for identifying household appliances based on the energy efficiency indexes provided by labels and standards (Garcia *et al.* 2020).

One commonly-used approach for measuring characteristics is multicriteria analysis (MCA). During past few decades, the importance of household energy efficiency measures has grown significantly. These measures are not only effective in mitigating energy consumption but also have the potential to improve socioeconomic development. Notwithstanding their cost-effectiveness, some of the most important energy efficiency measures in households require help with implementation. Energy policy must overcome various barriers to support their successful delivery (Zabaloy, Recalde & G uzowski (2019)).

It is essential to use effective methods to promote energy efficiency and understand the key factors that impact policy. This helps in designing policies that work well. However, identifying the relevant factors and developing suitable analysis methods can be a challenging task. To tackle this issue, a methodology was proposed that involved an empirical study of Latin American countries, including Brazil, Chile, Colombia, and Uruguay, in 2016. This study analyzed the enabling conditions influencing policy performance. Research has shown that the most effective energy efficiency practices for households depend on the specific national context. This includes factors such as government commitment, public awareness, energy pricing policies, access to financing, and favorable economic conditions. Considering the unique challenges and opportunities of different boundary conditions when implementing energy efficiency policies is important (Zabaloy, Recalde & Guzowski (2019)).

Looking at things from an economic and financial point of view, a fresh method has been developed to assess the potential for energy efficiency. This approach gives a more precise, detailed, and adaptable estimate of households' energy efficiency potential for different income levels [86]. I recently came across a study that looked at energy efficiency packages for single-family households in the US with an income of less than 200% of the federal poverty level. The study aimed to determine how to maximize net present value and save on energy costs. According to the survey, the tailored energy efficiency packages could lead to an estimated \$13 billion annually in energy cost savings (Wilson *et al.* 2019). These measures can also be applied to other regions, counties, and income levels. This is great news for policymakers for improving both the cost-effectiveness and the equity of various energy efficiency programs. This information is also helpful understanding how energy efficiency improvement possibilities vary across urban and rural areas. Energy efficiency can be an excellent tool for spurring economic development of high poverty areas for many years to come [86].

It is important to highlight the significance of the Koorie Energy Efficiency Project (KEEP) from a social standpoint. This initiative was launched in Victoria, Australia, to assist

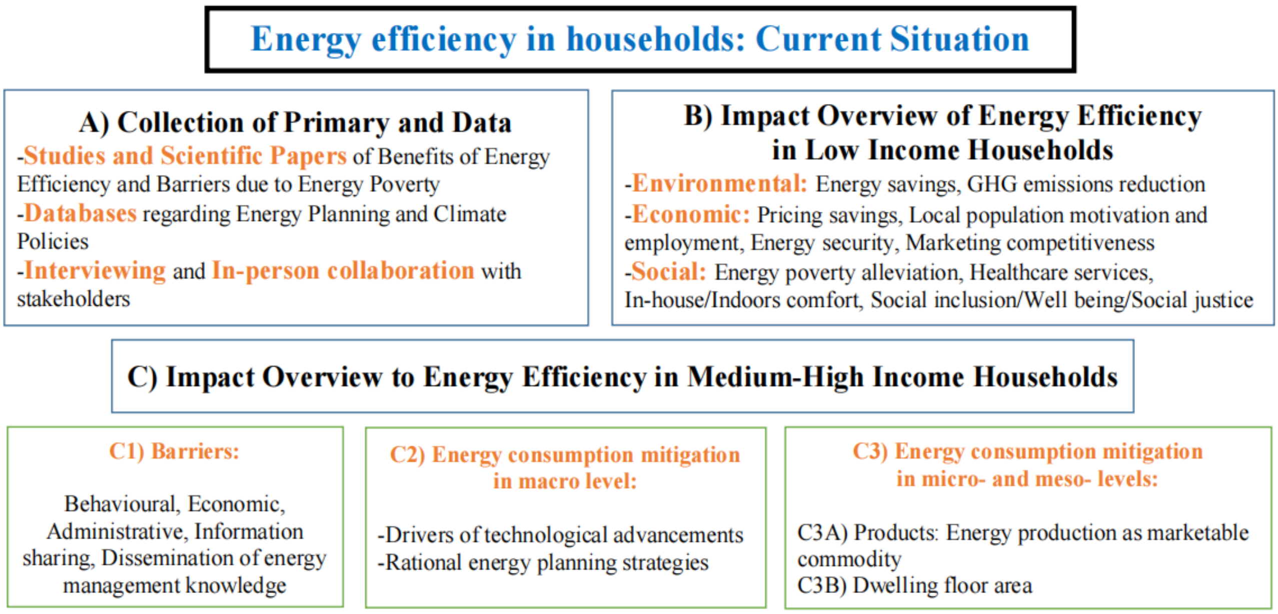

Fig 7. The current situation mapping of energy efficiency in households. Source: Authors own study.

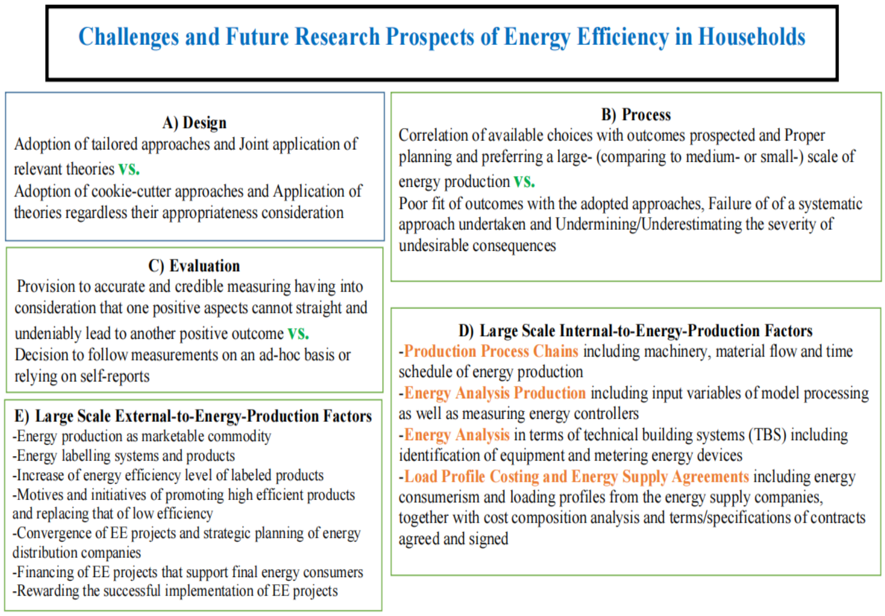

Fig 8. Overview of challenges and prospects regarding energy efficiency in households. Source: Authors' own study.

Indigenous households in managing their energy bills by regulating their energy consumption (Perényi *et al.* 2019). Trained Indigenous project employees implemented the program by visiting homes in metropolitan and regional areas of the state. The research goals included evaluating the energy efficiency knowledge, behaviors, and well-being of the primary household member before and after the home visit. It is essential to consider various factors, such as behaviors and environmental conditions, to promote well-being. Studies have shown that home visit options, types of homes, and their size and density can impact energy-related stress and discomfort. This highlights the need for socially responsible housing marketing programs that are culturally appropriate and respectful, like those used in the KEEP program. This can help drive positive change among indigenous communities by promoting property ownership and ensuring tenants' comfortable and affordable living conditions (Alberini & Filippini (2018); Fuerst & Singh (2018); Pelenur (2018); Perényi *et al.* 2019).

In the following two Figures, there is an integrated mapping and graphical representation of the current situation (Figure 7) as well as the challenging issues and the future research prospects (Figure 8) of household energy efficiency. Based on Figure 7 -and under the context of C3A-Products- the following key-aspects are noticeable:

- Surveillance and monitoring of electricity sales,
- Efficiency and sufficiency of funds direct to energy market,
- Integrated policies for the domains of energy efficiency, energy sufficiency and energy autonomy.

In parallel, under the context of C3B-Dwelling floor area, the following key-aspects are noticeable:

- Spatial comfort of floor area size per person,
- Policies and legally binding aspects of energy policies,
- Flexibility of housing translocation and provision of institutional instruments that support new forms of housing, including sharing flats and smaller dwellings preferences/choices of living and domestication.

Under the aforementioned graphical representation of Figure 8, the challenges and the future research prospects of energy efficiency in households revealed that realistic strategic planning priorities should be focused on critical energy production factors referring to the simulation and an evaluation of contemporary energy production systems. In this context, it is vital to the challenging and prospects of energy efficiency for households to taken into consideration:

- Parameters of modeling regarding the energy production design,
- Integration of measurable data in the light of energy-business-energy market contract specifications,
- Energy production evaluation in an integrated manner: environmental, technological, behavioural, economic, social, marketing and managerial,
- Coupling consideration and operational coordination of technical building systems (TBS) and energy production systems. Such energy production systems are also potential to employ low energy intensive techniques in large scale applications (Zamparas *et al.*, 2019) and green strategic plans (Skordoulis *et al.*, 2022).

Although it is widely believed that retrofit projects can help reduce fuel poverty and carbon emissions, there have been few large-scale evaluations of their effectiveness. [Webber, Gouldson & Kerr (2015); Androniceanu *et al.* 2020). The real effects of the methodological scheme have been highly differentiated from that predictable, implying that rebound effects can also be lower than has often been expected. The study (Ouyang, Long & Hokao (2010) found that the predicted impacts of energy use are consistent in lower-income areas but differ in middle and higher-income regions.

6. Conclusions

It can be concluded that achieving energy efficiency in households depends on various factors. Not all stakeholders have the same level of interest in this area. To summarize the key points, the following aspects should be taken into account when promoting energy use efficiency in households:

By combining household energy saving measures with population behavior change measures, effective results can be reached for reducing energy demand and related GHG emissions. Our analysis of the scientific literature showed that the final energy use in households depends on three main factors: i.e. technical characteristics of buildings; household characteristics such as socio-economic characteristics, individual interests, income, etc. and energy prices. Therefore, in addition to renovation and energy modernization of housing, measures to increase the efficiency of devices, measures to change the behavior of residents and increase their competences and education are distinguished in the scientific literature.

However, research shows that the acceptability of energy-saving activities varies depending on consumers' economic and socio-demographic characteristics. Therefore, it is very important that energy saving programs would be focused on subgroups of the population with different lifestyle characteristics and requirements. It is important to give special consideration to education of low-income households about energy use and energy use impact on the economy, environment and climate change.

Yet, a disparity exists between the potential and actual implementation of energy efficiency measures, commonly called the "energy efficiency gap." Being environmentally conscious and aware of energy efficiency sometimes translates to a willingness or intention to install energy-efficient technology. Households with proactive energy efficiency attitudes may require specific incentives to motivate them to enhance their home's energy efficiency. More than relying solely on environmental beliefs may be necessary to encourage them to take action.

Studies reveal that people who exhibit patience and are less present-biased tend to invest in energy-efficient appliances. Instead, when it comes to smaller purchases, such as light bulbs, time preferences do not have significant explanatory power. As of now, more research on obstacles that are causing difficulties in energy efficiency improvements, including behavioral flaws in decision-making is necessary. To achieve energy savings and reduce greenhouse gas emissions in households, it is recommended to implement both short-term policy measures, such as nudges, social norms, real-time usage information, and pricing, as well as long-term standards like energy-efficiency regulations, incentives for high-efficiency equipment purchases, and promoting changes in equipment usage habits.

The analysis of scientific literature showed that rebound effects can also be lower than has often been assumed. When considering the rebound effect on household energy efficiency, it is recommended to mitigate this effect in several ways: promotion of renewable energy use, increase of energy prices and promoting energy efficiency measures, and improving consumer behavior.

Finally, based on the conducted bibliometric analysis and findings it can be denoted that there are reported influential researches that collectively shape academic discourse and provide valuable insights for policymakers, industry leaders, and society. These research contributions span a spectrum, from economic implications to employment opportunities, underscoring the multifaceted advantages of energy efficiency at households. Through building up a robust knowledge foundation, these studies continue to inform the scientific community and inspire further research, policy development, and real-world applications. Their lasting and contemporary impact reaffirms their role as cornerstones in pursuing a sustainable and prosperous future (Chou et al., 2023). This statement also implies that a considerable amount of scholarly investigation has been dedicated to exploring the relationship between energy efficiency improvement at households. However, the collaborative endeavors of these individuals collectively contribute to the progression of knowledge and facilitate a more profound understanding of the complex interplay between policies applied to measure and to promote energy efficiency at households. It is also an imperative need to acknowledge that further investigation is necessary to explore the contributions of authors who are concentrated on this research field. This can be achieved through a comprehensive analysis of their publications, which should encompass an evaluation of the specific research topics they have addressed, the methodology they have employed, and the insights they have created (Chou et al., 2023).

Author Contributions: D.S.: Conceptualization, D.S. and G.L.K.: methodology, formal analysis, D.S. and G.L.K.: writing—original draft, D.S.; supervision, G.L.K: resources, B.Ś.: project administration, G.S.: writing—review and draft editing, D.S. and G.L.K: validation, B.Ś. and G.S.: writing—review of revised editing. All authors have read and agreed to the published version of the manuscript.

Funding: The author(s) received no financial support for the research, authorship, and/or publication of this article.

Conflicts of Interest: The authors declare no conflict of interest.

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