Energy Reports 10 (2023) 4641–4650

Contents lists available at ScienceDirect

Energy Reports

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

Integrated energy planning approach for accelerating energy transition of households

B. Pavlović [*], M. Živković, D. Ivezić

University of Belgrade, Faculty of Mining and Geology, Belgrade, Serbia

A R T I C L E I N F O

Keywords:
Energy planning
Integrated energy modeling
Energy transition
Households
Individual heating
LEAP

A B S T R A C T

The success of energy transition planning depends on several influential and variable factors that need to be considered and tracked in modeling to support policymakers. Expert-based energy models are mainly developed following the assumptions of experts and, in most cases, a limited number of stakeholders. This top-down modeling approach will provide satisfactory results in centrally managed energy sectors (electricity generation and distribution, district heating, etc.), where further decisions could be projected relatively precisely. However, the same approach will not provide such certain outcomes in energy sectors where numerous heterogeneous individuals make decisions about the energy future. Households are a typical example of such a sector. The future structure of energy consumption in this sector, selection of energy source, or application of specific technology, especially in households with individual heating systems, introduce significant uncertainty in expert-based energy modeling and the creation of policy. Besides prices, the decisions of households are influenced by their attitudes, social environment, and incentive measures, etc. The influence of these factors on the adoption of sustainable heating by households can be examined using a bottom-up modeling approach, like the agent-based simulation model. The output of the agent-based simulation model provides useful data that can be further incorporated as one of the main assumptions in scenario development in an expert-based energy model. This paper offers an integration of these two approaches (bottom-up and top-down) for the early assessment of supporting measures and mechanisms for accelerating the energy transition in the household sector. The integrated approach is applied and tested for exploring pathways and effects of policy measures on the transition of individual heating in the household sector in Serbia.

1. Introduction

The idea of a comprehensive, global energy transition of human civilization is a novelty of the 21st century (Smil, 2010; Smil, 2010). This idea has been consolidated through international conferences and agreements concerning the reduction of the anthropogenic impact of climate change and the transition towards low-carbon energy (UN Framework Convention on Climate Change (UN, 1994; UN, 1994), the Kyoto Protocol (UN, 1997; UN, 1997), the Paris Agreement on Climate Change in 2015 (UN, 2015; UN, 2015), the European Green Deal (EC, 2019; EC, 2019), etc.).

In terms of scope and dynamics, the current transition cannot be seen solely as a spontaneous process (Gielen et al., 2019; Gielen et al., 2019) of technological changes inspired by innovations in renewable energy technologies and the competitive nature of a commercial environment (Rubino et al., 2021; Rubino et al., 2021). It is a process that is also influenced by the international political framework, the state of the economy, rising concerns about climate change, and the aim for wider utilization of clean energies (Olave and Vargas-Payera, 2020; Olave and Vargas-Payera, 2020). The complexity of the process of current energy transition creates a need for a comprehensive approach to the energy planning process as an adequate response for treating complex phenomena (Felder et al., 2011; Felder et al., 2011).

With the help of planning, it is possible to assess future outcomes of various activities that are anticipated in the planning process (Valkenburg and Gracceva, 2016; Valkenburg and Gracceva, 2016). In this way, the risk of future uncertainties and ambiguities can be diminished or minimized (Hobbs and Meier, 2000; Hobbs and Meier, 2000). As noticed in (McGookin et al., 2021; McGookin et al., 2021), in recent years the focus of energy system modeling and planning is on assessing the social, economic, environmental, political, and technological feasibility of energy transition. This is primarily due to the need to build consensus on

* Corresponding author.
E-mail address: boban.pavlovic@rgf.bg.ac.rs (B. Pavlović).

https://doi.org/10.1016/j.egyr.2023.11.016
Received 8 February 2023; Received in revised form 25 October 2023; Accepted 9 November 2023
Available online 18 November 2023

the widely accepted and sustainable path forward.

Energy modeling for supporting the energy planning process aims to develop projections of future energy demand, the structure of energy consumption by fuel and by activity, the structure of energy transformation processes, and environmental impact, etc. These projections are most often based on historical trends, energy balances, expert assessments, or based on statistical methods and forecasts of prices of energy sources and technologies (IEA, 2023; IEA, 2023), (IRENA, 2018; IRENA, 2018; Tang et al., 2019; Tang et al., 2019). Such approaches mostly meet the needs of centrally managed energy sectors and sub-sectors, such as the sector of electricity production, district heating, various branches of industry, etc., characterized by a limited number of decision-makers. However, when it comes to projections of the household sector, especially individual heating in households, in which consumption is fragmented among individual households, and the structure of consumption is heterogeneous, outcomes of such approaches are followed by some uncertainties during the scenario development process, which reflects on some uncertainty of the results. To obtain more accurate outcomes from energy models, it is necessary to include, as much as possible, factors that influence decisions at the micro-level, which are usually neglected in classic top-down expert approaches for supporting decision-makers and policymakers. As Waisman et al. (2019) noted, to define a long-term decarbonization plan and to secure its implementation the plan "must be sufficiently understood and accepted by a majority of stakeholders, both those responsible for implementation and those affected by the transformation".

Regardless of heterogeneity, fragmentation, and stochasticity, the household sector is particularly interesting and important because it provides opportunities for significant improvement of energy efficiency and reduction of greenhouse gas (GHG) emissions (Johannsen et al., 2021; Johannsen et al., 2021). For example, the share of the household sector in the total final energy consumption in the European Union (EU) is slightly more than 1/4 (about 26%), while the largest share of the energy consumed in households (about 63.6%) is used for space heating (8). District heating systems (DHS) operate in 23 EU member states, and on average, about 24.5% of residential space is heated by DHS, which means that the dominant type of heating in the EU is based on individual systems (75.5%) (Sayegh et al., 2018; Sayegh et al., 2018). This distribution of household heating within the household sector underscores its reliance on the choices made by numerous individuals. Moreover, it underscores the challenges in developing an integrated long-term energy model for household heating due to its inherent complexity, necessitating extensive databases for a thorough consideration of individual household-level aspects (Mirakyan and De Guio, 2013; Mirakyan and De Guio, 2013).

The objective of this paper is to propose a new approach for modeling energy transition in the household sector, with an attempt to provide a broader framework and environment for planning and analysis, which would consider not only technical but also social, political, and economic aspects of the energy transition in such a large and heterogeneous population as households. The proposed methodology integrates a top-down approach based on experts' projections, official statistics, and strategic documents with a bottom-up approach based on the agent-based simulation model of household behavior related to space heating. The basic hypothesis is that by integrating the bottom-up approach and top-down expert modeling, the comparative advantages of both approaches can be utilized more effectively. By using an agent-based modeling (ABM) methodology, modeling of individual consumers and simulation of the influence of the social community, the long-term dynamics of the adoption of modern technologies and other aspects related to this field can be provided at an acceptable level of abstraction. By integrating ABM with classical tools for energy modeling, it is possible to expand the analysis by including aspects that do not depend only on household decisions yet have an impact on the energy transition in households and on the entire energy system, such as policy measures in other energy sectors, climate policy, energy efficiency policy, demographic trends, etc.

The proposed approach allows a comprehensive analysis of various aspects of decision-making at the household level, as well as aspects from a hierarchically higher level, i.e., the socio-political context in which the energy policy should be implemented. The results of the application of such an integrated approach are in the form of projections of energy demands and GHG emissions from individual heating. The main role of the proposed approach might be an early assessment of the effects of supporting measures and mechanisms for accelerating the energy transition of a large number of small-scale energy consumers, such as households with individual heating systems.

Furthermore, this research involves long-term energy planning within the household sector, which has significant implications for sustainability, particularly in terms of environmental, economic, and social dimensions. The research combines technical engineering viewpoints with social research aspects. This interdisciplinary approach aims to explore the intersection of technology and social factors in sustainable energy development. By doing so, the proposed integrative approach facilitates communication and knowledge exchange among experts (Lund and Mathiesen, 2009), end-consumers (households), and policymakers.

2. Materials and methods

One of the theoretical approaches to energy transition is the so-called multi-level perspective (MLP) (Hansen et al., 2019; Hansen et al., 2019). The specificity of the MLP approach is that it shapes the energy system into a multi-level hierarchy, in which the political environment (macro-level), social dynamics and its actors (meso-level), and technological innovations (micro-level) are in interaction. The conceptualization of the energy system according to the MLP is shown in Fig. 1. Favorable development of events on all three levels leads to a successful energy transition, that is, structural changes that enable elements of each level to interact with each other. The adoption of technological innovations and changes in the way energy is used by consumers is the key to energy transition. To ensure a high level of adoption of technological innovations, simultaneous changes in the socio-technical aspects that involve different actors and require the active role of the community as a whole are inevitable.

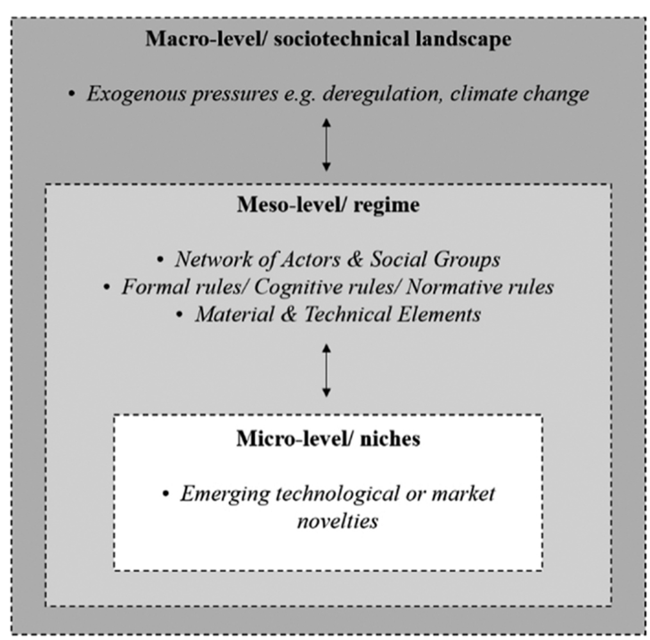

Fig. 1. The multi-level perspective of energy transition (Hansen et al., 2019; Hansen et al., 2019).

Securing more comprehensive planning of the energy transition, which would include macro-, meso-, and micro-levels, emphases a need to analyze energy policy and instruments by using several different methods and modeling approaches (Cajot et al., 2017; Cajot et al., 2017). The combination of several methods should result in a reduction of uncertainty in the projection of energy demand, GHG emissions, and extended quantitative and qualitative assessment of energy transition support instruments.

The integration of different aspects and influential factors on energy transition into a single energy planning approach is often the case in current practice for modeling energy systems and energy sectors, at the national, even regional, and global levels (Dioha and Kumar, 2020; Dioha and Kumar, 2020). Regarding the specific domain of household sector energy modeling, it is evident from relevant literature that there is a growing trend to merge diverse approaches, a response to the sector's inherent complexity. In the approach for modeling energy consumption and household behavior, proposed by Tian et al. (2021), an ABM approach is combined with a deep learning method in simulating household energy consumption. The main objective is to deeply understand and guide the energy transition of households. A series of scenarios were simulated based on actual survey samples (Tian et al., 2021; Tian et al., 2021). For the analysis of energy consumption in urban areas and the implications for air pollution, Csutora et al. (2021) proposed an approach that integrates qualitative and quantitative research methods. The objective was to investigate energy consumption patterns and household behavior. This approach includes household surveys to obtain empirical data, as well as expert assessments and focus group involvement for a narrative description of the research subject. Živković et al. (2016) proposed an approach for the analysis of urban heating scenarios and future development alternatives based on the methodology known as "Participatory Backcasting" in order to involve stakeholders in the joint formulation of future vision and goals and knowledge exchange. This methodology is integrated with energy planning in the LEAP (Low Emissions Analysis Platform) tool. Wang et al. (2015) introduced a field measurement and survey for computing occupant behavior. By using a bottom-up model, energy consumption in the household was simulated and processed at the individual household level and subsequently aggregated at the geographic level (Wang et al., 2015; Wang et al., 2015).

Examples from the literature argue for the presence of integrated methodological approaches in the field of energy planning and modeling of energy transition in the household sector. Compared to the analyzed approaches from the literature, the basic conceptual difference of the proposed approach in this paper is the tendency to include, in addition to technological and social system components, the macro-level component (governance structures) in the methodology and to connect all three (components) levels to each other. The advantages of integration could be reflected first of all, in a more detailed analysis of the research subject, model upgrading, model calibration, and merging of different databases. Other specifics of the proposed approach are explained below.

2.1. Methodological framework

A novel approach for long-term energy planning in the household sector is proposed (Fig. 2). The primary purpose of the new approach is to support the process of energy planning by assessing the potential policy instruments in the phases of their formulating, selecting, and managing. An integrative approach should guide and improve the entire planning process in such a way that it will indicate through the methodology whether, and if so, to what extent, a revision of the original policy is needed before implementation of the policy in the real system. The proposed approach enables new tests and updates because it should be taken into account that the input parameters to the models will change over time due to their stochastic nature. The basic elements of the new approach are two developed individual stand-alone models (ABM model of individual household heating and expert-based model) that are coupled together in an iterative manner where outputs of one phase are used as inputs for the other phase of modeling (Fattahi et al., 2020; Fattahi et al., 2020).

ABM model of household heating is created based on the conducted survey to describe households' behavior and response to different policy instruments related to the price of heating technologies and energy sources, subsidies/restrictions for the application of specific technologies, promotion of different energy efficiency measures, etc. This analysis of micro-level behavior and responses is introduced in an expert-based model to show their effects on a macro level. In the complex decision-making process, this macro-level analysis is used for the assessment and modification of policy instruments. In this way, this approach integrates current household heating structure, attitudes, and perceptions of consumers (obtained from the household survey) (Pavlović et al., 2021; Pavlović et al., 2021), agent-based simulation of energy-related behavior of each household, and energy statistics, balances, experts' knowledge, and energy policies (macro level components).

The lack of information on households' attitudes, long-term plans for investments, willingness to pay more for climate-friendly heating systems, level of satisfaction with current heating systems, reactions to

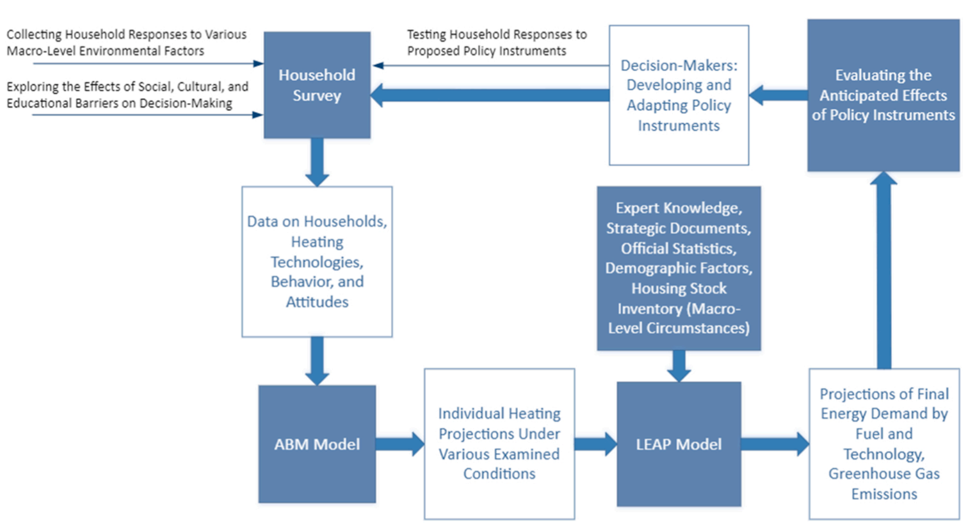

Fig. 2. Methodological framework.

potential restrictions or incentives in the future, perceptions of climate changes, etc., will greatly influence the future energy transition pathways. To formulate the proper policy measures for supporting energy transition, it is important to incorporate such data into the energy planning process. At this stage, a household survey may serve as a useful method for collecting empirical data. Surveys have been found to be valuable tools for collecting information regarding issues related to the energy transition in the household sector (Hu et al., 2017). The primary requirement for surveys is to ensure their representativeness concerning the entire surveyed population. In this particular survey, a conservative margin of error of 3% and a 95% confidence interval have been adopted (Pavlović et al., 2021). Based on these parameters, a sample of 1100 households was determined.

To create autonomous entities (households) that will have specific attributes based on empirical data from the household survey and to simulate households' heating-related behavior over a certain time frame, the ABM method appears as a practical and often-used approach (Hansen et al., 2019; Hansen et al., 2019). The ABM model uses computer simulation techniques to specify how households will act in certain situations. In this modeling approach, each household assesses its own situation and decides on future heating. Randomness at the individual level results in behavioral patterns that can be observed at the level of the entire population (Wilensky and Rand, 2015; Wilensky and Rand, 2015).

Using agent-based modeling to develop a simulation model for the transition in household heating is a suitable approach, due to the advantages that simulation models offer in facilitating long-term decision-making processes. These models provide citizens and policymakers with various potential choices, even if they may not all align with economic optimality based on current knowledge (Lund et al., 2017). Simulation models are fast, detailed, and well-suited for comparing future scenarios, making them valuable for discussions and planning for the desired future.

The projection of individual heating devices structure in households is often the hardest to provide when creating long-term energy models of the household sector. Using the household survey and ABM method, projections of the future structure of individual heating in households are obtained independently from individual expert assumptions or historical trends. Instead of predicting the rate of growth of certain technologies or the rate of decline in the use of outdated technologies, the dynamics and extent of changes in the observed period were tracked, based on the ABM simulation, free of any top-down assumptions. Also, projections of the structure of the heating devices in households relying exclusively on the projection of prices of devices and fuels was avoided since the ABM model takes into account other factors that influence the individual heating at the household level (such as willingness to pay more for sustainable heating, willingness to take government subsidies, physical and technical conditions, "neighboring effect", etc.) (Pavlović et al., 2022).

This comparative advantage of the proposed approach (Fig. 2) is that bottom-up modeling of the household energy transition can be further qualitatively and quantitatively upgraded through integration with expert-based modeling in the LEAP tool. This creates an environment for the integration of experts' knowledge, official statistics, energy studies, macroeconomic components, demographic trends, housing stock inventory and trends, etc., with results from the ABM model (Hainsch et al., 2022; Hainsch et al., 2022;Waisman et al., 2019; Waisman et al., 2019).

These complementary models are used in tandem, involving the pairing of top-down and bottom-up energy system modeling, in order to exploit their capabilities and potential for more nuanced insights into the consequences of household heating technology choices and to obtain a more flexible methodological framework for managing input and output parameters (Chang et al., 2021).

Bearing in mind that the methodological framework is tailored to investigate the demand side within the household sector rather than focusing on optimizing the energy supply side (Lund et al., 2021), the LEAP tool was chosen because it is recognized as suitable for comprehensive, policy-oriented energy planning and analysis. As such, it serves as a valuable resource for shaping long-term scenarios in the context of household heating transition by 2050. By focusing on the demand side and examining household heating technology choices, the approach contributes to the identification of more energy-efficient and environmentally friendly solutions, thereby supporting the Green Deal's objective of enhancing energy efficiency through reduced energy consumption. Furthermore, the methodological framework's emphasis on long-term planning and scenario analysis facilitates the development of sustainable energy policies that align with the Green Deal's commitment to sustainability (EC, 2019).

2.1.1. ABM phase

ABM is a relatively new approach to energy modeling and simulation. It offers an environment to model the dynamics of complex systems and complex adaptive systems composed of autonomous, interacting agents (Macal and North, 2010; Macal and North, 2010). ABM is especially applicable in cases where the object of modeling is a decentralized system or entity, heterogeneous in its characteristics, needs, purchasing power, and other objective influential factors. Agent-based bottom-up models are characterized by a high level of technical detail, so they can store and process large input databases (Truong et al., 2016; Truong et al., 2016).

Development of an ABM model inevitably means identifying and highlighting certain parts of reality to focus on the most important aspects in relation to one's specific purpose. In the case of modeling transition in household heating, numerous aspects of individual heating need to be identified and included. Table 1 shows the main inputs and data sources for the ABM model that are relevant for the simulation of energy transitions in individual heating.

As it is predefined in the ABM simulation model (Pavlović et al., 2022; Pavlović et al., 2022), a household makes a decision based on the maximum utility of its choice. That basically means that the household will choose a heating system from the set of available alternatives that has the highest utility function $u(A_i)$. Each of the alternatives is multidimensional and depends on several variables A_i = (energy demand, heating system price, heating system efficiency, fuel price, household's (un)willingness to pay more for sustainable heating, household's (un) willingness to take subsidies, and influence of social interactions) (For details, please see (Pavlović et al., 2022; Pavlović et al., 2022)).

The ABM phase of the proposed integrated approach should answer the question: "What will the energy transition pathway look like in the household heating sector by 2050?". The main output of this simulation model is household structure by mode of heating for different types of settlements in the next 30 years, starting from 2020.

Table 1
Description of the input parameters for the ABM model (Pavlović et al., 2022; Pavlović et al., 2022).

Input parameters	Description
Characteristics of agents	1. Type of settlement (urban/rural) 2. Heating space area (m^2) 3. Energy source 4. Heating system type 5. Heating system efficiency 6. Heating system age 7. Fuel consumption 8. Willingness to pay more 9. Unwillingness to change the current heating system 10. Willingness to take a subsidy
Characteristics of environment	1. Heating system prices 2. Fuel prices 3. Regulatory instruments 4. Social network / Neighborhood

2.1.2. Expert-based - LEAP phase

A particular challenge for planning the energy transition in the household sector is the estimation of energy demand and dynamics of individual choices on switching current heating systems over the next 30 years and local specifics related to energy policy, economic, demographic trends, residential construction trends, rates of energy rehabilitation of residential houses, technological development, and environmental issues (Johannsen et al., 2021; Johannsen et al., 2021).

As shown in Fig. 2, the energy modeling of the transition in household heating is performed in the LEAP tool after conducting a simulation in the ABM model. The LEAP tool enables energy modeling of different complexity and can be adapted to the extent of available data (Heaps, 2022; Heaps, 2022). In this particular case, LEAP was chosen for energy modeling of energy transition in individual heating in households for several reasons. This software tool is free to use for educational purposes, with registration. The most common application of LEAP is for case studies in time intervals of 20–50 years, and the tool itself is flexible, as it allows the creation of models based on various datasets with different structures of available data, evaluate alternative scenarios, and compares them by energy intensity, emissions, or other selected indicators (SEI, 2017; SEI, 2017).

Another advantage of LEAP is the low level of initial data requirements. Many energy modeling tools rely on very specific and often complex algorithms and therefore tend to be inflexible. Data development for such models requires a relatively high level of expertise and strong support of official statistics. In contrast, many aspects of modeling in LEAP are optional, thus the initial data requirements can be much lower and based on relatively simple statistical data processing and computational operations (Heaps, 2022; Heaps, 2022).

Energy demand calculations are most often carried out on an annual basis, which is suitable from the aspect of the transformation of the household structure by mode of heating, which in the ABM model is monitored seasonally by year (from 2020 to 2050). An additional advantage of the integration of the ABM model and the LEAP model is in the simple procedure of data import, bearing in mind that NetLogo, which was used for simulations, offers the possibility of exporting data to "XLS/XLSX" files, and the LEAP tool enables the import of these very files.

For the development of a long-term projection of energy demand for individual heating in the household sector, time-series of the structure of household by mode of heating (type of device/technology) and by fuel were obtained from the ABM and served as one of the main inputs for energy model development. Experts' knowledge was incorporated in the stage of development of specific assumptions, such as the development of the electricity generation sector, projection of future residential heating areas, demographic trends, the energy efficiency of various heating systems, and calibration of energy consumption for heating in households with individual heating devices. Table 2 shows the input data required in the energy modeling phase in LEAP.

Development of the model in the LEAP tool, as presented in the proposed approach (Fig. 2), provides the environment for analysis of different paths of the energy transition, their visualization, and mutual comparison according to the projected energy demand and resulting GHG emissions. The household sector, which is the subject of research, is now viewed in the broader context of the development of the entire energy system.

Table 2
Inputs for energy model.

Input parameters
Share of households by heating system technology and by fuel
Number of households
Distribution of households in urban and rural areas
Average residential heating area and future growth trend
Useful energy consumption by household (kWh/m^2 per year)
Efficiency of heating systems
GHG emissions from all types of fuel

3. Application of the integrative approach

3.1. Household heating in Serbia – Case study

The final energy consumption in Serbia in 2020 was 8.66 Mtoe (million tons of oil equivalent). The household sector had the largest share with a consumption of 3.49 Mtoe, which was about 40% of the total final energy consumption in the country (Eurostat, 2023; Eurostat, 2023). In the period from 2015 to 2019, that share amounted to 34–36%, which certainly makes the household sector one with the highest consumption in Serbia (Eurostat, 2023; Eurostat, 2023).

In the household sector in Serbia, the major share of final energy is used for space heating - about 66% (Eurostat, 2022) (Eurostat, 2022), while the rest is mainly used for preparing domestic hot water (12%), cooking (about 7%), and lighting and consumption of electrical appliances (about 14%) (Eurostat, 2022). Around 75% of households are heated by individual heating devices, approximately 1851,000 households (Pavlović et al., 2021; Pavlović et al., 2021). The rest of the households are heated via district heating systems. According to the historical trend, each year 0.4% of households in urban areas switched to the district heating system (DHBA, 2020; DHBA, 2020). Since the existing district heating network covers all cities and densely populated municipalities, experts do not foresee any significant expansion of existing district heating systems in the country (Jovanović et al., 2019; Jovanović et al., 2019).

In order to calibrate the energy model in LEAP, the final energy consumption for individual heating in households in Serbia for the base year (2020) was obtained as follows:

$$E_{IH} = E_T \times S_H - E_{DH} \quad (1)$$

where:

E_{IH} - Annual energy consumption for heating in households with individual heating systems (ktoe);.

E_T -Final energy consumption in the household sector for 2020 (3488.1 kten) (Eurostat, 2023; Eurostat, 2023);.

S_H -The share of final energy used for heating in households (66,3%) (Eurostat, 2022; Eurostat, 2022);.

E_{DH} -Energy consumption for heating in households supplied from district heating systems (436 kten) (SORS, 2022a; SORS, 2022a).

It follows that energy consumption for heating in households with individual heating in Serbia for the base year was:

$$E_{IH} = 1876{\cdot}6 \text{ kten} \quad (2)$$

The distribution of households by type of settlement and the average size of the heating area is shown in Table 3. Based on the growth trend of the number of apartments from 1971 to 2011 (SORS, 2022b; SORS, 2022b), an annual growth of the heating surface of 0.5% was determined and included in assumptions in the scenario development process in the LEAP tool.

The current structure of households with individual heating by energy sources that are dominantly used for heating is shown in Fig. 3. As can be noticed, the most used energy source is firewood, which is used in about 58% of households with individual heating, followed by electricity with around 16%, natural gas (around 12%), wood pellet (around

Table 3
Data for the type of settlement and heating area in the Serbian household sector (SORS, 2021; SORS, 2021; Pavlović et al., 2021; Pavlović et al., 2021; SORS, 2022b; SORS, 2022b).

Type of settlement	Households by the type of settlement (%)	Households by the average heating area (m^2)
Urban	58%	68,6 m^2
Rural	42%	74,9 m^2

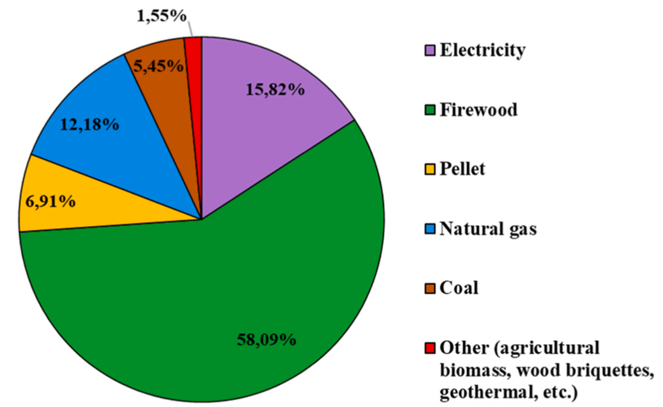

Fig. 3. Structure of households with individual heating by energy sources (Pavlović et al., 2021; Pavlović et al., 2021).

7%), coal (around 5.5%), and other energy sources (around 1.5%).

The structure of households by heating devices is shown in Fig. 4. By the configuration, almost 62% of households have local heating devices, mainly furnaces based on solid fuels (around 46%) and local electric space heaters (around 12,5%). This means that in the case of local heating devices, the dominant energy sources are firewood (71%) and electricity (20.15%). In the case of central heating configurations, firewood (37.14%), natural gas (25.24%), and pellets (15.71%) are the most used fuels. As can be seen from Fig. 5, the use of electricity for heating is characterized by outdated heating technologies, mainly local electric heaters, and boilers. The important parameter that should be considered when electricity-based systems are analyzed in Serbia is the structure of the national electricity generation mix, which is predominantly based on lignite, so electric heating cannot be considered acceptable or favorable from the aspect of GHG emissions and air pollution.

Based on the classification of households according to heating area (up to 50 m^2, up to 100 m^2, over 100 m^2) and the physical and technical conditions of households (settlement type, housing type), the ABM simulation model envisaged possible heating options that each individual household could choose. Table 4 provides an overview of heating technologies, i.e., heating systems and their efficiency, considered in the ABM simulation and later in energy modeling in LEAP (for more details, please refer to Pavlović et al., 2022).

For assessment of the effects of various policy measures, the GHG

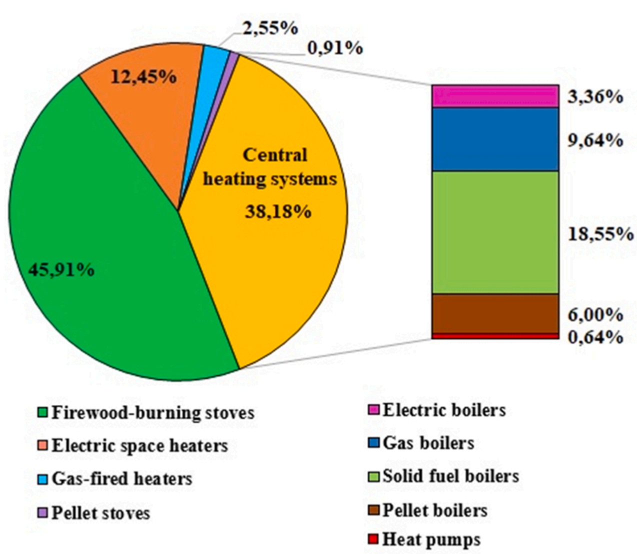

Fig. 4. Structure of households by type of individual heating device (Pavlović et al., 2021; Pavlović et al., 2021).

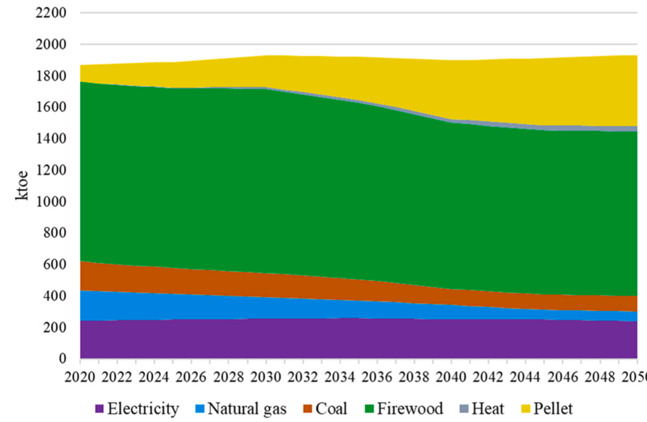

Fig. 5. Energy demand for heating and structure by fuel according to S1.

emissions from households with individual heating systems are calculated in the LEAP model. Global Warming Potential (GWP) (EPA, 2022; EPA, 2022) provides a common unit of measure, which allows analysts to summarize emissions of different gases and also to register the emissions that come from the burning of biomass, bearing in mind that this is the dominant fuel for heating in Serbia. The GWP expressed through CO_{2eq} allows policymakers to compare emissions reduction opportunities across different pathways of the energy transition process. Emissions are calculated using the 2006 IPCC Guideline and default emission factors, and they are related to fuel combustion only. Emissions resulting from the use of electricity for heating in Serbia are obtained from a model of the transformation sector built in the LEAP tool, based on experts' knowledge (BGEN, 2023; BGEN, 2023), (MME, 2023; MME, 2023).

3.2. Analyzed policy instruments and related energy scenarios

To assess the effects of different pathways of energy transition in individual heating in households by 2050, six case scenarios are selected. Table 5 shows the specific policy instruments related to these case scenarios. Projections of the final energy demand for heating and its structure in the households characterized by individual heating systems in the base year (both in rural and urban areas) by 2050 are shown in Figs. 5 – 10. All scenarios were developed by applying the proposed methodology of the integrative approach.

3.3. Results

The S1 scenario ("Business as usual") (Fig. 5) is the only scenario that envisaged an increase in final energy demand compared to other scenarios. The main reason for such an inferior result is that this scenario does not consider policy measures to support the transition to more efficient heating in its terms. Also, looking at the structure of consumption, it is observed that inefficient firewood heating stoves will remain the dominant mode of heating until 2050.

In terms of projected energy demand in 2050, S2 and S3 scenarios (Fig. 6 and Fig. 7) are the most similar, which could be interesting for policymakers. Restricting the use of obsolete technologies fueled by firewood and/or coal, and subsidies for the purchase of new and more energy-efficient heating devices, on the other hand, lead to a similar outcome. However, in terms of the structure of energy demand by fuel, S2 is characterized by greater reductions in the consumption of firewood and a significant increase in the electricity consumption for heating, and S3 is characterized by greater consumption of pellets and natural gas. Also, according to S3, wood will remain the dominant energy source, which means that subsidies alone cannot influence the abandonment or significant reduction of firewood consumption by 2050.

In the case of the simultaneous implementation of two proposed

Table 4
Input data for heating technologies (Dincer and Rosen, 2021), (AERS, 2020).

Heating technology	Firewood-based	Electricity-based	Natural gas-based	Pellet-based	Coal-based	Heat pump (Electricity)
Efficiency of transformation to heat	55%	100%	90%	80%	55%	COP = 3

Table 5
Scenario description and related policy instruments.

Scenario #	Description
S1 “Business as usual”	S1 analyzes the current trend of household heating system transition based on the input data and social interactions without external influences of policy measures.
S2 “Restricting fuel combustion in urban areas”	S2 introduces the restriction of buying new coal-based and firewood-based heating systems in all urban areas from 2030 (Karpinska and Śmiech, 2021; Karpinska and Śmiech, 2021).
S3 “Subsidies for more efficient heating”	S3 introduces a government subsidy of 50% for switching firewood and coal-based heating systems and electric heaters with heat pumps, natural gas, or pellet-based heating systems (EC, 2020; EC, 2020).
S4 “Reduction of prices of innovative technology” (S4)	S4 assumes that simultaneously with restrictions for firewood and coal and subsidies, the prices of heat pumps, as a technology innovation (Elia et al., 2021; Elia et al., 2021) for heating in the household sector, are expected to decrease by 2% every year. The cost reductions will make heat pumps more affordable (Mercure et al., 2021; Mercure et al., 2021).
S5 “Energy rehabilitation of residential objects”	S5 envisaged the lower useful energy demand for individual heating in households as a consequence of investing in energy rehabilitation of envelopes of 1% of building stocks annually.
S6 “Aggregated scenario”	S6 analyzes the aggregated effects of S4 and S5.

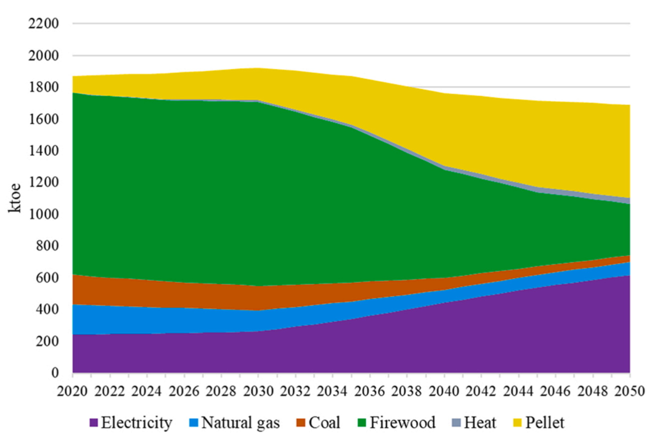

Fig. 6. Energy demand for heating and structure by fuel according to S2.

policy measures (restriction for firewood and coal combustion, and subsidies for efficient heating) and projected decrease in the price of innovative technologies for heating (2% annual price drop of heat pumps for individual heating in households) (Fig. 8), a significant reduction in energy demand can be expected by 2050. The biggest reason for such an outcome is the reduction in the use of firewood-based heating due to the restrictions, and the increase in the share of more efficient options for heating, mainly heat pumps, which are expected to be more affordable and more competitive on the market. Given the efficiency of heat pumps, the increase in their number in households will not lead to a greater increase in electricity consumption for heating, as would be the case with conventional electric heaters and boilers.

The S5 scenario (“Energy rehabilitation”) (Fig. 9) envisaged a lower energy demand compared to S1, S2, and S3, however, it is necessary to

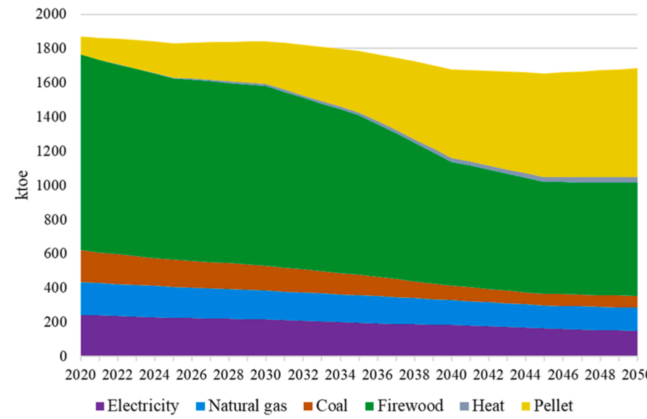

Fig. 7. Energy demand for heating and structure by fuel according to S3.

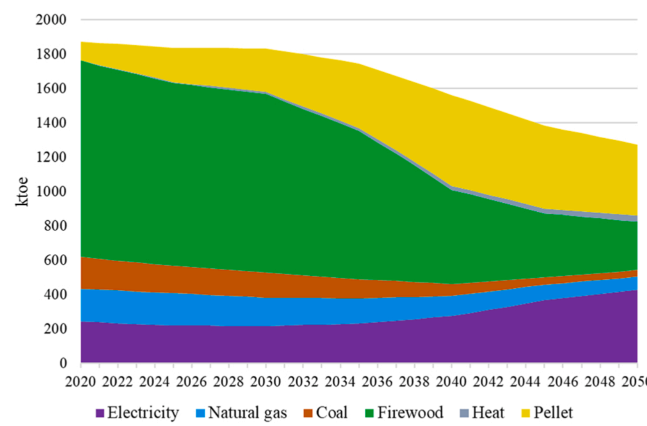

Fig. 8. Energy demand for heating and structure by fuel according to S4.

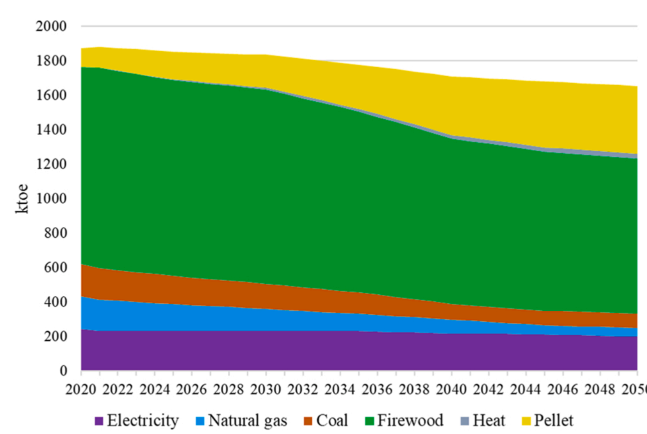

Fig. 9. Energy demand for heating and structure by fuel according to S5.

emphasize that the structure of heating systems will be the same as in the “business as usual” scenario (S1). The reason for the decrease is exclusively lower energy consumption (kWh/m^2), which is a consequence of the energy rehabilitation of buildings.

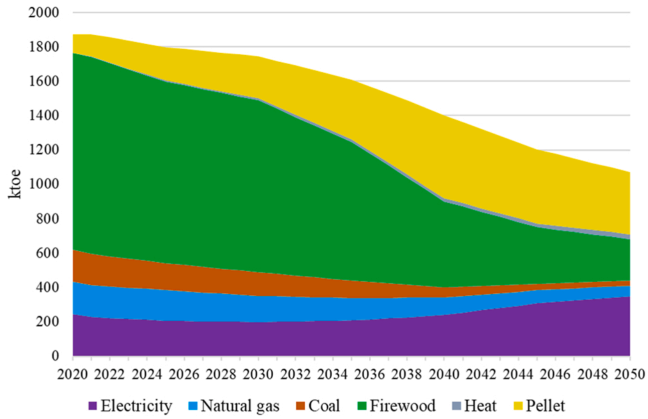

Fig. 10. Energy demand for heating and structure by fuel according to S6.

The biggest decrease in energy demand could be expected in the case of the S6 (Fig. 10) which envisaged the implementation of all proposed policy measures, energy rehabilitation, and a projected decrease in the price of heat pumps for household heating. Practically, in S6 the structure of energy demand is the same, but the energy demand is lower, due to the energy rehabilitation of the buildings.

Table 6 gives a summary of the effects of individual scenarios regarding the energy demand by the end of the analyzed period. As can be seen, energy demand in 2050 can vary from 3% (S1) higher demand for individual heating 2050–43% lower energy demand in case of predicted conditions for the most favorable scenario (S6).

For assessment of GHG emissions, CO_{2eq} emissions (with the resulting emissions from the production of electricity used for heating) from individual heating in households are calculated. Greenhouse gas emissions are presented in units of thousands of tonnes of carbon dioxide equivalent (kt CO_{2eq}). Fig. 11 indicates the potential of each energy transition scenario for GHG emission reduction. If all policies and measures, as well as the projected lower prices of heat pumps, would be implemented and conducted, which is the case of S6, the emissions will be 60% lower than in the case of S1.

Summarizing the results from the test case of the Serbian household sector, it can be concluded that the focus of policy should be directed towards energy savings and reduction of GHG emissions, which can be achieved by reducing useful energy demand together with increasing the efficiency of heating. With the projected reduction of emissions from the electricity generation sector (per produced kWh of electricity), and with the increase in the competitiveness of heat pumps on the market, the policy effects of subsidies, restrictions on wood and coal heating in urban areas, and investments in energy rehabilitation can lead to the most favorable path of energy transition in the Serbian household sector.

Integration has shown that for a more detailed analysis of the household sector, observation of the development of the sector within the wider socio-political context is inevitable. In a certain sense, this confirms the basic hypothesis that it is necessary to take advantage of the integration of different methods and models into a single approach to perceive the impact of the transition in household heating on the entire energy system and its effects on climate change and make the optimal decision in the process of defining and managing the energy policy in the household sector.

Table 6
Energy demand projections, in ktoe.

Scenario #	2020	2030	2040	2050
S1	1876.6	1928.9	1898.3	1931.9
S2	1876.6	1922.4	1761.0	1690.6
S3	1876.6	1843.8	1678.2	1685.3
S4	1876.6	1833.2	1562.2	1272.4
S5	1876.6	1834.3	1710.0	1653.9
S6	1876.6	1743.5	1402.9	1069.6

4. Conclusion

Transformation of household heating, both on the demand and supply sides, by decreasing useful energy demand and changing the manner of meeting needs, represents the foundation for the successful energy transition in the household sector. Special enigmas are the dynamics and achievements of the transition of individual heating. Relying exclusively on expert knowledge in the case of the household energy transition could have failed to provide output that would include real-world data, attitudes, perceptions, and values of heterogeneous consumers as input parameters for the energy model for supporting the energy planning process and exploring the progress of considered policy options.

By the introduction of ABM in the assessment of potential pathways of energy transition in household heating, the perspective and decisions of the end-user are taken into consideration. This ensures that obstacles and drivers for switching to more sustainable heating at the individual level are considered and that their synergistic effect at the level of the entire household sector is quantified. The ABM model for simulating households' behavior related to heating and creating long-term projections of the heating in households contributes to the analysis and early assessment of the effects of policy instruments aimed to accelerate the energy transition. Using the ABM model can serve as a support in the research of fields that remained vague, inadequately or partially researched, or completely neglected. However, this model alone is not sufficient for overall decision support for policymakers. To ensure a wider practical application, it is crucial to integrate the ABM simulation model into a wider framework that would provide such an environment where household behavior and its response to the policy measures and instruments for supporting energy transition could be continuously monitored and evaluated. Such an approach would expand to aspects of transition that do not come exclusively from household heating-related behavior but have an impact on the energy transition in households and on the entire energy system at the local or national level.

The proposed approach in this paper has been predominantly developed to provide a methodology for the holistic planning of transition in household heating to support the decision-making process by integrating the ABM bottom-up approach with expert-based modeling, whose input parameters are primarily conceived as a top-down approach. The proposed framework is developed with the aim of indirectly including technical, social, political, economic, and environmental aspects and their impacts on the energy transition. The methodology is aimed to be used in the decision-making process when assessing the effects of potential policy measures or support mechanisms in the early phase of policy instrument development. This enables timely reconsideration, modification, and adjustment of measures and new testing through the proposed ABM and LEAP models until the preferable outcome is achieved.

As a whole, the practical importance of the proposed approach to support energy planning is primarily reflected in:

- Investigation of the attitudes of end consumers and their behavior related to heating.
- Simulation of different pathways of household heating with projections of the structure of heating devices and input energy sources.
- Quantification of energy savings for different case scenarios and implementation of policy measures.
- Projections of GHG emissions from individual heating in households.
- Possibilities for further assessment of the cost-effectiveness of policy measures.

The results obtained by the proposed approach in the case of the Serbian household sector indicate substantial potential for achieving energy savings in household heating if existing outdated heating devices

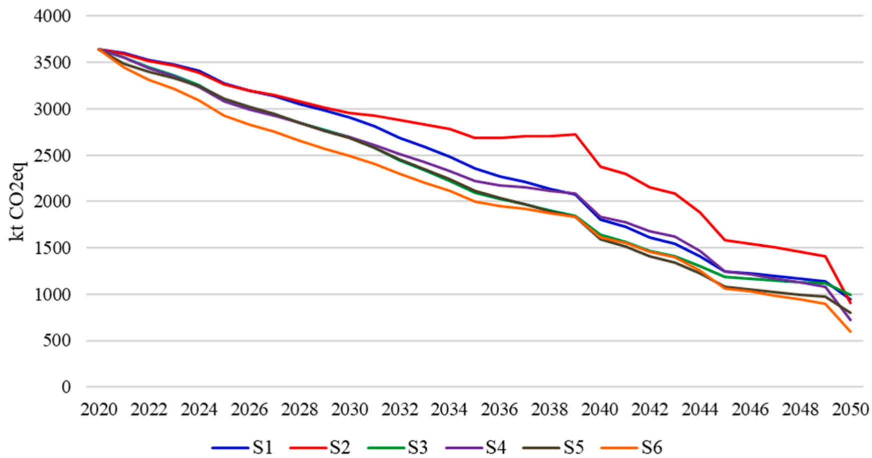

Fig. 11. GHG emissions from individual heating in households.

are replaced by more sustainable technologies, primarily heat pumps, but also if investments are made in the energy rehabilitation of residential objects. With the implementation of policy measures and instruments, it is possible to reduce energy demand in the range between 186 and 807 ktoe. Especially in the case of more massive use of heat pump technology, and by abandoning firewood and stoves and boilers burning solid fuels. With the projected reduction of emissions from the electricity generation sector, a significant reduction of GHG emissions from individual heating in households could be expected for all case scenarios in the range between 2.6 and 3.0 Mt CO_{2eq}. The obtained energy transition pathways provide insight into the effects of certain policy measures and instruments, and the difference between the most ambitious and least ambitious path is the interval in which the outcome of the energy transition in household heating can be expected. The format of the obtained results enables the calculation of selected indicators, which can then be used to set targets in the process of implementing and evaluating the national energy policy.

Analyzing the characteristics of the proposed approach, it can be concluded that the proposed integration approach for energy planning support meets the requirements of scientific research - systematicity, controllability, objectivity, and repeatability. The listed advantages of the proposed approach ensure the integrality and multi-level perspective of the energy transition. The proposed methodology of the integrative approach provides the possibility of reevaluation in certain time intervals, using the same representative sample. This ensures the possibility of correcting the instruments that support the transition, taking into account changes in the energy market and the effects of some other instruments, but also uncertainties that cannot be predicted in advance and captured by the models.

The main limitation is related to data quality. Ideally, the required input data should be updated in a period of one to two years and the trends of certain variables should be observed over a longer time horizon. The complexity of changes that are the subject of research, as well as the household reaction to changes, cannot be simulated in all their complexity, but the trend of changes in the micro and macro environment of households can be observed and conclusions can be drawn about the consequences for energy consumption, GHG emissions, and the whole household energy sector. However, for further development, it would be useful to create more detailed divisions of households by specific characteristics and division of heating technologies which would ensure more precise projections.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property. We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author.

Data availability

Data will be made available on request.

Acknowledgments

This research was supported by the Science Fund of the Republic of Serbia, GRANT 4344, Forward-Looking Framework for Accelerating Households' Green Energy Transition - FF GreEN.

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.

References

AERS, Energy Agency of the Republic of Serbia, 2020. Energy costs for heating residential space. Belgrade (in Serbian): ⟨https://www.aers.rs/g/vesti/file/Dokumenti/2020_10_12%20Grejanje%20CENE%20Okt_2020.pdf⟩. (accessed 1 February 2023).
BGEN (Balkan Green Energy News), 2023. Elektroprivreda Srbije's Go Green Road plan valued at EUR 4.8 billion. ⟨https://balkangreenenergynews.com/elektroprivreda-srbijes-go-green-road-plan-valued-at-eur-4-8-billion/⟩. (accessed 1 February 2023).
Cajot, S., Peter, M., Bahu, J.M., Guignet, F., Koch, A., Maréchal, F., 2017. Obstacles in energy planning at the urban scale. Sustain. Cities Soc. 30, 223–236. https://doi.org/10.1016/j.scs.2017.02.003.
Chang, M., Thellufsen, J.Z., Zakeri, B., Pickering, B., Pfenninger, S., Lund, H., Østergaard, P.A., 2021. Trends in tools and approaches for modelling the energy transition. Applied Energy, 290, 116731. https://doi.org/10.1016/j.apenergy.2021.116731.

Csutora, M., Zsoka, A., Harangozo, G., 2021. The Grounded Survey – An integrative mixed method for scrutinizing household energy behavior. Ecol. Econ. 182, 106907 https://doi.org/10.1016/j.ecolecon.2020.106907.

DHBA Serbia (District Heating Business Association "Toplane Srbije"), 2020. Work Report on the District Heating System in the Republic of Serbia (in Serbian). ⟨https://www.toplanesrbije.org.rs/uploads/ck_editor/files/izvestaj%202019%20S.pdf⟩. (accessed 1 February 2023).

Dincer I., Rosen M.A., 2021. Exergy, Energy, Environment and Sustainable Development. 3rd edition. Elsevier Science. https://doi.org/10.1016/C2016–0-02067–3.

Dioha, M.O., Kumar, A., 2020. Exploring sustainable energy transitions in sub-Saharan Africa residential sector: The case of Nigeria. Renew. Sustain. Energy Rev. 117, 109510 https://doi.org/10.1016/j.rser.2019.109510.

EC (European Commission), 2019. The European Green Deal. ⟨https://ec.europa.eu/info/sites/default/files/european-green-deal-communication_en.pdf⟩. (accessed 1 February 2023).

EC (European Commission), 2020. Stepping up Europe's 2030 climate ambition - Investing in a climate-neutral future for the benefit of our people. ⟨https://ec.europa.eu/transparency/documents-register/api/files/SWD(2020)176_0/090166e5d40db2ad?rendition=false⟩. (accessed 1 February 2023).

Elia, A., Kamidelivand, M., Rogan, F., Gallachóir, B.Ó., 2021. Impacts of innovation on renewable energy technology cost reductions. Renew. Sustain. Energy Rev. 138, 110488 https://doi.org/10.1016/j.rser.2020.110488.

EPA (Environmental Protection Agency), 2022. Understanding Global Warming Potentials. ⟨https://www.epa.gov/ghgemissions/understanding-global-warming-potentials⟩. (accessed 1 February 2023).

Eurostat, 2022. Energy consumption in households. ⟨https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Energy_consumption_in_households_by_type_of_end-use⟩. (accessed 1 February 2023).

Eurostat, 2023. Energy statistics, Energy balances. ⟨https://ec.europa.eu/eurostat/web/energy/data/energy-balances⟩. (accessed 1 February 2023).

Fattahi, A., Sijm, J., Faaij, A., 2020. A systemic approach to analyze integrated energy system modeling tools: A review of national models. Renew. Sustain. Energy Rev. 133, 110195 https://doi.org/10.1016/j.rser.2020.110195.

Felder, F.A., Andrews, C.J., Hulkower, S.D., 2011. Chapter 2 - Which Energy Future? In: Sioshansi, F.P. (Ed.), Energy, Sustainability and the Environment. Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-385136-9.10002-6.

Gielen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorini, R., 2019. The role of renewable energy in the global energy transformation. Energy Strategy Rev. 24, 38–50. https://doi.org/10.1016/j.esr.2019.01.006.

Hainsch, K., Löffler, K., Burandt, T., Auer, H., del Granado, P.C., Pisciella, P., Zwickl-Bernhard, S., 2022. Energy transition scenarios: What policies, societal attitudes, and technology developments will realize the EU Green Deal? Energy 239 (Part C), 122067. https://doi.org/10.1016/j.energy.2021.122067.

Hansen, P., Liu, X., Morrison, G.M., 2019. Agent-based modelling and socio-technical energy transitions: A systematic literature review. Energy Res. Soc. Sci. 49, 41–52. https://doi.org/10.1016/j.erss.2018.10.021.

Heaps, C.G., 2022. LEAP: The Low Emissions Analysis Platform. Stockholm Environment Institute,, Somerville, MA, USA. ⟨https://leap.sei.org⟩. accessed 1 February 2023.

Hobbs, B.F., Meier, P. (Eds.), 2000. Energy Decisions and the Environment. Springer Science+Business Media, New York. https://doi.org/10.1007/978-1-4615-4477-7.

Hu, S., Yan, D., Guo, S., Cui, Y., Dong, B., 2017. A survey on energy consumption and energy usage behavior of households and residential building in urban China. Energy Build. 148, 366–378. https://doi.org/10.1016/j.enbuild.2017.03.064.

IEA (International Energy Agency), 2023. World energy outlook. ⟨http://www.iea.org/weo⟩. (accessed 1 February 2023).

IRENA (International Renewable Energy Agency), 2018. A Roadmap to 2050. ⟨https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf⟩. (accessed 1 February 2023).

Johannsen, R.M., Østergaard, P.A., Maya-Drysdale, D., Mouritsen, L.K.E., 2021. Designing Tools for Energy System Scenario Making in Municipal Energy Planning. Energies 14, 1442. https://doi.org/10.3390/en14051442.

Jovanović, M., Bakić, V., Vučićević, B.S., Turanjanin, V.M., 2019. Analysis of different scenarios and sustainability measurement in the district heating sector in Serbia. Therm. Sci. 23 (3B), 2085–2096. https://doi.org/10.2298/TSCI181009298J.

Karpinska, L., Śmiech, S., 2021. Will energy transition in Poland increase the extent and depth of energy poverty? J. Clean. Prod. 328, 129480 https://doi.org/10.1016/j.jclepro.2021.129480.

Lund, H., Mathiesen, B.V., 2009. Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy 34, 524–531. https://doi.org/10.1016/j.energy.2008.04.003.

Lund, H., Thellufsen, J.Z., Østergaard, P.A., Sorknæs, P., Ridjan Skov, I., Mathiesen, B.V., 2021. EnergyPLAN – Advanced analysis of smart energy systems. Smart Energy 1, 100007. https://doi.org/10.1016/j.segy.2021.100007.

Lund, H., Arler, F., Østergaard, P.A., Hvelplund, F., Connolly, D., Mathiesen, B.V., Karnøe, P., 2017. Simulation versus Optimisation: Theoretical Positions in Energy System Modelling. Energies 10, 840. https://doi.org/10.3390/en10070840.

Macal, C.M., North, M.J., 2010. Tutorial on agent-based modelling and simulation. J. Simul. 4, 151–162. https://doi.org/10.1057/jos.2010.3.

McGookin, C., Gallachóir, B.Ó., Byrne, E., 2021. Participatory methods in energy system modelling and planning – A review. Renew. Sustain. Energy Rev. 151, 111504 https://doi.org/10.1016/j.rser.2021.111504.

Mercure, J.F., Salas, P., Vercoulen, P., Semieniuk, G., Lam, A., Pollitt, H., et al., 2021. Reframing incentives for climate policy action. Nat. Energy 6, 1133–1143. https://doi.org/10.1038/s41560-021-00934-2.

Mirakyan, A., De Guio, R., 2013. Integrated energy planning in cities and territories: A review of methods and tools. Renew. Sustain. Energy Rev. 22, 289–297. https://doi.org/10.1016/j.rser.2013.01.033.

MME (Ministry of Mining and Energy of the Republic of Serbia), 2023. Integrated National Energy and Climate Plan. ⟨https://www.mre.gov.rs/en/node/1429⟩. (accessed 6 February 2023).

Olave, M.S., Vargas-Payera, S., 2020. Chapter 12 - Environmental impact assessment and public participation of geothermal energy projects: the cases of Chile, Costa Rica, Colombia, and Mexico. In: Guimarães, L.N. (Ed.), The Regulation and Policy of Latin American Energy Transitions. Elsevier Science, pp. 209–221. https://doi.org/10.1016/B978-0-12-819521-5.00012-7.

Pavlović, B., Ivezić, D., Živković, M., 2021. State and perspective of individual household heating in Serbia: A survey-based study. Energy Build. 247, 111128 https://doi.org/10.1016/j.enbuild.2021.111128.

Pavlović, B., Ivezić, D., Živković, M., 2022. Transition pathways of household heating in Serbia: Analysis based on an agent-based model. Renew. Sustain. Energy Rev. 163, 112506 https://doi.org/10.1016/j.rser.2022.112506.

Rubino, A., Sapio, A., La Scala, M., 2021. Handbook of Energy Economics and Policy. Academic Press,. https://doi.org/10.1016/C2017-0-01718-4.

Sayegh, M.A., Jadwiszczak, P., Axcell, B.P., Niemierka, E., Bryś, K., Jouhara, H., 2018. Heat pump placement, connection and operational modes in European district heating. Energy Build. 166, 122–144. https://doi.org/10.1016/j.enbuild.2018.02.006.

SEI (Stockholm Environment Institute), 2017. The Long-range Energy Alternatives Planning - Integrated Benefits Calculator (LEAP-IBC). ⟨https://mediamanager.sei.org/documents/Publications/SEI-Factsheet-LEAP-IBC-2.pdf⟩. (accessed 30 January 2023).

Smil V., 2010. Energy transitions: history, requirements, prospects. ABC-CLIO, Santa Barbara.

SORS (Statistical Office of the Republic of Serbia), 2021. Regions in Serbia (In Serbian). ⟨https://publikacije.stat.gov.rs/G2021/Pdf/G202126001.pdf⟩. (accessed 30 January 2023).

SORS (Statistical Office of the Republic of Serbia), 2022a. Energy balances 2020. ⟨https://publikacije.stat.gov.rs/G2022/Pdf/G20225681.pdf⟩. (accessed 30 January 2023).

SORS (Statistical Office of the Republic of Serbia), 2022b. A comparative review of the number of apartments (In Serbian). ⟨https://www.stat.gov.rs/sr-Latn/oblasti/popis/popis-2011/popisni-podaci-eksel-tabele⟩. (accessed 30 January 2023).

Tang, L., Wang, X., Wang, Xi, Shao, C., Liu, S., Tian, S., 2019. Long-term electricity consumption forecasting based on expert prediction and fuzzy Bayesian theory. Energy 167, 1144–1154. https://doi.org/10.1016/j.energy.2018.10.073.

Tian, S., Lu, Y., Ge, X., Zheng, Y., 2021. An agent-based modeling approach combined with deep learning method in simulating household energy consumption. J. Build. Eng. 43, 103210 https://doi.org/10.1016/j.jobe.2021.103210.

Truong, T.M., Amblard, F., Gaudou, B., Blanc, C.S., 2016. CFBM - A Framework for Data Driven Approach in Agent-Based Modeling and Simulation. In: Vinh, P., Barolli, L. (Eds.), Nature of Computation and Communication. Springer, Cham. https://doi.org/10.1007/978-3-319-46909-6_24.

UN (United Nations), 1994. General Assembly United Nations Framework Convention on Climate Change adopted by the General Assembly, A/RES/48/189. ⟨https://www.refworld.org/docid/3b00f2770.html⟩. (accessed 30 January 2023).

UN (United Nations), 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. ⟨https://unfccc.int/resource/docs/convkp/kpeng.pdf⟩. (accessed 30 January 2023).

UN (United Nations), 2015. Paris Agreement. ⟨https://sustainabledevelopment.un.org/content/documents/17853paris_agreement.pdf⟩. (accessed 30 January 2023).

Valkenburg, G., Gracceva, F. Chapter 8 - Towards Governance of Energy Security, in: {C} Lombardi, P., Gruenig, M.{C} (Eds.), Low-carbon Energy Security from a European Perspective. Academic Press. https://doi.org/10.1016/B978–0-12–802970-1.00008–5.

Waisman, H., Bataille, C., Winkler, H., Jotzo, F., Shukla, P., Colombier, M., et al., 2019. A pathway design framework for national low greenhouse gas emission development strategies. Nat. Clim. Change 9, 261–268. https://doi.org/10.1038/s41558-019-0442-8.

Wang, Z., Zhao, Z., Lin, B., Zhu, Y., Ouyang, Q., 2015. Residential heating energy consumption modeling through a bottom-up approach for China's Hot Summer–Cold Winter climatic region. Energy Build. 109, 65–74. https://doi.org/10.1016/j.enbuild.2015.09.057.

Wilensky, U., Rand, W., 2015. An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with Netlogo. The MIT Press,, Cambridge.

Živković, M., Pereverza, K., Pasichnyi, O., Madžarević, A., Ivezić, D., Kordas, O., 2016. Exploring scenarios for more sustainable heating: The case of Niš, Serbia. Energy 115, 1758–1770. https://doi.org/10.1016/j.energy.2016.06.034.