Energy Reports 15 (2026) 109356

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Challenges and opportunities of households' thermal energy security: An empirical study in the time of energy crisis

Javanshir Fouladvand [a,*], Orestis Kiriakidis [a], Özge Okur [b]

[a] Copernicus Institute of Sustainable Development, Utrecht University, Netherlands
[b] Multi-Actor Systems Department, Technology, Policy and Management Faculty, Delft University of Technology (TU Delft), Netherlands

ARTICLE INFO

Keywords:
Thermal energy transition
Renewable heating
Energy security
Empirical data
Natural gas
Energy behaviour

ABSTRACT

The ongoing energy crisis affects the European energy system, its transition towards sustainability and different actors, particularly households. This study aims to investigate how households perceive the energy crisis, which strategies they have adopted to mitigate its impact, and to what extent they consider these strategies effective. The main challenges of the (thermal) energy systems during the energy crisis are structured through the 4 A's energy security concepts as follows: (i) Economic Challenges (Energy Affordability), (ii) Techno-physical Challenges (Energy Availability), (iii) Information and skills Challenges (Energy Acceptability) and (iv) Infrastructural Challenges (Energy Accessibility). Two interactive workshops with 17 highly educated households from the Netherlands took place to collect data on these challenges. The results delineate that the participants mostly faced and were frustrated by economic, and information and skills challenges, while they also found them the easiest ones to solve. Furthermore, grid congestion and monopoly of companies are the main issues related to techno-physical and infrastructural challenges. The participants indicated that energy efficiency measures and local renewable energy systems are the best strategies for the local thermal energy transition. The findings contribute to understanding the households' perception and strategies related to their energy security. Considering the challenges the energy crisis imposes, the study sheds light on facilitating local thermal energy transition and provides detailed discussions and recommendations.

1. Introduction

Over the last couple of years, the global energy system, specifically the European energy system, has faced an energy crisis, mainly due to the COVID-19 pandemic and ongoing crises in Eastern Europe and the Middle East (Pollitt, 2024; Pye et al., 2025). The increase in prices of fossil fuels, particularly natural gas and crude oil (Pollitt, 2024; Eurostat, n.d.), resulted from the energy crisis has influenced most of the European sectors and actors, as more than 40% of the European gas demand was covered by imports in 2019, mainly from Russia (and 27% of crude oil) (European comm, n.d.). Such an energy crisis has influenced the European energy transition, specifically household energy consumption/ demand (Matschoss et al., 2025), usually referred to as the local (thermal) energy transition.

In the Netherlands, the surge in energy prices hit all sectors, particularly the Dutch households, the final energy consumers (Urbano et al., 2023; Pollitt et al., 2024). Dutch households are responsible for approximately 30% of national energy consumption (Majcen et al., 2013). Around 75% of this consumption is dedicated to thermal purposes (e.g., heating spaces, hot tap water and cooking), which the majority of it has been met by natural gas consumption (e.g., through natural gas boilers in houses) (Majcen et al., 2013; ECN, 2015). Therefore, the ongoing energy crisis and the surge in energy prices significantly impacted Dutch households (Fouladvand and Fiori, 2024).

In this context, various studies explored the Dutch local thermal energy transition, households' natural gas consumption, and the impact of the energy crisis. For instance, the factors influencing Dutch households' adoption of renewable heating systems are explored in (Okur et al., 2024). Factors affecting household natural gas consumption are investigated in studies such as (Fouladvand and Fiori, 2024; Conradie et al., 2023). The influence of the availability of different natural gas energy sources on the local thermal energy transition is presented in (Fouladvand et al., 2024a), while alternative solutions, such as thermal energy communities (Fouladvand, 2023), are studied in various studies

* Corresponding author.
E-mail addresses: j.fouladvand@uu.nl, javanshir.fouladvand.work@gmail.com (J. Fouladvand), orestisrk@gmail.com (O. Kiriakidis), O.Okur-1@tudelft.nl (Ö. Okur).

https://doi.org/10.1016/j.egyr.2026.109356
Received 11 June 2025; Received in revised form 13 March 2026; Accepted 2 May 2026
Available online 9 May 2026

(e.g., (Fouladvand et al., 2022a; Fouladvand et al., 2022b)). By focusing on the energy crisis, studies such as (Pollitt et al., 2024) analyse trends in energy markets and provide recommendations for a future-proof Dutch energy system (i.e. electricity market). The possible changes in the Dutch households' energy-related behaviour during a crisis are studied in (Vasseur and Backhaus, 2024). The effectiveness of several local Dutch interventions (e.g., installing minor energy-saving measures in homes and offering advice on sustainable energy practices by municipalities) on energy poverty, aimed at mitigating the impact of the energy crisis, is explored in (Croon et al., 2025). The potential effect of the households' energy-related behaviour resulting from the energy crisis on the natural gas demand is presented in (Bagheri et al., 2024).

Although the impact of the energy crisis and some of its consequences have been studied, limited research has explored how households have perceived this crisis and what strategies they have adopted to overcome it. Understanding these lived experiences, including their perceptions of the crisis and the strategies they have adopted, is vital to inform and support locally driven thermal energy transition. On the other hand, while studies such as (Fouladvand and Fiori, 2024; Fouladvand et al., 2024a; De Jager and Doran, 2025; de Wildt et al., 2020; Beauchampet and Walsh, 2021) demonstrated, the perceptions of households, their attributes and the availability of different alternative options for fostering (local) energy transition, they did not explore these perceptions (and the ways households experience them) during the energy crisis.

To address this gap, this study employs the 4 A's energy security concept (i.e., availability, affordability, acceptability and accessibility) (Tongsopit et al., 2016) from energy security literature. Energy security is among the primary considerations of any actor, particularly households, influencing their energy choices (Fouladvand et al., 2022c; Fouladvand et al., 2022d), and it is one of the first aspects jeopardised during the energy crisis (Belaïd et al., 2023; Dumitru and Dumitru, 2023), the 4 A's concept helps us understand how the crisis has affected households and how they've adapted, especially in terms of heating and energy use at the local level. Although energy security is not the central theme of this study, the 4 A's concept provides a useful structure for the workshops and helps capture the key socio-technical aspects shaping local responses to the crisis.

To summarise, there is no specific study that investigates how households perceive the energy crisis, the strategies they have adopted to mitigate its impact, and the extent to which they consider those strategies effective. To address this knowledge gap, this study explores Dutch households' perceptions of the energy crisis's influence on their energy systems and energy security. The study empirically approaches its aim by collecting and analysing data through interactive workshops with highly educated households. Highly educated households are usually those with higher incomes and a greater willingness to change their behaviour (e.g., early adopters of energy innovations and, in this case, reducing natural gas consumption) (Faiers et al., 2007; Egbue and Long, 2012). This can be translated as: a sample could be more representative of individuals with relatively greater resources to overcome the challenges posed by the energy crisis, and who are also potentially willing to change their behaviour. By such a systematic approach, the study contributes to the literature on energy-related behaviour and energy policy. The study aims to provide concrete insights and recommendations to relevant actors, particularly the (local) policy-makers and households. In addition, such insights and recommendations could contribute to energy policy at higher levels (such as national, European, and International Energy Agency (IEA) levels) to increase resilience to the energy crisis. The study can also be seen as a response to concerns about the energy crisis caused by the ongoing war in Eastern Europe, as demonstrated in studies such as (Aitken and Ersoy, 2022; Moskalenko et al., 2024).

The structure of the paper is as follows: Section 2 provides the theoretical background. Section 3 elaborates on research methods. The results are presented in Section 4. Section 5 demonstrates the discussion and conclusions, including the recommendations.

2. Theoretical background: 4A's energy security

In the vast literature on energy security with different definitions (as presented in (Sovacool, 2010)), which involves various concepts and disciplines, such as public policy, economics, and engineering, contributing to its definition (Kruyt et al., 2009; Brown et al., 2014). In the literature, there are more than 45 definitions, including those developed by the International Energy Agency (IEA) (Bartos and Robertson, 2014), Association of Southeast Asian Nations (ASEAN) (Security, 2017), World Energy Council (WEC) (WEC, 2017) and Ang and his colleagues (Ang et al., 2015a). The definition developed by the Asia Pacific Energy Research Centre (APERC) is one of the most well-known ones, which defines energy security as: "The ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy" (Security, 2017).

Consequently, for assessing energy security, each definition has its own unique set of energy security dimensions, such as security of supply (i.e. availability), affordability, accessibility and efficiency (Ang et al., 2015a). For instance, availability, affordability, efficiency and environmental stewardship are discussed as energy security dimensions in (Sovacool and Brown, 2010), while availability, adequacy of capacity (e.g., infrastructure and accessibility), affordability and sustainability are presented in (Chester, 2010). Ang and his colleagues also present availability, energy prices, infrastructure, social effects, environment, governance and efficiency as energy security dimensions (Ang et al., 2015a). Furthermore, APERC proposes the "4 A's concept" for energy security assessment, comprising the following dimensions: availability, affordability, accessibility, and acceptability (Security, 2017). As presented in (Sovacool, 2010; Azzuni and Breyer, 2018), these energy security definitions (with their representative dimensions) are employed to study national and international energy security.

In this extensive branch of literature, there are a few studies specifically focusing on the energy security of households and the neighbourhood level (Fouladvand et al., 2024b). While most of these studies focus on one of the energy security dimensions (e.g., energy availability (Wang and Perera, 2019), energy affordability (Yang et al., 2024), and governance (Ghorbani et al., 2020)), a few studies, such as (Fouladvand et al., 2022c; Fouladvand, 2022; Wejnert-depue et al., 2025), include several dimensions following the 4 A's energy security concept. In this vein, a systematic overview of the literature on the energy security of households and neighbourhoods is provided in (Wejnert-depue et al., 2025) by using the 4 A's energy security concept. Furthermore, the 4 A's energy security concept has been adopted in studies such as (Fouladvand et al., 2022c), which investigated the households' energy security by employing agent-based modelling and simulation, while (Fouladvand, 2022) explored the influence of the behavioural attributes on the collective energy security.

Following these studies, which employed the 4 A's energy security concept to study energy security of households and neighbourhoods, and to incorporate a multidimensional perspective on energy security (to understand the associated trade-offs), the 4 A's concept is used in this study. Furthermore, compared with broader energy security frameworks and definitions, such as those presented by the IEA (Bartos and Robertson, 2014) and Ang et al. (Ang et al., 2015a), the 4 A's concept is more suitable for this study because it is more closely aligned with the household level (rather than higher-level infrastructure and governance dimensions), and the workshop-based empirical approach adopted here. Further context on the four dimensions is as follows:

Availability refers to the physical existence of the energy resources to be used for the energy system (Kruyt et al., 2009). Given the increasing share of renewables in energy generation, an indicator of the availability dimension is the energy system's domestic energy generation per capita

(whether from fossil or renewable sources) (Escribano Francés et al., 2013). The shortage percentage is another indicator that can be used to measure the availability. Shortages occur when demand and supply mismatch, leaving individuals disconnected from energy supplies (Reichl et al., 2013).

Affordability is related to the costs of the energy system and whether it is affordable or not (Demski et al., 2018). Among different affordability indicators, the energy price function is the most common (Kruyt et al., 2009). Another way to measure affordability is the mean-variance portfolio (MVP) theory (Stempien and Chan, 2017). The size of investments made to improve energy security (Kruyt et al., 2009) is another affordability indicator in the literature.

Accessibility can be defined as "having sufficient access to commercial energy to promote an equal society" (Erahman et al., 2016), which reflects on aspects such as a large spatial discrepancy between the location of energy consumption and the location of the energy generation (Kruyt et al., 2009). Among different indicators, diversification of energy resources is popular for increasing and measuring accessibility (Kruyt et al., 2009). Multiple integrated diversity indicators are presented in the literature: the Shannon index (Bartos and Robertson, 2014) and the Herfindhal-Hirschman index (Greenleaf et al., 2009).

Acceptability refers to social opinion and supportive behaviour towards energy sources (Kruyt et al., 2009; Sovacool and Brown, 2010). This is often linked to societal elements such as welfare and fairness (Ang et al., 2015a) and environmental issues (Sovacool and Brown, 2010). Although APERC uses an economy's effort to switch away from carbon-intensive fuels as an indicator of acceptability (Security, 2017), the carbon content of an energy system as a whole is also suggested as an indicator (Kruyt et al., 2009). Carbon intensity, as the ratio of CO_2 emissions to GDP and carbon factor, as the ratio of CO_2 to TPES, are used as indicators for environmental acceptability (Ang et al., 2015b).

3. Research methods: interactive workshops

Two separate, similar interactive online workshops with 17 highly educated participants took place in January 2024 to investigate how households perceived the energy crisis. The duration of each workshop was 90 min, and, as elaborated in the introduction, since the research focuses on the Dutch context, all participants live in the Netherlands.

Each workshop consists of two parts; the first part is structured based on four main challenges of the thermal energy systems during the energy crisis, as representatives of the dimensions of 4 A's energy security as follows: (i) Economic Challenges (Energy Affordability), (ii) Techno-physical Challenges (Energy Availability), (iii) Information and skills Challenges (Energy Acceptability) and (iv) Infrastructural Challenges (Energy Accessibility). For each of these challenges (i.e., energy security dimensions), the following three questions were posed:

- ❖ How did you experience this challenge?
- ❖ What was your strategy to overcome this challenge?
- ❖ How effective was your strategy/ solution?

The second part was dedicated to three ranking questions with pre-defined alternative choices as follows:

- ❖ Please rank the six challenges related to the local thermal energy transition from most frustrating to least frustrating. (meaning 1 is the most frustrating option and 6 is the least frustrating option),

A. The surge in energy prices,
B. Costs of renewable thermal energy options,
C. Low availability of renewable thermal energy alternatives,
D. Lack of options to purchase/ import natural gas from,
E. Lack of information and skills
F. Reliable infrastructure

- ❖ Please rank the six challenges related to the local thermal energy transition from hardest to solve to easiest to solve. (meaning 1 is the easiest to solve and 6 is the hardest to solve),
  A. The surge in energy prices,
  B. Costs of renewable thermal energy options,
  C. Low availability of renewable thermal energy alternatives,
  D. Lack of options to purchase/ import natural gas from,
  E. Lack of information and skills
  F. Reliable infrastructure
- ❖ Please rank the following seven solutions related to the local thermal energy transition from the most to least effective one for solving the local thermal energy transition. (meaning 1 is the most effective solution and 7 is the least effective solution)
  A. Demand reduction through retrofitting buildings,
  B. Increasing the efficiency of heating systems,
  C. Implementing collective renewable thermal energy systems,
  D. Implementing individual renewable thermal energy systems,
  E. Importing natural gas from allied countries,
  F. Renewable gases (e.g., hydrogen and biogas),
  G. Electrification of thermal energy purposes.

The pre-defined alternative choices included in the ranking exercise were selected based on the literature on household thermal energy transition, energy security, and natural gas reduction, particularly studies relevant to the Dutch and European context, such as (Fouladvand and Fiori, 2024; Okur et al., 2024; Wejnert-depue et al., 2025; Koirala et al., 2016; Hesselink and Chappin, 2019). First, a broader set of potential challenges and solutions was identified from the literature. This set was then screened by the authors based on three considerations: (i) relevance to household-level thermal energy practices during the energy crisis, (ii) applicability to the Dutch context, and (iii) suitability for comparison in an interactive workshop setting. The number of options was kept limited to six challenge items and seven solution items to make the ranking exercise manageable within the 90-minute workshop format, while still covering the main themes identified in the literature. While the selected options were informed by the 4 A framework (e.g., surges in energy prices and costs of renewable thermal energy options are related to energy affordability, and a lack of information and skills is connected to energy acceptability), they were not designed to correspond to its dimensions in a strict one-to-one manner, because household-level challenges and solutions often overlap across dimensions rather than fitting neatly within a single category; as also discussed in detail in (Kruyt et al., 2009; Wejnert-depue et al., 2025).

During the workshops, participants joined a Miro board page, an online collaborative platform, where they could share their answers as virtual post-its. In this setting, the workshops allowed participants to interact and learn from one another while expressing their own perceptions of the energy crisis. Other studies used similar approaches to study different topics in the energy-related literature. For instance, by employing interactive workshops, studies such as (Boyle et al., 2022) explore the role of citizen and community engagement in climate mitigation projects, particularly related to climate infrastructure development in the Irish context. Workshops focused on public response and engagement in industrial decarbonisation in the UK are presented in (Smith et al., 2025). Furthermore, workshops are also used in (Cass et al., 2023) to investigate the United Kingdom's energy consumer behaviour/in favour of or against climate change. To bridge different views and gather insights into British retrofitting challenges and potential solutions, (Wise et al., 2025) also conducted workshops with homeowners, professionals, and local policy-makers. Participatory stakeholder workshops aiming at exploring future energy scenarios for an ecologically intentional community in Scotland are presented in (Copeland et al., 2023). The limitations of this approach are elaborated in Section 5.1.

4. Results

Following the two parts of the workshops, the results are also presented in two parts: (i) qualitative results on the challenges and solutions and (ii) quantitative ranking of the challenges and solutions.

4.1. Qualitative results

As explained in Sections 2 and 3, the challenges are structured and discussed following the 4 A's energy security concept. Overall, the participants indicated that information and skills challenges (Energy Acceptability) and economic challenges (Energy Affordability) are more difficult than infrastructural challenges (Energy Accessibility) and techno-physical challenges (Energy availability). For each of these challenges, the experience, the strategies used to overcome them, and their effectiveness are discussed.

4.1.1. Economic challenges (Energy affordability)

The respondents' experience of the economic challenges was divided into two main categories: (i) not a challenge, 5 out of 17 participants; (ii) very expensive energy bills, 12 out of 17 participants. The first category of participants were those with fixed long-term contracts for their energy supply, and mostly lived in rental accommodation. If such participants value sustainability, saving energy, and solidarity, they try to reduce their energy consumption (e.g., by turning heating systems down and wearing more clothes). As these strategies did not directly affect energy affordability (because they had fixed energy contracts), their effectiveness could not be determined.

On the other hand, among the participants who experienced very expensive energy bills, feelings of (extreme) fear, insecurity and uncertainty were reported. "We freaked out", and "sudden intense increases in the energy prices" were mentioned during the workshops. Although these participants were highly educated and had more available resources, such as information and a budget to overcome the influence of the crisis, they still experienced severe economic challenges. While some participants did nothing (because they felt powerless or did not know how/ where to start), the majority reduced their energy consumption by changing their behaviours (e.g., wearing more clothes, lowering the thermostat setting, and shifting the heating time). After behavioural changes, technological solutions such as increasing energy efficiency through different housing insulation approaches and installing RETs (e.g., solar PV and heat pumps) were implemented. Although all the solutions were found effective, the behavioural change solutions (which also did not require significant initial investment) were reported as the most effective.

4.1.2. Techno-physical challenges (Energy availability)

As all these participants live in urban areas, they are connected to the natural gas grid and did not report any techno-physical challenges with it. The experiences related to techno-physical challenges are mainly focused on alternative solutions to natural gas and can be divided into three main categories: (i) not a challenge, (ii) installation of RETs, (iii) installation of insulation and energy efficiency technologies. 8 out of 17 participants (i.e., 47%) indicated they did not face significant techno-physical challenges and changes. These participants either lived in a rental accommodation or did not have enough budget (or the willingness to invest) to address their challenges.

The other 9 participants decided to install RETs, energy efficiency measures (e.g., insulation), or both to address their energy availability challenges. The main challenges here are related to installing and implementing the RETs and energy efficiency measures, such as "finding companies to provide the services" or "installing floor heating". Easy and low-technological solutions, such as installing "air stoppers" in front of doors and windows, were also mentioned. The participants found their strategies effective in overcoming such techno-physical challenges.

4.1.3. Information and skills challenges (Energy acceptability)

The majority of participants, 13 out of 17 (approximately 75%), indicated a lack of information and skills regarding thermal energy transition. The 4 participants who have reported having sufficient information and skills are experts in the energy field, aware of the different technologies and policies for the heating transition in the Netherlands (and of alternative options). The other 13 participants mentioned they either (i) do not have information on the thermal energy transition, the possible solutions, including the technologies and related policies in general, or (ii) have some general idea of the thermal energy transition but do not have specific information on the thermal energy transition solutions within the municipality they are living in.

The participants found the relevant information and skills mainly in their own personal circles (e.g., family, friends and neighbourhood social groups) or on the internet. Although the participants reported these strategies as effective and easy to find relevant information, they might be inaccurate as they are not proven/ confirmed by an energy expert or institutes such as municipalities. On the other hand, 3 participants explicitly mentioned that their strategy to overcome their lack of information and skills was to contact the energy companies (e.g., installers, manufacturers and consultants). Although this strategy has been reported to be effective and accurate, it is time-consuming. On the other hand, only one participant consulted umbrella organisations, such as Energie Samen and their municipalities, to get information.

4.1.4. Infrastructure challenges (Energy Accessibility)

More than half of the participants, 9 out of 17 (approximately 53%), reported not facing any infrastructural challenges, while 5 indicated grid congestion issues, 4 mentioned provider monopoly and 1 reported the diversity of energy providers as their infrastructure challenges.

Those who do not face any infrastructure challenges have long-term energy contracts (which, in the event of termination, have substantial consequences for energy companies) or live in less congested areas (e.g., North Holland and Groningen). On the other hand, grid congestion and the energy providers' monopoly were identified as the biggest challenges in this context, and participants could not do anything about them in the short term. These challenges are primarily related to higher decision-making levels, expanding the grid to avoid congestion, and diversifying energy providers to avoid a monopoly in the long term. However, participants who reduced their dependency on the national grid (e.g., by installing RETs, increasing insulation and changing their behaviour) found these strategies useful for mitigating the negative impacts of infrastructure challenges.

4.2. Quantitative ranking

As elaborated in Section 3, this section is structured around the three ranking questions that were posed in the second part of the workshops.

Fig. 1 illustrates the "most frustrating/ affecting your life" challenge that participants reported. "Surge in energy prices", "Costs of renewable thermal energy options", and "Lack of information and skills" are the three challenges which caused the most frustration for the participants. These challenges highlight that economic and social challenges (i.e., energy affordability and energy acceptability) are most frustrating for individual households. On the other hand, "Lack of options to purchase/ import natural gas from" and "Reliable infrastructure", with a considerable difference, were the least frustrating challenges, which are related to techno-physical and infrastructural challenges (i.e., energy availability and energy accessibility).

On the other hand, as Fig. 2 shows, the lack of information and skills is the challenge participants believe can be solved most easily. The next two challenges participants perceived as easier to address are the limited availability of renewable thermal energy alternatives and the surge in energy prices. The hardest challenge is reliable infrastructure, highlighting the hardship of maintaining and improving the national grid.

Finally, the participants shared their perception of the best strategy

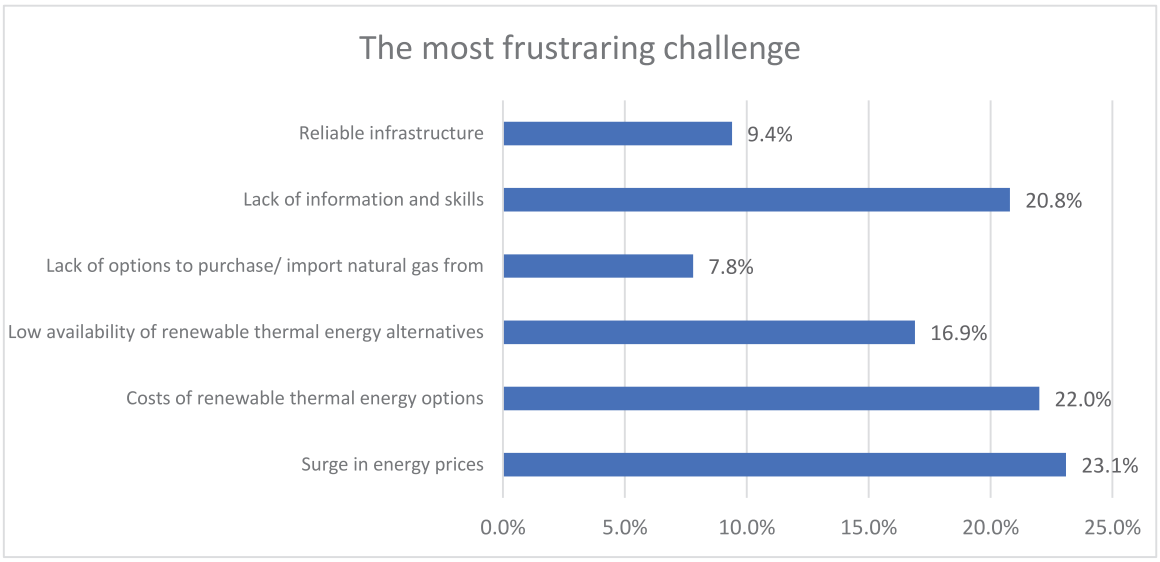

Fig. 1. The most frustrating challenge of Thermal Energy Transition (i.e., the challenge affecting your life the most); Distribution of 100% between 6 choices.

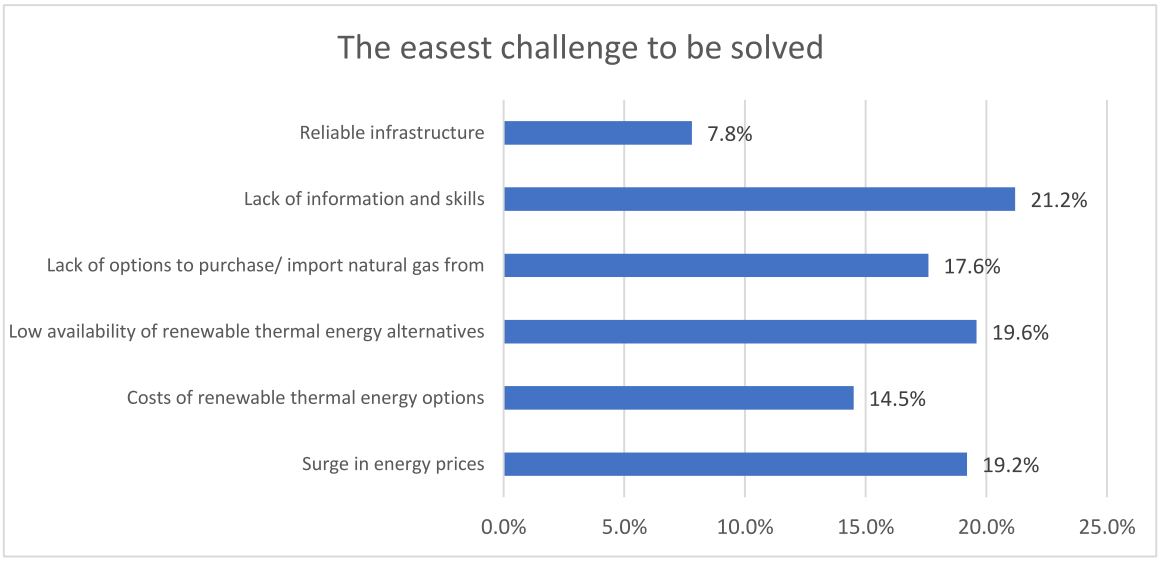

Fig. 2. The easiest challenge to solve for the Thermal Energy Transition; Distribution of 100% between 6 choices.

for household thermal energy transition in the Netherlands, as presented in Fig. 3. They perceive demand reduction through retrofitting buildings as the best strategy, highlighting the need for more efficient, careful energy consumption on the demand side rather than increasing energy generation on the supply side. Increasing the efficiency of heating systems was chosen as the third-best solution, further emphasising this point. Individual renewable thermal energy systems (e.g., heat pumps and solar collectors) are considered the second-best strategy (and the best energy generation strategy), followed by collective renewable thermal energy systems (e.g., district heating and geothermal energy). Electrification and renewable gases (e.g., hydrogen and biogas) are considered the least favourable sustainable options. Importing natural gas from other countries is considered to be the least appealing strategy for addressing households' thermal energy transition.

5. Discussion and conclusions

Due to the COVID-19 pandemic, ongoing crises in Eastern Europe and the West Asia/Middle East, and other challenges, the global energy system, specifically the households across the world, particularly in Europe, have faced an energy crisis. While there are several studies focused on the impacts of such an energy crisis, no specific study has investigated how households perceive the energy crisis, what strategies they have adopted to overcome its impacts, and to what extent they consider their strategies effective. Therefore, this study collected data on households' perceptions of the energy crisis through interactive online workshops with 17 highly educated Dutch households. The workshops consist of two parts, one based on four challenges that households face, namely (i) economic challenges, (ii) techno-physical challenges, (iii) information and skills challenges and (iv) infrastructure challenges (structured based on the 4 A's energy security concept to also delve into the household's energy security) and the second part based on ranking questions of challenges and solutions.

The results demonstrated that among the four challenges, the economic and, information and skills challenges were the ones most participants faced, which is in line with studies such as (Frankowski et al., 2025), which highlighted the importance of the social and economic factors in Polish energy commons during the energy crisis. For both of

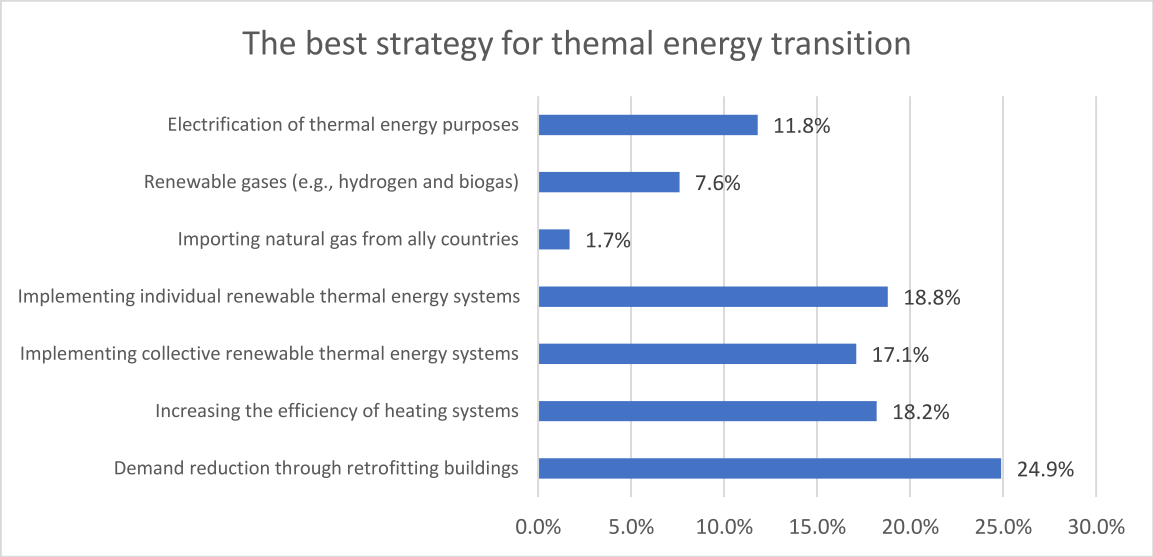

Fig. 3. The best strategy perceived in Thermal Energy Transition; Distribution of 100% between 7 choices.

these challenges, more than 75% of participants reported issues such as high prices, limited information, and difficulty finding information, which led to fear, stress, and frustration. Although finding accurate information was difficult, the participants relied on their social networks and the internet, and they perceived their adopted strategies, such as behavioural changes to reduce consumption and installing insulation and RETs, as effective in addressing these challenges. Along with being the challenges faced the most, these were also reported to be the most frustrating. Particularly, the surge in energy prices, the cost of renewable thermal energy options, and the lack of information and skills are reported as the most frustrating, causing high levels of fear and stress, as reported by the participants. In contrast, participants also perceive these challenges, specifically the lack of information and skills, to be the easiest ones to solve.

On the other hand, participants reported that techno-physical challenges (50%) and infrastructural challenges (45%) were the least faced. The main challenge in techno-physical challenges lies in the lack of companies to install RETs and insulation, which highlights the need for more "blue-collar" workers and experts in the field, which aligns with the previous research. On the other hand, the reported infrastructural challenges, the grid congestion, and the monopoly of a certain company are systemic issues that individual households do not have the resources to solve. Studies such as (Vitéz and Lavrijssen, 2020; De Winkel et al., 2025) also highlighted these challenges, particularly in the Dutch energy system, and provided recommendations to policy-makers and grid operators on how to overcome them. From an energy security perspective, the results can be translated into the higher importance of the acceptability and affordability dimensions of the 4 A's concept rather than the availability and accessibility dimensions. This is also in line with studies such as (Fouladvand et al., 2024a; Fouladvand et al., 2022c; Fouladvand et al., 2024b), which emphasise such dimensions.

Finally, the participants see demand-reduction strategies (including insulating buildings through retrofitting and increasing the energy efficiency of energy systems) as the best strategy in the thermal energy transition. Confirming findings of studies such as (Fouladvand et al., 2022d; Hesselink and Chappin, 2019) highlight the importance of demand reduction solutions compared to increasing energy generation through renewable energy technologies. The participants clearly indicated a strong preference for decentralised renewable energy systems (individual and collective energy systems) over electrification and renewable gases. These results contrast with the ongoing debates on supporting electrification and renewable gases as solutions for the Dutch thermal energy transition.

5.1. Limitations

Although this study, by its structural approach, brought new insights to light, it has several limitations that need to be considered. First, from a theoretical perspective, the study investigates the households' thermal energy transition and their perceptions of it through an energy security lens. However, other theoretical lenses, such as social acceptance, could be adopted by future studies to examine the same topic. Further, the current study employs the 4 A's energy security concept as one of the most well-known concepts for studying energy security (of households). However, employing other energy security concepts, such as the one presented in (Ang et al., 2015a) (including the following seven dimensions: energy availability, infrastructure, energy prices, societal effects, environment, governance and energy efficiency) and the one suggested in (Fouladvand et al., 2024b) (tailored for community energy systems), could bring further insights to light.

Secondly, from a research method perspective, the study collected its data through interactive workshops. As presented in Section 3, this approach was chosen not only to collect data but also to increase participants' knowledge and information. However, it may introduce bias, such as conforming to the dominant viewpoints of participants or relying on familiar narratives, thereby reducing cognitive diversity and the breadth of emergent themes. Future research could also consider other empirical data collection approaches (e.g., surveys and interviews). Furthermore, the number of participants is limited to 17 highly educated households, which could be increased to expand the sample size and potentially confirm current outcomes. Although highly educated households could provide more structured insights (as explained in Section 3), for future studies, diversifying the participants (e.g., by focusing on one neighbourhood) could enlarge the sample size and potentially confirm the current findings (or lead to new insights). As presented in studies such as (Fouladvand, 2024; Fouladvand, n.d.,), computational social simulation approaches, particularly agent-based modelling and simulation, can also be employed to study such topics in a virtual environment.

Thirdly, the study focuses on the Netherlands, which has unique characteristics for households' thermal energy transition. Although the Netherlands provides an opportunity to explore the impact of the energy crisis on households' thermal energy transition, this choice is a limitation due to its specific context. Exploring similar questions (with the

same approach) in the context of other European countries (e.g., Germany, Denmark, and Spain) and regions (e.g., Africa or Asia) could lead to different results. Thus, it is insightful for future research to explore the questions in other contexts. Also, future research could focus on one type of local energy system, such as solar energy communities (Narjabadifam et al., 2023), and wind energy communities (Brouwer et al., 2025), to evaluate the findings of this study.

Finally, since data collection in January 2024, international (geopolitical) settings have evolved (e.g., the 2024 United States presidential election and the right-wing movements in Europe), which could potentially influence the energy crisis. Considering these changes and their consequences on the energy crisis (and the energy transition), there is a need for a dynamic, continuous study to capture these changes, their consequences and how households perceive them.

5.2. Recommendations

Considering the results and limitations presented in previous sections, the following recommendations are formulated:

- Lack of information and skills is perceived to be one of the most frustrating and easiest to solve. Therefore, the (local) policy-makers are urged to provide necessary information and skills for the citizens (for instance, through webpages, brochures and community meetings).
- As the economic and information challenges are the ones that are most faced and frustrate the participants, policy-makers are recommended to focus more on them rather than only on the techno-physical and infrastructural challenges.
- To address the techno-physical and infrastructural challenges, there is a considerable need for diverse companies, experts, and technicians (who are the front-runners in installing energy technologies). Therefore, energy companies and entrepreneurs are encouraged to recruit and educate more technicians. Policy-makers are also recommended to support such initiatives to facilitate the (thermal) energy transition.
- Building retrofits and increasing energy efficiency are considered the best strategies for the local thermal energy transition. Therefore, all relevant actors, such as energy companies, (local) policy-makers and municipalities, are encouraged to prioritise such strategies.
- From the energy generation side, local renewable thermal energy systems (both individual and collective) are perceived as better strategies than electrification and renewable gases (e.g., hydrogen and biogas). Therefore, policy-makers are recommended to focus on and allocate more resources to such systems.

In conclusion, with its structured approach, the study provided insights into how the households perceived the energy crisis and how they saw the local thermal energy transition. While the recommendations are helpful for different stakeholders, it is crucial to keep in mind that this is one of the first attempts of its kind, and the results underscore the need for further consideration and investigation of the energy crisis and its influence on different actors, particularly households.

CRediT authorship contribution statement

Orestis Kiriakidis: Writing – review & editing, Software, Methodology, Investigation, Data curation. **Javanshir Fouladvand:** Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Okur Ozge:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the workshop's participants for their time and information. The author would also like to thank the Public Engagement Seed Fund of Utrecht University for their substantial support for this research. The authors would like to sincerely thank the Copernicus Institute of Sustainable Development support staff, specifically Harmina IJben-Wolters, Lisa Bettoni, Fanny Recher and Ilaria Flisi. In addition, the support of Ernest Worrell, Martin Junginger and Jesus Rosales Carreon for this study was highly appreciated.

Data availability

Data will be made available on request.

References

Aitken, C., Ersoy, E., 2022. War in Ukraine: The options for Europe's energy supply 887–896. https://doi.org/10.1111/twec.13354.

Ang, B.W., Choong, W.L., Ng, T.S., 2015b. A framework for evaluating Singapore's energy security. Appl. Energy 148, 314–325. https://doi.org/10.1016/j.apenergy.2015.03.088.

Ang, B.W., Choong, W.L., Ng, T.S., 2015a. Energy security: definitions, dimensions and indexes. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2014.10.064.

Azzuni, A., Breyer, C., 2018. Definitions and dimensions of energy security: a literature review. Wiley Interdiscip. Rev. Energy Environ. 7 (1), 1–34. https://doi.org/10.1002/wene.268.

Bagheri, M., et al., 2024. Reduction of gas demand through changes in heating behaviour in households: novel insights from modelling and empirical evidence. Energy Build. 318. https://doi.org/10.1016/j.enbuild.2024.114257.

J. Bartos and A. Robertson, "Energy Supply Security: Emergency Response of IEA Countries," *Int. Energy Agency*, p. 606, 2014, [Online]. Available: ⟨https://www.iea.org/publications/freepublications/publication/energy-supply-security-the-emergency-response-of-iea-countries-2014.html%5Cnhttps://www.iea.org/publications/freepublications/publication/ENERGYSUPPLYSECURITY2014.pdf⟩.

Beauchampet, I., Walsh, B., 2021. Energy citizenship in the Netherlands: the complexities of public engagement in a large-scale energy transition. Energy Res. Soc. Sci. 76, 102056. https://doi.org/10.1016/j.erss.2021.102056.

Belaïd, F., Al-Sarihi, A., Al-Mestneer, R., 2023. Balancing climate mitigation and energy security goals amid converging global energy crises: the role of green investments. Renew. Energy 205, 534–542. https://doi.org/10.1016/j.renene.2023.01.083.

E. Boyle, M. Galvin, A. Revez, A. Deane, O. Brian, and G. Mullally, Flexibility & structure: Community engagement on climate action & large infrastructure delivery, vol. 167, no. May, 2022, doi: 10.1016/j.enpol.2022.113050.

Brouwer, B., Van Bergem, R., Renes, S., Kamp, L.M., Hoppe, T., 2025. Does local ownership matter ? A comparative analysis of fourteen wind energy projects in the Netherlands. Energy Res. Soc. Sci. 120.

Brown, M.A., Wang, Y., Sovacool, B.K., D'Agostino, A.L., 2014. Forty years of energy security trends: a comparative assessment of 22 industrialized countries. Energy Res. Soc. Sci. 4, 64–77. https://doi.org/10.1016/j.erss.2014.08.008.

Cass, N., Büchs, M., Lucas, K., 2023. How are high-carbon lifestyles justified ? Exploring the discursive strategies of excess energy consumers in the United Kingdom. Energy Res. Soc. Sci. 97, 102951. https://doi.org/10.1016/j.erss.2023.102951.

Chester, L., 2010. Conceptualising energy security and making explicit its polysemic nature. Energy Policy. https://doi.org/10.1016/j.enpol.2009.10.039.

Conradie, P., et al., 2023. Why do people turn down the heat? Applying behavioural theories to assess reductions in space heating and energy consumption in Europe. Energy Res. Soc. Sci. 100, 103059. https://doi.org/10.1016/j.erss.2023.103059.

Copeland, C., Mackerron, G., Foxon, T.J., 2023. Futures for Findhorn: exploring challenges for achieving net zero in an ecological intentional community. Futures 149, 103155. https://doi.org/10.1016/j.futures.2023.103155.

Croon, T.M., et al., 2025. Energy coaching and 'fix team' retrofitting to mitigate energy poverty: an ex-post analysis of treatment and interaction effects. Energy Res. Soc. Sci. 119. https://doi.org/10.1016/j.erss.2024.103807.

De Jager, L., Doran, R., 2025. Expert and citizen perceptions of the drivers of the energy transition: a mental model approach. J. Clean. Prod. 494. https://doi.org/10.1016/j.jclepro.2025.144949.

De Winkel, E., Lukszo, Z., Neerincx, M., Dobbe, R., 2025. Adapting to limited grid capacity: perceptions of injustice emerging from grid congestion in the Netherlands. Energy Res. Soc. Sci. 122, 103962. https://doi.org/10.1016/j.erss.2025.103962.

Demski, C., et al., 2018. National context is a key determinant of energy security concerns across Europe. Nat. Energy 3. https://doi.org/10.1038/s41560-018-0235-8.

Dumitru, R., Dumitru, M., 2023. Energy Security in the Context of European.
ECN, "Nationale Energieverkenning 2015," Ecn-O–14-036, pp. 1–276, 2015, [Online]. Available: ⟨http://www.cbs.nl/NR/rdonlyres/C0F1D74C-1EB1-4E3B-9A46-ECA28ABFED7E/0/2015nationaleenergieverkenning.pdf⟩.
Egbue, O., Long, S., 2012. Barriers to widespread adoption of electric vehicles: an analysis of consumer attitudes and perceptions. Energy Policy 48, 717–729. https://doi.org/10.1016/j.enpol.2012.06.009.
Erahman, Q.F., Purwanto, W.W., Sudibandriyo, M., Hidayatno, A., 2016. An assessment of Indonesia's energy security index and comparison with seventy countries. Energy 111, 364–376. https://doi.org/10.1016/j.energy.2016.05.100.
Escribano Francés, G., Marín-Quemada, J.M., San Martín González, E., 2013. RES and risk: Renewable energy's contribution to energy security. A portfolio-based approach. Renew. Sustain. Energy Rev. 26, 549–559. https://doi.org/10.1016/j.rser.2013.06.015.
European comm, "From where do we import energy?" [Online]. Available: ⟨https://ec.europa.eu/eurostat/cache/infographs/energy_2021/bloc-2c.html?lang=en#:~:text=As⟩ mentioned in the part,crude oil and natural gas.(n.d.).
Eurostat, "Natural gas price statistics." [Online]. Available: ⟨https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics⟩ (n.d.).
Faiers, A., Cook, M., Neame, C., 2007. Towards a contemporary approach for understanding consumer behaviour in the context of domestic energy use. Energy Policy 35 (8), 4381–4390. https://doi.org/10.1016/j.enpol.2007.01.003.
Fouladvand, J., 2022. Behavioural attributes towards collective energy security in thermal energy communities: environmental-friendly behaviour matters. Energy 261, 125353. https://doi.org/10.1016/j.energy.2022.125353.
Fouladvand, J., 2023. Thermal energy communities: what, why and how to formulate complex collective action for the thermal energy transition in Europe. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/acdd14.
Fouladvand, J., 2024. Why and how can agent-based modelling be applied to community energy systems? A systematic and critical review. Energy Res. Soc. Sci. 114, 103572. https://doi.org/10.1016/j.erss.2024.103572.
Fouladvand J., *Evolution of Agent-Based Modelling and Simulation for Studying Community Energy Systems: The Case of Collective*. Springer Nature Switzerland. doi: 10.1007/978-3-031-91782-0.(n.d.).
Fouladvand, J., Fiori, F., 2024. Perception towards reducing natural gas consumption and imports in Europe: a theoretical and empirical investigation. Heliyon 10. https://doi.org/10.1016/j.heliyon.2024.e30719.
Fouladvand, J., Ghorbani, A., Sarı, Y., Hoppe, T., Kunneke, R., 2022d. Energy security in community energy systems: an agent-based modelling approach. J. Clean. Prod. 366, 132765. https://doi.org/10.1016/j.jclepro.2022.132765.
Fouladvand, J., Ghorbani, A., Mouter, N., Herder, P., 2022a. Analysing community-based initiatives for heating and cooling: a systematic and critical review. Energy Res. Soc. Sci. 88, 102507. https://doi.org/10.1016/j.erss.2022.102507.
Fouladvand, J., Aranguren, M., Hoppe, T., Ghorbani, A., 2022b. Simulating thermal energy community formation: institutional enablers outplaying technological choice. Appl. Energy 306, 117897. https://doi.org/10.1016/j.apenergy.2021.117897.
Fouladvand, J., Verkerk, D., Nikolic, I., Ghorbani, A., 2022c. Modelling Energy Security: The Case of Dutch Urban Energy Communities, no. Cml. Springer International Publishing. https://doi.org/10.1007/978-3-030-92843-8_30.
Fouladvand, J., Ateş, E., Sarı, Y., Okur, Ö., 2024a. Does the availability of alternative energy choices lead to more environmentally friendly outcomes? The case of thermal energy communities and natural gas consumption. Appl. Energy 374. https://doi.org/10.1016/j.apenergy.2024.123932.
Fouladvand, J., Sarı, Y., Ghorbani, A., 2024b. Infrastructure and governance: prioritising energy security dimensions for community energy systems. Energy Res. Soc. Sci. 116, 103676. https://doi.org/10.1016/j.erss.2024.103676.
Frankowski, J., Prusak, A., Sokołowski, J., Mazurkiewicz, J., Świetlik, T., 2025. Energy commons during crisis: understanding housing cooperative strategies through dramaturgical sociology. Int. J. Commons 19 (1), 278–292. https://doi.org/10.5334/ijc.1476.
Ghorbani, A., Nascimento, L., Filatova, T., 2020. Growing community energy initiatives from the bottom up: simulating the role of behavioural attitudes and leadership in the Netherlands. Energy Res. Soc. Sci. 70, 101782. https://doi.org/10.1016/j.erss.2020.101782.
J. Greenleaf *et al.*, "Analysis of impacts of climate change policies on energy security," p. 352, 2009, [Online]. Available: ⟨http://ec.europa.eu/environment/integration/energy/pdf/cces.pdf⟩.
Hesselink, L.X.W., Chappin, E.J.L., 2019. Adoption of energy efficient technologies by households – Barriers, policies and agent-based modelling studies. Renew. Sustain. Energy Rev. 99, 29–41. https://doi.org/10.1016/j.rser.2018.09.031.
B.P. Koirala, E. Koliou, J. Friege, R.A. Hakvoort, and P.M. Herder, "Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems," 2016. doi: 10.1016/j.rser.2015.11.080.
Kruyt, B., van Vuuren, D.P., de Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy. https://doi.org/10.1016/j.enpol.2009.02.006.
Majcen, D., Itard, L.C.M., Visscher, H., 2013. Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: discrepancies and policy implications. Energy Policy 54, 125–136. https://doi.org/10.1016/j.enpol.2012.11.008.
Matschoss, K., Laakso, S., Rinkinen, J., 2025. Disruptions and energy demand: How Finnish households responded to the energy crisis of 2022. Energy Res. Soc. Sci. 121, 103977. https://doi.org/10.1016/j.erss.2025.103977.
Moskalenko, N., Löffler, K., Hainsch, K., Hanto, J., 2024. Europe's independence from Russian natural gas — effects of import restrictions on energy system development. Energy Rep. 11, 2853–2866. https://doi.org/10.1016/j.egyr.2024.02.035.
Narjabadifam, N., Fouladvand, J., Gül, M., 2023. Critical review on community-shared solar—advantages, challenges, and future directions. Energies 16 (8). https://doi.org/10.3390/en16083412.
Okur, Ö., Fiori, F., Fouladvand, J., 2024. Adoption of renewable heating systems and thermal energy communities in the Netherlands: an empirical study. Energy Rep. 11, 3815–3823. https://doi.org/10.1016/j.egyr.2024.03.036.
Pollitt, M.G., 2024. Energy markets under stress: some reflections on lessons from the 2021–2023 energy price crisis in Europe. Econ. Energy Environ. Policy 13 (2), 83–102. https://doi.org/10.5547/01956574.45.4.mpol.
Pollitt, M.G., von der Fehr, N.H.M., Willems, B., Banet, C., Le Coq, C., Chyong, C.K., 2024. Recommendations for a future-proof electricity market design in Europe in light of the 2021-23 energy crisis. Energy Policy 188. https://doi.org/10.1016/j.enpol.2024.114051.
Pye, S., et al., 2025. The global implications of a Russian gas pivot to Asia. Nat. Commun. 16 (1), 1–11. https://doi.org/10.1038/s41467-024-55697-7.
Reichl, J., Schmidthaler, M., Schneider, F., 2013. The value of supply security: the costs of power outages to Austrian households, firms and the public sector ☆. Energy Econ. 36, 256–261. https://doi.org/10.1016/j.eneco.2012.08.044.
Security, E., 2017. The Transformation of ASEAN 2.
Smith, H., Henwood, K., Pidgeon, N., 2025. The infrastructural ecologies of industrial decarbonisation: Visual methods and psychosocial logics in place-based public engagement. Energy Res. Soc. Sci. 120, 103874. https://doi.org/10.1016/j.erss.2024.103874.
Sovacool, B.K., 2010. Introduction: Defining, measuring, and exploring energy security. The Routledge handbook of energy security. Routledge, pp. 19–60.
Sovacool, B.K., Brown, M.A., 2010. Competing dimensions of energy security: an international perspective. Annu. Rev. Environ. Resour. 35. https://doi.org/10.1146/annurev-environ-042509-143035.
Stempien, J.P., Chan, S.H., 2017. Addressing energy trilemma via the modified Markowitz Mean-Variance Portfolio Optimization theory. Appl. Energy 202, 228–237. https://doi.org/10.1016/j.apenergy.2017.05.145.
Tongsopit, S., Kittner, N., Chang, Y., Aksornkij, A., Wangjiraniran, W., 2016. Energy security in ASEAN: a quantitative approach for sustainable energy policy. Energy Policy. https://doi.org/10.1016/j.enpol.2015.11.019.
Urbano, E.M., Kampouropoulos, K., Romeral, L., 2023. Energy crisis in Europe: the European Union's objectives and countries' policy trends—new transition paths? Energies 16 (16). https://doi.org/10.3390/en16165957.
Vasseur, V., Backhaus, J., 2024. The influence of disruptive events on energy-related household practices: results of a longitudinal study in the Netherlands. Environ. Innov. Soc. Transit. 53. https://doi.org/10.1016/j.eist.2024.100920.
Vitéz, B., Lavrijssen, S., 2020. The energy transition: democracy, justice and good regulation of the heat market. Energies 13 (5). https://doi.org/10.3390/en13051088.
Wang, Z., Perera, A.T.D., 2019. Robust optimization of power grid with distributed generation and improved reliability. Energy Procedia 159, 400–405. https://doi.org/10.1016/j.egypro.2018.12.069.
WEC, "World Energy Trilemma Index | 2017," p. 145, 2017, [Online]. Available: ⟨https://www.worldenergy.org/wp-content/uploads/2017/11/Energy-Trilemma-Index-2017_Executive-Summary_WEB.pdf%0Ahttps://www.worldenergy.org/wp-content/uploads/2017/11/Energy-Trilemma-Index-2017-Report.pdf⟩.
Wejnert-depue, C., Zhang, Y., Casper, K., Neill, B.C.O., Waldhoff, S.T., 2025. A conceptual framework for residential energy security in the context of clean energy transitions. Energy Res. Soc. Sci. 126, 104096. https://doi.org/10.1016/j.erss.2025.104096.
deWildt, T.E., Chappin, E.J.L., van de Kaa, G., Herder, P.M., van de Poel, I.R., 2020. Conflicted by decarbonisation: five types of conflict at the nexus of capabilities and decentralised energy systems identified with an agent-based model. Energy Res. Soc. Sci. 64, 101451. https://doi.org/10.1016/j.erss.2020.101451.
Wise, F., Gillich, A., Palmer, P., 2025. Retrofit information challenges and potential solutions: perspectives of households, retrofit professionals and local policy makers in the United Kingdom. Energy Res. Soc. Sci. 119, 103866. https://doi.org/10.1016/j.erss.2024.103866.
Yang, D., et al., 2024. Optimised operation of integrated community energy system considering integrated energy pricing strategy: a two-layer Stackelberg game approach. J. Energy Storage 87, 111383. https://doi.org/10.1016/j.est.2024.111383.