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Energy Sufficiency in the Household Sector of Lithuania and Hungary: The Case of Heated Floor Area

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Abstract: Economic development and rising welfare lead to higher demand for energy services, which can limit or even negate the results of costly energy efficiency (EE) upgrades. At present, some consumption patterns in Central and Eastern European countries are more sustainable compared to the European Union (EU) average but are rapidly approaching it. Energy sufficiency (ES) leading to an absolute reduction in energy demand will be essential for achieving net zero climate goals, as it will contribute to reducing energy use and the significant investment needs associated with the electrification of the energy system. Various regulatory solutions can be deployed in pursuit of ES targets, but little information is available on the possible impacts on energy use and greenhouse gas (GHG) emissions, especially at the national level. This paper focuses on the residential building sector of two Central and Eastern European countries: Lithuania and Hungary. It attempts to quantify the potential energy demand reduction, associated GHG savings and the resulting change in the energy mix from limiting the per capita heated floor area using scenario analysis with the MESSAGE and HU-TIMES energy system models. The findings suggest that final energy demand could be reduced by 3.6% in Lithuania and 0.9% in Hungary. This would lead to a change in the energy production mix resulting in lower GHG emissions and savings on new energy generation capacity. The results of the research are indicative, as no costs were assigned to ES measures and the calculations were based on assumed levels of ES indicators. However, they suggest that it is worth identifying the consumption segments with ES potential, as a combination of the relevant measures can largely contribute to the achievement of net zero emissions.

Keywords: sustainability; behaviour change; climate change mitigation; energy sufficiency; households; indicators and assumptions; floor area per capita; potential; impacts

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1. Introduction

Like other European Union (EU) Member States, Lithuania and Hungary have been addressing the key global issue of climate change in their climate and energy agendas [1–3]. Lithuania committed to cutting greenhouse gas (GHG) emissions by 70% by 2030, 85% by 2040 and 100% by 2050 [3], and Hungary by 40% by 2030 and 100% by 2050 [4]. Although the most significant reductions are expected in the sectors covered by the EU emission trading system (EU-ETS), non-EU-ETS sectors are also very important. In Lithuania, sectors falling outside the EU-ETS will have to lower GHG emissions by at least 25% (compared to 2005 levels) and in Hungary by 7% (by 2030), the latter probably rising to 18.7% according to the proposal in the "Fit for 55" regulatory package [5]. These ambitious GHG emission targets require changes in the energy systems that need to undergo significant transformations. Currently, the transformations are being planned and implemented mainly on the supply side of energy systems [6] at a scale determined by the gradual phase-out of fossil fuels and rapid penetration of renewables and sustainable fuels [7]. Meanwhile, on the demand side, Lithuania will reduce primary and final energy intensity by 2.4 times and Hungary will reduce final energy consumption (FEC) by at least 30% by 2050 [7], as outlined in national energy efficiency (EE) strategies.

According to Cordroch et al. [8] and Saheb [9], three decades of climate mitigation actions can fail, as renewables and EE are not enough to limit global warming to 1.5 °C, making reductions in energy service demand crucial. Therefore, energy sufficiency (ES), which thus far is an underrepresented climate mitigation strategy tool, favouring low energy services and change in behaviour and lifestyles, should be recognised as an additional pillar to EE and renewables [10,11]. Best et al. (2022) reviewed European and national policies and identified 281 policy instruments from seven sectors falling under ES [11]. The majority can be found in the transport and building sectors. While modal shifts from cars to public transport and active modes like walking and cycling dominate in the transport sector, the policy instruments in the building sector are of the "avoid" type. They aim at " ... an efficient use of living space and development of the existing building stock, focusing on quality of living and by that reduce overall living space and required land sealing ... " [11]. FORESIGHT Climate & Energy [12] found a widespread shortage of ES measures in Europe.

ES in Lithuania's National Energy Climate Plan 2030 (NECP2030) is mainly related to changing consumer behaviour by promoting eco-driving, inland waterway transport, public road transport or cycling and the emergence of co-transport services. It includes measures to reduce energy poverty and agreements between energy suppliers to train and advise consumers on energy savings. Hungary's NECP2030 and Long-term Strategy (LTS) [7] highlight the importance of incentives for public transportation and increased use of non-motorised transport modes. The National Energy Strategy [13] also encourages measures to promote teleworking. However, ES has not yet appeared on the strategic policy agenda for buildings.

A review of national strategic documents shows that ES is overlooked in both Lithuania and Hungary and potential positive impacts are not understood in any economic sector. Scenario analysis needed for planning national energy strategies would require the identification of energy services with the highest ES potential and the estimation of the possible future values of key ES indicators. These potential values are strongly influenced by the socio-economic and cultural context and the main policy orientations of the countries, which are also important to consider for the estimation of ES potential. Among others, Zell-Ziegler et al. [14] stress the need for evaluating ES policies and their interrelationship with other policies as part of energy and climate strategies.

Taking this into account the research aims at assessing the potential impact of ES in households towards national energy and climate targets in Lithuania and Hungary.

The goal of the research is (1) to explore whether the Lithuanian and Hungarian household sectors have ES potential; (2) to identify ES indicators in households and establish assumptions for their development in the countries; (3) to calculate related reductions in fuels and energy consumption; (4) to identify changes in energy production structures and (5) to assess the related GHG emissions.

The research results are valuable from the perspective of national energy and climate target setting and related climate change mitigation strategies. The results support ES as a relevant approach to supplement renewable energy deployment and EE contributing to reductions in GHG emissions. They initiate the discussion on policy measures unlocking ES potential in households.

The rest of the paper is organised as follows. Section 2 reviews the literature on the concept of ES and its potential impact. Section 3 overviews the development of household energy consumption in Lithuania and Hungary. Section 4 introduces the research method applied, explaining the assumptions, scenarios and modelling. Section 5 presents the results of the analysis, including the reductions in energy consumption, changes in the energy production structure and GHG emissions. Section 6 discusses the results. Finally, Section 7 draws conclusions.

2. Literature Review

2.1. Concept of Energy Sufficiency

There are several concepts of sufficiency presented in scientific publications from different disciplines. Jungell-Michelsson et al. [15] stated that "... sufficiency is understood both as an end in itself and as a means of ensuring that consumption and production stay within ecological limits ...". In general, sufficiency is a transdisciplinary concept about "enoughness". Spengler [16] claims that "enoughness" can refer to two different types of limits—minimum and maximum levels, which are closely related, and their combination determines the concept of sustainability. Many researchers share the view that sufficiency requires substantial changes in consumption, including Sandberg [17], Niessen et al. [18], Freudenreich et al. [19], Bocken et al. [20] and Lorek et al. [21]. According to Sandberg [17], sufficiency can be related to four types of changes in consumption patterns: absolute reduction, modal shift, product longevity and sharing practices. However, the transition to sufficient consumption is hampered by a number of barriers, including consumer attitudes and behaviour, the economic and political system and culture [15,17,22].

The limitation of current global energy demand and its gradual reduction towards a sustainable level is a key component of decarbonisation pathways. Hence, ES can play an important role. It is defined as a state in which people's basic needs for energy services, including space and water heating, space cooling, cooking, lighting and electrical appliances for washing, drying, freezing, etc., are met equitably and ecological limits are respected [23]. ES policies encourage change in behaviour and lifestyles of end-users in a way that consumption of energy services is limited or reduced towards sustainable levels [24,25] focusing on micro, individual actions, as well as collective agreements [26]. It should be highlighted that reaching ES goals does not necessarily entail a reduction in the well-being of consumers because lower consumption does not lead to substantial utility loss in case of overconsumption. Also, ES can be improved when the demand for energy services is met in a different way (e.g., online administration or teleworking instead of car use, etc.), and thus, should be accompanied by technological and infrastructure development. At the same time, the significant positive gains for energy users, including improved air quality, more green areas, less noise, increased social interactions, etc., contribute to increased well-being [26–28].

2.2. Potentials and Impacts of Energy Sufficiency

Literature on the potential impact of ES is scarce but has intensified during the past decade at micro and macro levels [29,30]. A review of the recent literature on the potential impact of ES is presented in the following sub-sections, identifying the areas of research, the results achieved and the gaps that this research aims to fill. The review mostly focuses on indicators, policies and initiatives for ES.

2.2.1. Micro-Level Research

Micro-level research refers to the analysis of ES actions taken by a single entity, be it a household [29] or groups of individuals. Brischke [31] found that the energy-saving potential of ES can be twice as much as that of EE, and the typical household in Germany could save up to 75% of electricity by pursuing both EE and ES policies. Fuerst et al. [32] showed that in the United Kingdom (UK) large households (up to 10 members) consume up to 10 times less gas for space heating per capita than small households. Ivanova and Büchs [33] found that in the EU, the per capita carbon and energy footprint of a single-person household is about twice of that households with five or more members. They examined household economies of scale (change in carbon footprint and energy use with rising household size) considering consumption categories and urban-rural typology, as well as the social, cultural, geographic, infrastructural and political context. They concluded that policies should encourage larger household sizes and higher occupation of dwellings, e.g., through home-sharing, although, according to their results, the potential savings are much larger in Northern and Central Europe than in Southern and Eastern European countries. Ali et al. [34] investigated the factors that determine the electricity consumption of households in an expanding city in Malaysia and identified household income (socio-economic factor) and the number of rooms (housing variable) to be the most important determinants of electricity consumption. They found that a person living in a flat can reach 48% higher electricity savings compared to a person living in a single-storey house (bungalow). Navamuel et al. [35] draw attention to the increasing electricity consumption in Spain caused by the higher energy use of detached houses built as part of urban sprawl growth. Underwood and Zahran [36] highlighted a trend towards smaller and wealthier households, leading to increased carbon dioxide (CO_2) emissions.

In addition to quantitative research, qualitative research focusing on the impact of ES is deep, especially for teleworking and sharing, including accommodation. This research is a valuable starting point for the possible quantification of the costs and benefits of energy user behaviour change. The impacts of teleworking were analysed by Hooks et al. [37], de Vries et al. [38], Karacsony [39], Catana et al. [40], Belostecinic et al. [41] and Ferrari et al. [42], showing that teleworking is closely related to well-being, productivity, workers' flexibility, autonomy, work-life balance, mental and physical health and safety, cost reductions, job satisfaction, etc. According to studies by Enochsson [43], Song et al. [44], Ginindza and Tichaawa [45] and Barron et al. [46], accommodation sharing impacts urban liveability, safety and the job market. It can cause a rise in the price of rents and houses in the short term but help vacancy rates fall in the long term.

2.2.2. Macro-Level Research

Macro-level ES research is concerned with communities, countries or even the whole world using a traditional energy scenario approach. After the ES lifestyle analysis in the established Global Energy scenario, Samadi [47] concluded that the most cited studies principally ignore the potential of possible behavioural changes towards ES lifestyles, although several attempts to integrate ES into future Global Energy scenario studies in a quantitative manner were made. Mainly, this refers to behavioural changes in the transport sector in the form of modal shifts. Researchers identified several international studies which explicitly examine the lifestyle changes within scenarios to 2032 [48] and 2050 [49]. Saheb [50] claimed that during 1990–2018 EE improvement reduced emissions by 324 $MtCO_2$, equivalent to 34% of 1990 emissions, while the lack of ES measures increased emissions by 306 $MtCO_2$, equivalent to 32% of 1990 emissions, largely as the result of increased floor area per capita. The WEO defined three 2040 pathway scenarios [51] considering consumer behaviour and acceptance next to other factors. Despite changing consumer habits, the consumers in all three scenarios increase energy consumption. However, socially responsible energy behaviour results in the decoupling of economic growth from energy demand. IEA [52] prepared the Net-Zero Emissions by 2050 Scenario, which requires a broad range of policy tools and technologies, including behavioural changes to reduce excessive or wasteful energy use, modal shifts in transport and efficient use of materials. They found that decreasing space heating and cooling temperatures in buildings to 19–20 °C and 24–25 °C on average, respectively, as well as excessive hot-water temperatures could reduce global energy demand and emissions by 10% by 2050. The results of the Global Urban Density scenarios, prepared by Guneralp et al. [53] showed that urban density impacts future energy use as much as EE. In all Global Urban Density scenarios, the advanced energy technologies result in heating and cooling savings of about 7 EJ/year. Grubler et al. [54] collected household activity data and quantified the related energy intensity for major energy services to calculate energy savings. Based on a bottom-up approach, and using an integrated assessment framework, they found that global final energy demand could be 245 EJ by 2050, 40% lower than in 2018. They claimed that downsizing the energy systems makes the supply side transformation much more feasible for reaching the 1.5 °C climate target without using negative emission technologies [54]. Millward-Hopkins et al. [55] estimated the final energy demand associated with decent living standards (defined by Rao and Min [56]) for a list of basic material needs for the global population in 2050, also using a bottom-up model). By combining the proposed activity levels with the associated energy intensities, they estimated that the global final energy demand could be reduced to 149 EJ in 2050, or 15.3 GJ per capita, 60% less than today.

Country-specific scenarios were also developed. Kenkmann et al. [57] estimated the energy and CO_2 saving potential of limiting average dwelling floor area per capita (44.2 m^2/cap) in Germany to be 15 TWh a year and around 3.4 $MtCO_{2eq}$. The négaWatt Association [10] published an Energy Transition scenario for France based on the pillars of ES, EE and renewables, showing that ES could enable a 23% reduction in FEC by 2050 compared to 2020, reducing emissions from 480 to 71 $MtCO_{2eq}$. Surahman et al. [58] investigated household energy consumption in urban residential buildings of major cities in Indonesia during the COVID-19 pandemic and found that average annual consumption actually increased with more appliances like air conditioning in use. They recommended measures to control household size and encourage energy-saving lifestyles. Eyre et al. [59] developed a scenario analysing the impact of lifestyle changes in the UK, finding that lifestyle changes can reduce national energy use and CO_2 emissions by 35%. de Almeida et al. [60] estimated the potential electricity savings of EU households through existing technologies and behaviour changes to be 48%. Researchers also highlight the importance of behaviour change in electrical equipment selection and operation. van Sluisveld et al. [61] defined lifestyle measures related to space heating, water heating, appliance use and waste management. The analysis showed that a 15% reduction in CO_2 emissions can be achieved by reducing the use of energy appliances and changing hot water preparation habits. Zozmann et al. [62] analysed the potential of ES measures and their impact on the supply side of a 100% renewables system in Germany, finding that FEC could be reduced by up to 20.5%, with 11.3–25.6% cost saving. It identified the heating sector to have the greatest potential for ES measures.

3. Energy Consumption Trends

Lithuania is about two-thirds the size of Hungary with about a quarter of the population [63]. In 2020, the gross domestic product (GDP) per capita of Lithuania was EUR 17,810 and EUR 14,140 in Hungary representing 0.4% and 1% of the EU's GDP respectively [64]. As shown in Figure 1, Lithuania's economic sectors consume about three times less energy than Hungary (please note the different magnitudes of measurement units on the two axes of the following graphs).

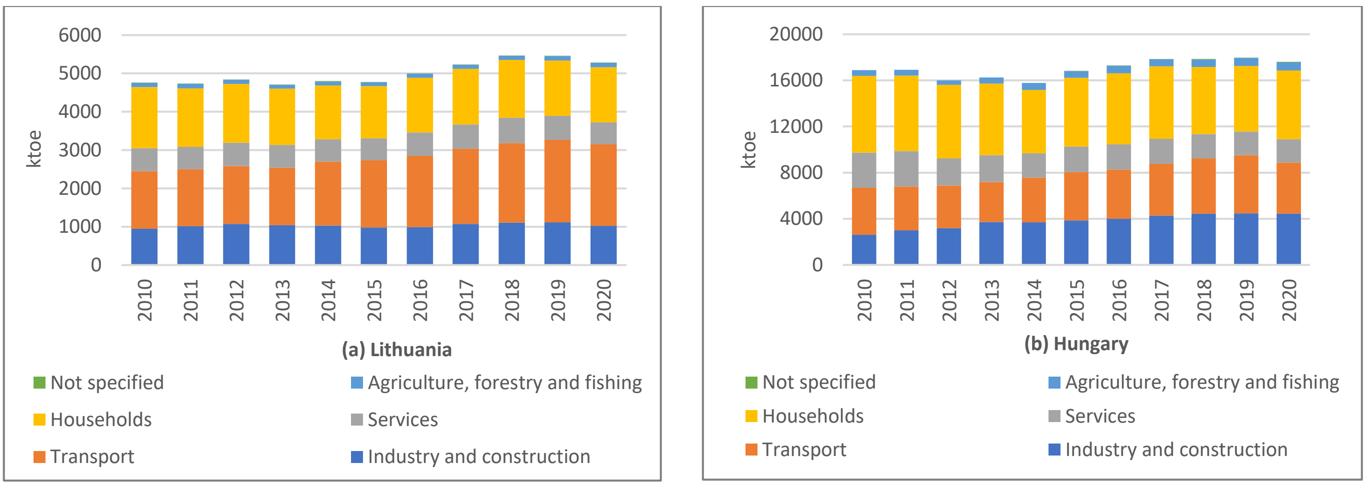

Figure 1. Final energy consumption by sector in Lithuania and Hungary, ktoe (Eurostat, [65]).

The FEC grew by 1.1% a year in Lithuania and 0.4% in Hungary over the last decade. In 2020, Lithuania's FEC was 5284.2 ktoe and 17601.5 ktoe in Hungary. Although household energy consumption declined by 1.1% a year in both countries, it remains one of the highest consuming sectors, with a share of 27% in Lithuania and 34% in Hungary (2020). Therefore, there is great potential for ES in this segment.

Figure 2 shows the composition of household energy consumption by end-use in both countries.

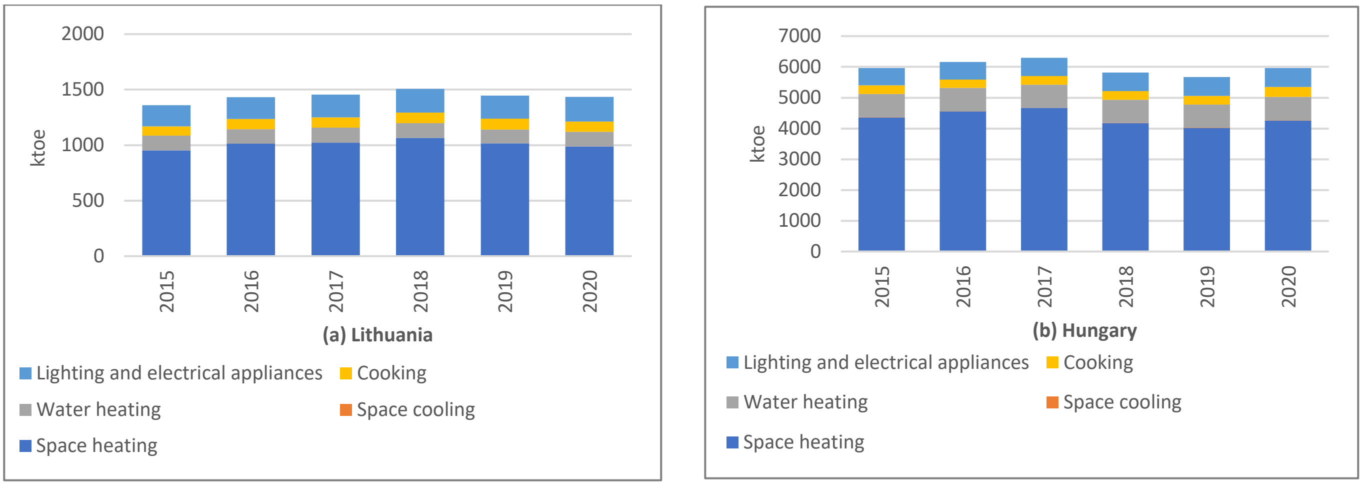

Figure 2. Household energy consumption by end-use in Lithuania and Hungary, ktoe (Eurostat [66] and Lithuanian Statistics [67]).

Households use about 70% of their energy for heating, equating to 988.8 ktoe in Lithuania and 4257.5 ktoe in Hungary (2020). Water heating in Hungary (13% in 2020) and lighting and electrical appliances in Lithuania (15% in 2020) also represented important shares, while cooking and cooling remained minor (up to 7%). The high share of heating in total household energy use suggests that ES related to heating is worth analysing further.

The composition of energy use for space heating by fuel can be seen in Figure 3.

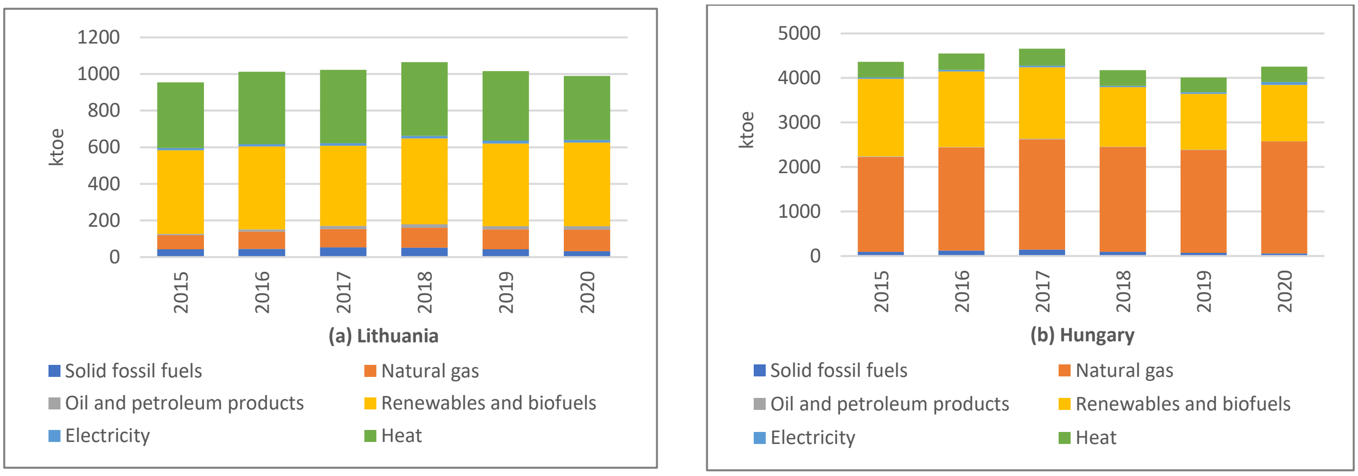

Figure 3. Energy used for household space heating by fuel in Lithuania and Hungary, ktoe (Eurostat [66] and Lithuanian Statistics [67]).

In Lithuania, renewables (45%) and district heat (DH) (38%) make up the majority of space heating energy use, while in Hungary it is natural gas (up to 60%) and renewables (34%). Since the GHG emission reduction potential of ES measures is significantly impacted by the initial energy mix, ES measures might result in lower savings in Lithuania than in Hungary. Natural gas consumption in space heating for Hungarian households has increased by 3.4% while renewables have declined by 6.2%, mostly firewood and garden residuals burnt in outdated stoves. The variation in gas and wood consumption was influenced by the relative cost of gas and firewood under the regulated household energy price regime in Hungary [68]. The energy price regulation (utility rate cut) introduced in 2013 kept household utility rates at a near-constant level until 2022, following the phased 20% reduction. In Lithuania, natural gas consumption increased by about 8.8% over the 10-year period with renewables remaining stable, but DH decreased by 0.6% due to EE measures.

The trends and fuel structure of energy consumption suggest that ES-driven reductions in households are worth researching in both countries. Energy for heating can be reduced through several ES interventions, the most important of which are related to the amount of total floor area heated. Other possibilities include changing the related routines and behaviour, e.g., setting lower temperatures for heating and changing, adjusting ventilation, heating only part of the buildings, etc. Unfortunately, information related to these behavioural changes is limited, therefore, heated floor area was the focus of the research.

4. Methodology

Our analysis attempted to answer: What is the energy-saving potential of ES in households? How will the structure of energy production change as a result? What is the associated impact on GHG emissions?

Based on the energy consumption trends highlighted earlier, the use of heating energy in households was selected as the focal point of this analysis. Assumptions for determining Hungary's and Lithuania's average household size and the 2050 sufficiency value of per capita floor area were based on ES potential estimations in the relevant literature and national trends. This part of the analysis relied on the work previously done in the frame of the CACTUS research project [69].

The calculations were done using national energy system models: the MESSAGE for Lithuania and HU-TIMES for Hungary. Each shares common traits, such as bottom-up partial equilibrium models of the national energy sectors, based on linear programming. The MESSAGE model is "... a system engineering optimization model used for planning medium to long-term energy systems, analysing climate change policies and developing scenarios, for national or global regions. It allows determining cost-effective portfolios of GHG emission limitation and reduction measures" [70]. The HU-TIMES model is also used for planning future energy systems taking into account technological options, by using a social cost-minimising approach with exogenous final demands and other pre-defined macroeconomic factors (such as GDP, population and fuel prices). The specificities of the models in the context of the current energy paradigm are well described by Spittler et al [71].

The analysis relied on time series data for the period of 2008–2020 collected from the databases of Lithuania Statistics, Hungarian Central Statistical Office, Eurostat, ODYSSEE-MURE [72], the NECPs2030 and the Long-term Strategies of Hungary, as well as the Energy Independence Strategy of the Republic of Lithuania (NEIS2050 [1]). This 12-year time horizon allowed us to identify trends and project them to 2050, in line with the roadmap of the European Green Deal.

4.1. The Calculation of Energy Savings Potential

Lithuania's NEIS2050 and the NECP2030 served as a starting point to identify the key determinants of household energy consumption. Under the former's Base (non-green) scenario the household final energy demand ($EEHC_t$) was forecasted based on indicators like GDP, energy price, energy substitution and energy savings, from the previous year fed into the econometric model developed by Lithuanian Energy Institute (LEI) [73].

The two models already take into consideration EE technologies, meaning that Baseline scenario outcomes reflect EE potential without accounting for ES. To determine the additional energy savings potential from ES measures, the "sufficient" heated floor area had to be estimated.

The total floor area of the heated dwelling stock ($HDWS_t$) was calculated based on:

$$HDWS_t = FA_{person,t} \times HS_t \times NoH_t \quad (1)$$

$HDWS_t$—total floor area of heated dwelling stock in year t, (thousand m^2); $FA_{person,t}$—useful floor area per person in year t, (m^2/person); HS_t—household size in year t, [persons]; NoH_t—number of households in year t, (thousand units). $FA_{person,t}$ based on historical data, literature review and regression analysis. Each household has only one heated dwelling for ES. Therefore, the number of households (NoH_t) is the underlying determinant of heated dwelling stock.

NoH_t was calculated based on:

$$NoH_t = P_t : HS_t \tag{2}$$

P_t—population in year t (thousand persons). The projections of P_t were taken from the Eurostat database [63].

Energy-sufficiency-related consumption in households $(ESHC_t)$ in Lithuania based on:

$$ESHC_t = HDWS_t \times FEC_t \tag{3}$$

$ESHC_t$—energy sufficiency related consumption in households in year t, (ktoe), FEC_t—final energy consumption in households per m^2 in year t, (kgoe/m^2). FEC_t was fixed to the average level of 2008–2020.

The formula for the saving potential is the following:

$$\Delta EHC_t = ESHC_t - EEHC_t \tag{4}$$

ΔEHC_t—ES reduction in fuel and energy consumption relative to energy efficiency in households; $EEHC_t$—final energy demand of households in year t under the Base (non-green) scenario of NEIS2050, [ktoe]. $EEHC_t$ includes the impact of EE measures.

For Hungary, the Early Action scenario of the Hungarian LTS [7] was used as the Baseline scenario. The analysis focused on household final heating and hot water demand ($FEC_{h,t}$), while the Lithuanian analysis was based on total household energy consumption ($EEHC_t$, also including EE for lighting, cooking and appliances). This does not make any difference for the ES savings potential (the difference between energy use with and without sufficiency) but is necessary because of the different building module makeup of the national models. In the HU-TIMES model, ($FEC_{h,t}$) is defined exogenously. The model incorporates data on dwellings categorised according to a national building typology of 23 building types (including 4 newly built) characterised by special initial heating and hot water energy consumption per m^2. The number of dwellings in the model adjusts annually with the changes in population and average household size. The demand for heating energy and hot water for a given building type ($FEC_{h,t,BT}$) in year t (ktoe) is calculated based on the number of dwellings ($NoDW_{t,BT}$, the average dwelling size (ADS_{BT}) (m^2) and the specific consumption per m^2 ($FE_{h,BT}$ (ktoe/m^2) of the building types (BT) according to the following formula:

$$FEC_{h,t,BT} = NoDW_{t,BT} \times FE_{h,BT} \times ADS_{BT} \tag{5}$$

The endogenous net final energy consumption in the Baseline scenario ($NFEC_{h,t,BT,baseline}$) represents final heating and hot water demand ($FEC_{h,t,BT}$) minus the endogenously calculated energy savings due to the energy efficiency measures ($EEHC_{h,t,BT}$) selected by the model for each year (t) and building type (BT) modelled:

$$NFEC_{h,t,BT,baseline} = FEC_{h,t,BT} - EEHC_{h,t,BT,baseline} \tag{6}$$

EE investments are technologies built into the model with corresponding cost profiles. Given that the HU-TIMES model is a social cost-minimising optimisation model, these EE investments can be used as least-cost solutions while meeting the final energy demand and considering different constraints. In determining whether and to what extent to apply these EE solutions, both the endogenously determined net final demand $NFEC_{h,t,BT}$—the actual end-use consumption and the energy savings ($EEHC_{h,t,BT}$) are outputs of the model. The above-mentioned assumptions provide the basis for both the baseline and alternative scenarios in the Hungarian modelling exercise. Under the Sufficiency scenario, the estimation of the net final energy consumption (described in Equation (6)) is extended by considering ES in households as follows:

$$NFEC_{h,t,BT,sufficiency} = FEC_{h,t,BT} - EEHC_{h,t,BT,sufficiency} - ESHC_{h,t,BT} \quad (7)$$

$ESHC_{h,t,BT}$ depicts the energy savings due to exogenously determined ES measures for each building type (BT) in year t. The total energy saving potential is the difference between the sum of the savings related to all building types in the Sufficiency and Baseline scenarios:

$$\Delta NFEC_{h,t} = NFEC_{h,t,sufficiency} - NFEC_{h,t,baseline} = ESHC_{h,t} + \left(EEHC_{h,t,sufficiency} - EEHC_{h,t,baseline}\right) \quad (8)$$

4.2. Sufficient Levels of Indicators in 2050

Assumptions for key indicators of household ES were derived from projections of the population (P_t) to 2050 (Figure 4).

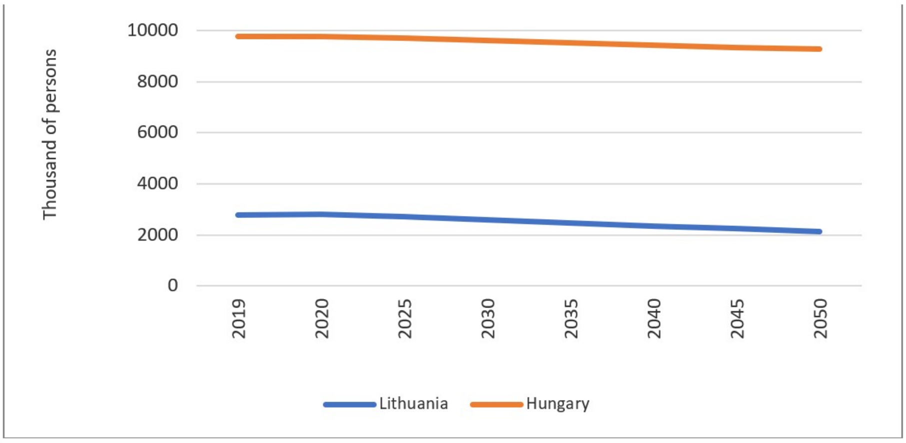

Figure 4. Population in Lithuania and Hungary to 2050, in persons (Eurostat [74]).

As shown in the graph, the population (P_t) will fall by almost 23% in Lithuania to 2,137,900 and by 5% in Hungary to 9,270,400 by 2050. This is mainly a result of emigration and negative natural change in the countries.

To construct the Sufficiency scenarios for each country, there was a need to estimate "sufficient values" for the average household size and per capita floor area for 2050. The CACTUS research project [75] provided these estimates based on literature, the review of economic and socio-cultural trends and policies and expert dialogue. This analysis relied on ES estimations from studies covering regions that include Lithuania and Hungary. The indicators used in our models drew on Grubler et al. [54], Millward-Hopkins et al. [55], Bierwirth and Thomas [76] the negaWatt Association [10] and Kuhnhenn et al. [77]. The historical trends and their projected development to 2050 were included in the Sufficiency scenarios.

Table 1 shows the values of ES indicators in the base year (2017) and their assumed levels for 2050 relative to the literature.

Table 1. Assumptions for key sufficiency indicators used in the modelling.

Indicator	Abbreviation	Theoretical Ranges for 2050 from Literature	Lithuania		Hungary	
			Base Year Data (2017)	Assumed Level for 2050	Base Year Data (2017)	Assumed Level for 2050
Average household size, in persons	HS_t	2–4 [55]	2.2 *	2.2 **	2.3 [78]	2.15 ***
Average floor area per person, m^2 per person	$FA_{person,t}$	29 [54]–35 [76]	33.2 *	32.3 **	28.44 [79]	max. 35.0 for new buildings [52] in [50]
Number of households, thousand units heated	NoH_t	-	1357.0 *	971.8 **	4134	4304.7
Heated dwelling stock, million m^2	$HDWS_t$	-	100.19 *	68.97 **	278.63	286.49

Notes: * Lithuanian Statistics [67], ** Own estimation, *** projections based on [78] and used in the HU-Times model.

The assumptions in the literature regarding the potential for HS_t range from 2 to 4 persons [55,77,80]. The average HS_t decreased in both Lithuania and Hungary over the past decade, following the European trend of improving living standards and a higher share of smaller households consisting of one or two people [81]. The average HS_{2050} is assumed to stabilise at 2.2 persons in Lithuania and fall to 2.15 in Hungary.

Bierwirth and Thomas [76] suggest that the sufficient $FA_{person,t}$ should be between 30 and 35 m^2, while Rao and Min [56] and Grubler et al. [54] determined 29–30 m^2 per person to be sufficient. According to the historical trends, $FA_{person,t}$ increased in both countries, like the rest of Europe, showing increased wealth goes together with higher per capita floor area [50]. In Lithuania, the average $FA_{person,2017}$ was 33.2 m^2. After applying the power function to historical $FA_{person,t}$ data, it was assumed that $FA_{person,2050}$ could reach 32.3 m^2. This corresponded to the value estimated based on the 2020 "Energy saving" survey, suggesting that $FA_{person,t}$ could be 31 m^2 [82]. In Hungary, the $FA_{person,2017}$ for the assessed building stock was 28.44 m^2 [79], which is smaller than the sufficient value set for Lithuania. Therefore, the modelling assumption is that the area of newly built dwellings cannot exceed 35 m^2 per capita which is the average of Global scenarios aiming at a 1.5 °C temperature increase in 2050 [9].

Changes in P_t and HS_t will presumably lead to declining NoH_t. The NoH_{2050} will fall by 28% in Lithuania compared to the NoH_{2017} and will amount to 971.8 thousand in 2050. The decline will be less significant in Hungary than in Lithuania in relative terms, 4304.7 thousand households in 2050 according to the calculations.

The assumed $FA_{person,t}$ and HS_t, would correspond to 71.1 m^2 average dwelling size in Lithuania and 80.5 m^2 in Hungary in 2050. In Hungary, the size of the newly built building types having higher than 35 m^2 floor area per capita (calculated with the average household size) will be limited to meet the ES assumption. As a result, the total heated dwelling stock ($HDWS_{2050}$) will decrease by 31% in Lithuania and by 13% in Hungary and will amount to 68.97 million m^2 and 286.49 million m^2, respectively.

4.3. Scenarios and Modelling

The Sufficiency scenarios were created using the above-presented assumptions for the average household size and sufficient floor area in 2050. Although both the MESSAGE and the HU-Times model are social cost-minimising mathematical optimisation models, and cost parameters play a crucial role in finding the optimal solution, the models did not explicitly model ES, due to the lack of information about the associated costs and benefits. Therefore, at this initial stage of the research, the costs related to the implementation of ES were not considered. ES was exogenously applied by reducing the final energy demand by $\Delta EH_{consumption,t}$ (MESSAGE) and by $\Delta NFEC_{h,t}$ (HU-Times). This approach also allowed us to analyse the deployment of EE investments with or without ES in households.

To better explore the impact of ES in households, no CO_2 emission limits were set in Lithuania, but the price of CO_2 would rise from 52 EUR/t in 2020 to 104 EUR/t in 2030 and then remain constant until 2050. However, in Hungary, the model works within the constraint of a gradual limitation of emissions to net zero by 2050, and therefore it was not possible to calculate GHG savings specifically linked to ES.

Due to these limitations, the results should be taken as indicative of the direction and scale of possible effects.

5. Results

5.1. Impact on the Level of Energy Consumption

The next figures present the results of modelling with the above-presented assumptions. As Figure 5 shows, Lithuania has more energy-saving potential than Hungary.

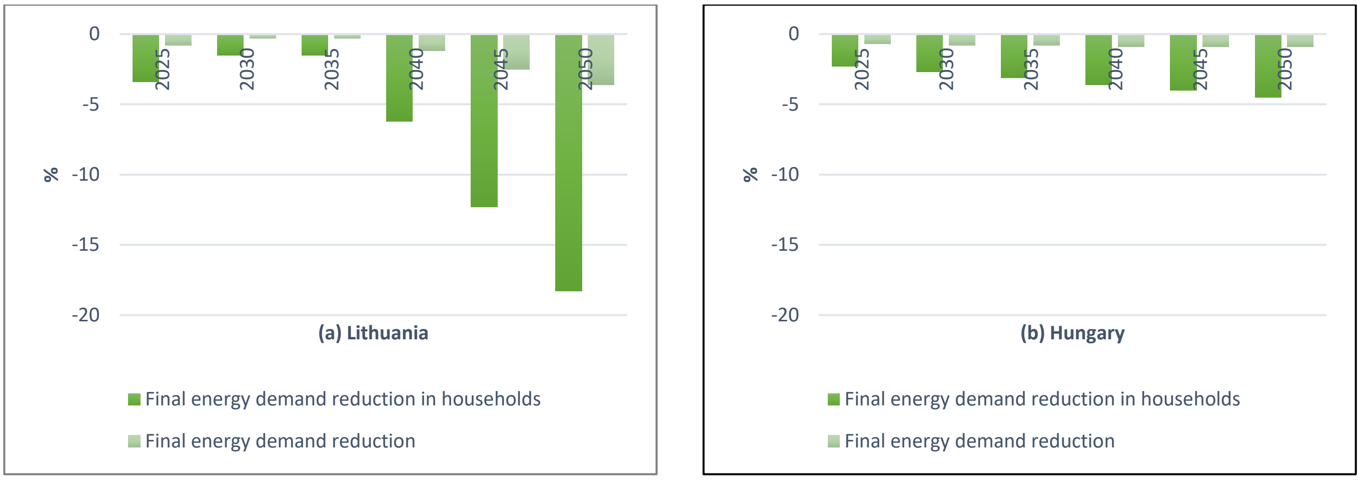

Figure 5. Change in household energy consumption due to ES in Lithuania and Hungary, % (own estimations).

In the short term, Lithuania's annual reduction in household energy consumption is small (around 1.5% per year) but grows to 18.3% by 2050 compared to the *Baseline scenario* (which already takes EE measures into account). This corresponds to an FEC reduction of 3.6% or 240 ktoe by 2050. The relative impact of ES measures is more linear in Hungary and less significant in percentage terms. This is because the average dwelling size can only be limited by the size of new build dwellings larger than 35 m^2 per capita. In reality, this only holds true for one of the new build dwelling categories and does not entail significant reductions in total heated floor area. The annual reduction in FEC for households varies between 2.3% and 4.5% year-on-year. Similarly, final energy demand falls linearly from 0.7% to 0.9% per year by 2050. In absolute terms, the savings from the size limitation of new buildings is estimated at 210 ktoe. The estimations prove that a change in dwelling size results in energy savings that are greater the closer a household gets to a sufficient floor area per capita.

5.2. Impacts on the Energy Production Mix

The fall in energy consumption under the *Sufficiency scenario* is attributable to a reduction in electricity and DH production. Figure 6 shows the change in the final electricity demand and the electricity generation by fuel for both countries.

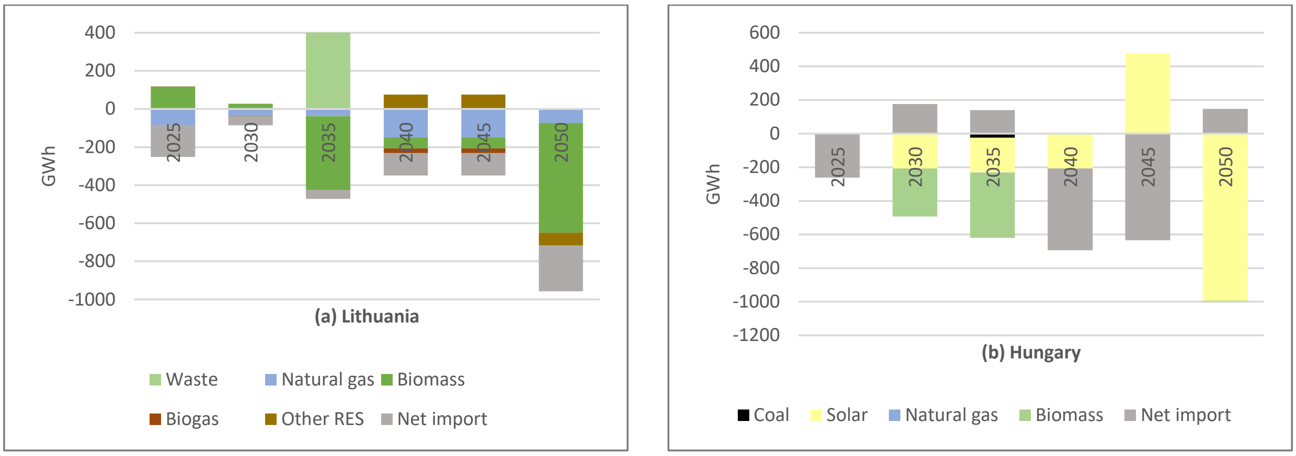

Figure 6. Change in the electricity generation mix under the Sufficiency scenario compared to the Baseline scenario in Lithuania and Hungary, GWh (own estimations).

In Lithuania, the final electricity demand will grow in the future under any scenario, but at different rates. Under the Baseline scenario, it will increase by 4.5% a year, but under the Sufficiency scenario the increase is expected to be lower than −4.3% a year—suggesting that in the Sufficiency scenario the growth slows from 111 GWh (1%) in 2025 to 811 GWh (4.6%) in 2050, resulting in 4,381 GWh cumulative electricity savings over the period. Lithuania will be self-sufficient in electricity generation with mainly renewable energy sources, with a 92% share in 2050, but the share of natural gas increases to about 20% by 2040. The country will produce 24.1 TWh of electricity under the Sufficiency scenario, 2.9% less than under the Baseline scenario. The use of biomass, followed by natural gas and other renewable energy sources, will decrease by 577, 72 and 67 GWh, respectively, by 2050. Electricity exports will increase, accounting for 7.8% of electricity generation in 2050 compared to 6.6% in the Baseline scenario. However, net imports of electricity will decrease by 241 GWh in 2050.

In Hungary, electrification is one of the four main preconditions for reaching a net zero economy by 2050. Therefore, the installed capacity of non-fossil fuel-based power plants (PPs) and electricity consumption are expected to increase significantly in the Baseline scenario. Final electricity demand is projected to increase to 110.3 TWh by 2050, largely met by solar PPs (62% of domestic demand), nuclear and biomass PPs (17% and 10%, respectively) and net imports (8% of domestic electricity demand). The difference in final electricity consumption falls between 0.2% to 1.3% which corresponds to 155 and 850 GWh.

Figure 7 shows the change in the DH production by source for both countries.

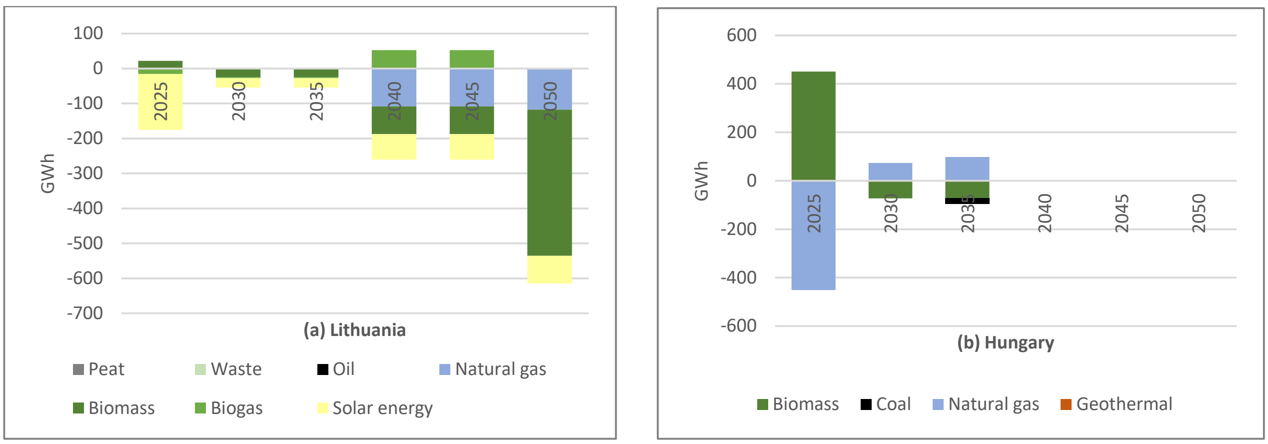

Figure 7. Changes in DH production by source, compared to the Baseline scenario in Lithuania and in Hungary, GWh (own estimations).

As a result of DH EE policies, Lithuania's final demand for DH will fall by 17% between 2017 and 2050 under the Baseline scenario. Under the Sufficiency scenario, it reaches 22%, or an extra saving of 614 GWh in 2050, consisting of less biomass (by 418 GWh), natural gas (115 GWh) and solar heat production (79 GWh). The cumulative DH savings will be 4007 GWh. Most of this will come from reduced consumption of biomass (34%), natural gas (30%) and solar energy (11%). Under the Sufficiency scenario, biogas consumption will increase by 53 GWh per year over the last two decades.

For Hungary, DH declines significantly between 2025 and 2050 in the Baseline scenario, from 14.4 TWh to 5.5 TWh. It is replaced by electricity in the residential, commercial and industrial sectors, and hydrogen in the industrial sector. Due to the large-scale energy efficiency investments and electrification required to get to net zero by 2050 in the household sector, DH consumption in Hungarian households will be eliminated by 2050. This explains why ES has no impact on the level and composition of DH production in the Sufficiency scenario.

Achieving sufficient consumption of energy services would also reduce total installed capacity, as shown in Figure 8.

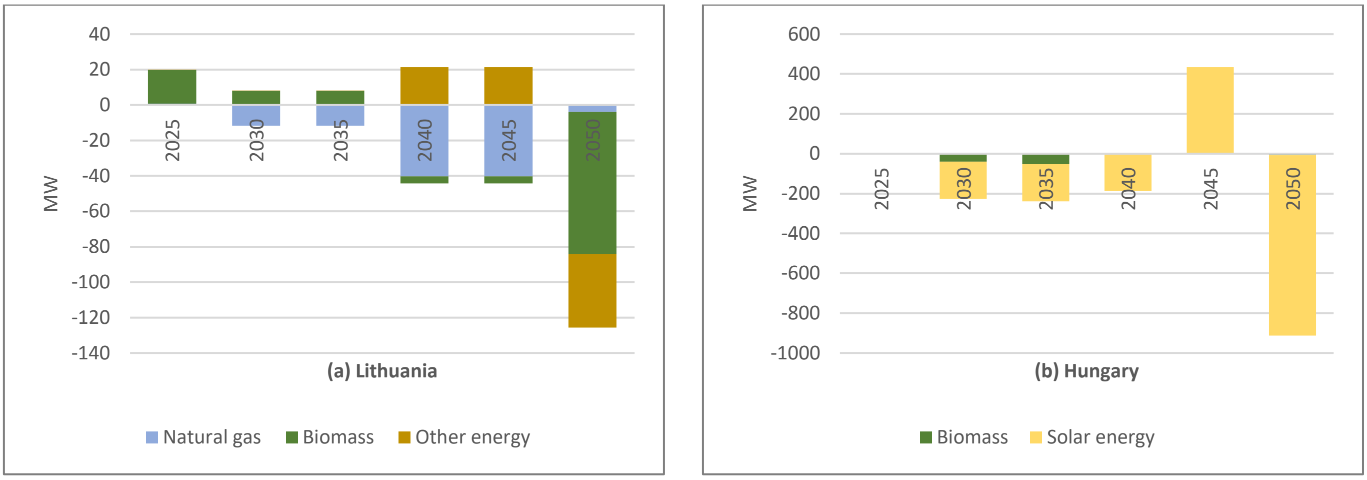

Figure 8. Changes in installed capacity due to ES in households of Lithuania and Hungary, MW (own estimations).

In Lithuania, under the Sufficiency scenario, the total installed capacity will decrease by 125 MW in 2050, mainly affecting biomass capacity, which will be 80 MW lower, followed by a reduction of 41 MW for other energy and 4 MW for natural gas. The reduction will be 1.3%.

Under the Baseline scenario, Hungary's installed PP capacity increases from 12 GW in 2025 to 67.1 GW in 2050. At the end of the period, baseload electricity is mainly provided by nuclear (2.4 GW) and biomass with carbon capture, use and storage (CCUS) technology (1.5 GW_e). Furthermore, solar capacity is expected to reach 62.5 GW, requiring an additional 10 GW of electricity storage capacity to maintain the balance between power supply and demand. Lower final energy demand under the Sufficiency scenario decreases the amount of electricity needed for heat pumps, which displaces 1 GW capacity over the modelling period.

The results of impacts on the energy production mix demonstrated that due to ES consumption in households the electricity and DH savings could be accumulated. However, they are assessed as minor taking into account the assumption of limiting the floor area per capita in the countries.

5.3. Impacts on Greenhouse Gas Emissions

As shown in Figure 9, household ES reduces CO_2 emissions in Lithuania and Hungary.

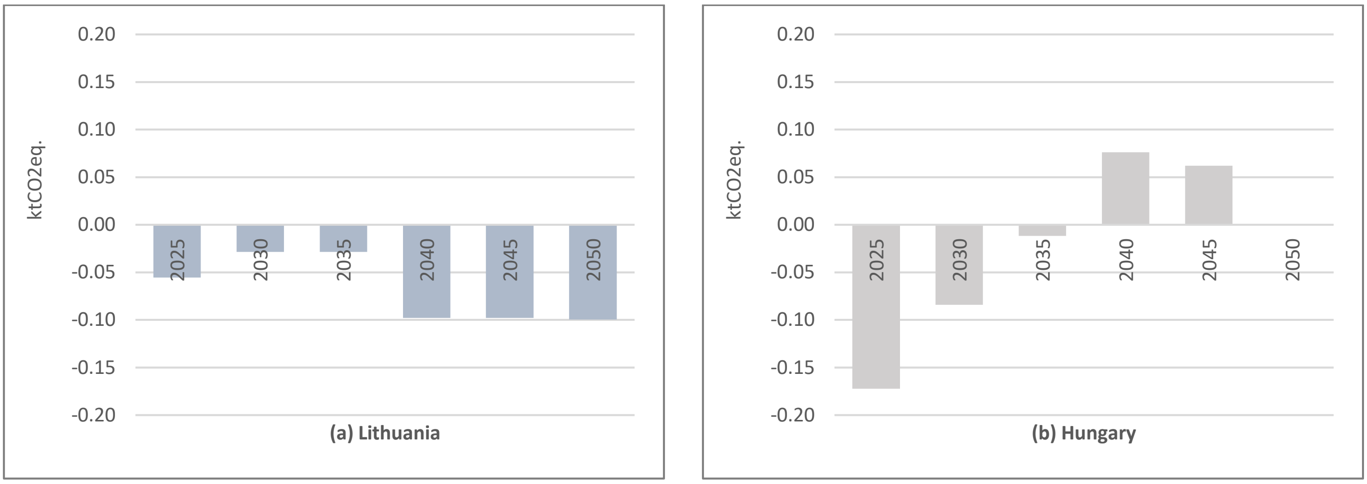

Figure 9. Change in CO_2 emissions due to ES in Lithuania and Hungary, $ktCO_{2eq}$. (own estimations).

In Lithuania, CO_2 emissions fall by 0.03–0.1 kt per year mainly due to reductions in household natural gas consumption, saving 1.63 $ktCO_{2eq}$ over the period. In Hungary, the impact of ES on GHG emissions is mainly driven by modelling assumptions. Since sufficiency potential is exogenous, the reduction in final energy demand reduces household fossil fuel consumption until 2040, and fewer reductions are needed in other end-use sectors to meet mitigation goals (compared to the Baseline scenario). However, these investments, which would otherwise occur in the industry sector, are only delayed requiring less abatement in the household sector over the same period.

6. Discussion

The high dependency on fossil fuel imports and limited access to energy for some segments of society will amplify the need for fair and reduced consumption of fuels and energy, especially in light of the current geopolitical situation. While the national energy strategies of Lithuania and Hungary focus on renewables and EE, behavioural and lifestyle changes are rarely addressed, and ES is not seriously considered a tool for decarbonisation, security of supply and energy poverty. Increased energy prices have induced some changes in the attitudes of energy users, but they are unlikely to stick once the prices normalise.

The present research and our previous findings in Bartek-Lesi et al. [83] and Konstantinaviciute et al. [84] show that ES-driven changes in energy consumption practices in the residential buildings and transport sectors can contribute to the decarbonisation of energy sectors The potential value of ES contribution varies according to the energy consumption area. For example, our analysis of the indicator of per capita floor area resulted in relatively lower savings, while higher savings can be achieved by reducing transport demand [83,84]. The combined effect of ES across different energy demand segments can be instrumental for meeting ambitious EU targets at relatively low cost. In addition, ES-driven behavioural and lifestyle changes can save both fossil fuel and renewable energy use. This will help diversify from Russian fossil fuels outlined in the REPowerEU plan [85] and require lower energy system costs and peak demand costs [86].

In addition to the direct benefits of ES highlighted above, indirect benefits should also be considered. Less PPs and a lower need for biomass in heating will lower emissions and improve quality of life and mental well-being, thereby reducing public health expenditures [87]. The pattern of household income distribution shifts from satisfying physiological needs to providing higher needs of self-actualisation [88]. The faster climb to the top of the Maslow pyramid [88] shifts the pattern of time use in favour of time spent on developing creativity and learning.

ES-oriented practices should be promoted to unlock the energy-saving potential of behavioural and lifestyle changes in Lithuanian and Hungarian households. According to Durande [89], ES initiatives and solutions should be implemented across different levels of governance (for example, region, city and community). In Germany, ES measures are usually implemented at local and community levels and financially supported by national programs of the relevant Ministry. Considering the assumptions of lower floor area per capita and stabilised household size, a number of possible ES policy measures have been identified: encouraging elderly people living in oversized dwellings to move to smaller dwellings; supporting investors in building or renovating dwellings in which the total floor area does not exceed a given m^2; promoting rooms for shared use and co-living; supporting the establishment of multifunctional spaces (bubbles) for work, leisure and living; imposing fiscal measures on real estate, and banning the construction of individual houses in certain areas with taxes in areas of urban sprawl; taxing vacant dwellings.

Our research has its limitations. We focused on the role of reducing the per capita heated floor space assuming that average household size will stabilise for effective policies. ES indicators were based on assumptions from the literature, which might not incorporate the full potential of households in the assessed countries. In the Hungarian modelling, the reduction in average heated floor area per capita only accounted for new buildings without considering the possibility of decreasing per capita living space in existing buildings. However, some policies can cause an increase in the average household size, thus reducing the number of households and occupied dwellings (such as encouraging co-tenancy).

It is important to note that the modelling is based on national averages for the selected ES indicators, which masks the heterogeneity of groups of households belonging to different income categories. In reality, reaching sufficiency would increase the consumption of energy services for some and lower it for others. Also, the current modelling does not consider dwellings that are not in use, albeit in order to preserve the fabric of the buildings, and also because of occasional use, they consume some amount of energy. An additional question to analyse could be how to utilise vacant buildings instead of new builds since many unused flats are purchased as investments.

The limitations of ES modelling need to be addressed in the future. A detailed cost–benefit analysis could help to assess the impacts of ES, including the personal costs to consumers changing their daily routines. The modelling will also need to be extended to a wider range of ES indicators.

7. Summary and Conclusions

So far, there is little research investigating the potential energy savings from ES at the national level, especially for lower-income economies with lower per capita consumption compared to more developed EU countries. This study aims to help fill the gap by analysing the effects of ES in the residential building sectors of Lithuania and Hungary.

Floor area is an important determinant of heating energy use, which is responsible for about 70% of the energy consumption of households in both countries. ES assumptions for 2050 were based on relevant literature and the political, socio-economic and cultural context in the countries. The sufficient floor area was assumed to be 32 m^2 per capita for Lithuania and 35 m^2 per capita for Hungary. Two national energy system models, the MESSAGE and HU-TIMES were used for modelling, which are dynamic partial equilibrium models used for scenario analysis and energy policy planning in the two countries. The most recent net-zero climate and energy strategy scenarios formed the Baseline scenario, which already considered the planned energy efficiency measures and their impacts. In the Sufficiency scenario, ES assumptions were set exogenously.

The analysis shows that Lithuania has higher energy savings potential than Hungary in relative terms (3.6% and 0.9% of final energy consumption, respectively), albeit the absolute savings deviate less (240 and 210 ktoe), because of the latter's larger population. Although the savings do not appear to be significant, per capita floor area is only one of the potential sources of sufficiency in residential buildings. Its effect, however, cannot be neglected, especially supplementing other emission abatement options, for example, lower temperatures set in the dwellings or changes in cooling and hot water consumption practices. The current energy crisis and high energy prices prompted residential users to rethink their energy consumption routines, although it remains to be seen if changes will be maintained. Nevertheless, these energy consumption segments are the subject of further analysis to determine savings potentials, expected impact and appropriate regulatory solutions. Another area of improvement for the modelling involves the assessment and inclusion of personal costs for changing energy use practices, as well as the estimation of indirect costs and benefits, such as external costs.

The goal of current and future analysis is to draw the attention of policymakers to the energy-saving potential inherent in ES, which can significantly contribute to reaching the ambitious climate targets set by the EU at relatively low costs while mitigating the necessary investment costs required for the expansion of electricity systems and upgrading existing grids to serve the net-zero economy.

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